International Telecommunication Union

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Radiocommunication Sector of ITU

Recommendation ITU-R M.1177-4

(04/2011)

Techniques for measurement of unwanted emissions of radar systems

M Series

Mobile, radiodetermination, amateur and related satellite services

International Telecommunication Union

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Note: *This ITU-R Recommendation was approved in English under the procedure detailed in Resolution ITU-R 1.*

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RECOMMENDATION ITU-R M.1177-4*

Techniques for measurement of unwanted emissions of radar systems

(Question ITU-R 202/5)

(1995-1997-2000-2003-2011)

Scope

This Recommendation provides two techniques for the measurement of radiated radar unwanted emissions. It should be used to measure the spurious domain emissions and to check emission power against limits specified in Appendix 3 (Section II) of the Radio Regulations (RR), or to measure the level of unwanted emissions falling within the out-of-band domain.

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 *considering* 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 Recommendation ITU-R SM.329 specifies the maximum values of unwanted emissions in the spurious emission domain from radio transmitters;

f) that Recommendation ITU-R SM.1541 specifies the generic limits for unwanted emissions in the out-of-band domain,

recommends

1 that measurement techniques as described in Annex 1 should be used to provide guidance in quantifying radiated unwanted emission levels from radar stations operating above 400 MHz;

2 that measurement techniques as described in either Annex 1 or Annex 2 should be used, as appropriate based upon radar design, to provide guidance in measuring radiated unwanted emission levels for radar stations operating between 50 MHz and 400 MHz;

3 that measurement techniques described in Annex 2 should be used to provide guidance in quantifying radiated unwanted emission levels from radar stations operating below 50 MHz.

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

Annex 1

Measurement of unwanted emissions of radar systems as detailed in *recommends* 1 and 2

1 Introduction

Two measurement techniques known as the direct and indirect methods are described.

The direct measurement method is recommended and measures unwanted emissions from all radars including those that preclude measurements at intermediate points within the radar transmitters. Examples include those which use distributed-transmitter arrays built into (or comprising) the antenna structure.

The indirect method separately measures the components of the radar and then combines the results. 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.

2 Reference bandwidth

For radar systems, the reference bandwidth, B_{ref}, used to define unwanted emission limits (Recommendations ITU-R SM.329 and ITU-R SM.1541, and RR Appendix 3) should be calculated for each particular radar system. For the four general types of radar pulse modulation utilized for radionavigation, radiolocation, acquisition, tracking and other radiodetermination functions, the reference bandwidth values are determined using the following formulas:

– for fixed-frequency, non-pulse-coded radar, one divided by the radar pulse length (e.g. if the radar pulse length is 1 μs, then the reference bandwidth is 1/1 μs = 1 MHz);

– for fixed-frequency, phase-coded pulsed radar, one divided by the phase chip length (e.g. if the phase coded chip is 2 μs long, then the reference bandwidth is 1/2 μs = 500 kHz);

– for FM or chirped radar, the square root of the quantity obtained by dividing the chirp bandwidth (MHz) by the pulse length (μs) (e.g. if the FM is from 1 250 MHz to 1 280 MHz or 30 MHz during the pulse of 10 μs, then the reference bandwidth is $(30 \text{ MHz}/10\ \mu\text{s})^{1/2} = 1.73$ MHz);

– for radars operating with multiple waveforms the reference bandwidth is determined empirically from observations of the radar emission. The empirical observation is performed as follows: the measurement system receiver is tuned to one of the fundamental frequencies of the radar, or is tuned to the centre frequency within the chirp range of the radar. The measurement system bandwidth is set to the widest available value, and the received power level from the radar in this bandwidth is recorded. The measurement bandwidth is then progressively narrowed, and the received power level is recorded as a function of the bandwidth. The end result is a graph or table showing measured power as a function of measurement system bandwidth. The required bandwidth is the smallest bandwidth in which the full power level is still observed and the reference bandwidth can be calculated from a knowledge of the impulse response of the measurement receiver using the factor, measurement bandwidth ratio (MBR), as described below. If a reduction in power level is observed immediately, then the widest available bandwidth should be used.

In all cases, where the bandwidths above are greater than 1 MHz, then a reference bandwidth, B_{ref}, of 1 MHz should be used.

3 Measurement bandwidth and detector parameters

The measurement bandwidth, B_m, is defined as the impulse bandwidth of the receiver and is greater than the IF bandwidth, B_{if}, (sometimes referred to as resolution bandwidth for spectrum analyzers). The measurement bandwidth, B_m, may be derived from the following equation:

$$B_m = B_{if} \times MBR$$

The MBR needs to be determined for the measurement receiver being used. MBR is approximately 3/2 for a –3 dB IF bandwidth Gaussian filter as typically used in many commercial spectrum analyzer receivers (in some instruments the IF bandwidth is defined at the –6 dB point).

An appropriate receiver IF bandwidth should be selected to give one of the following recommended measurement bandwidths.

Measurement bandwidth B_m[1]

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

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

≤ $(B_c/T)^{1/2}$ for swept-frequency (FM, or chirp) radars, where B_c is the range of frequency sweep during each pulse and T is the pulse length (e.g. if radar sweeps (chirps) across the 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 bandwidth should be ≤ $((30\text{ MHz})/(10\ \mu\text{s}))^{1/2} = \sqrt{3}$ MHz ≈ 1.73 MHz. In accordance with footnote [1] a measurement bandwidth close to but less than or equal to 1 MHz should be used in this example.

≤ the result of a measurement is as follows: for radars operating with multiple waveforms the measurement bandwidth is determined empirically from observations of the radar emission. The empirical observation is performed as follows: the measurement system receiver is tuned to one of the fundamental frequencies of the radar, or is tuned to the centre frequency within the chirp range of the radar. The measurement system bandwidth is set to the widest available value, and the received power level from the radar in this bandwidth is recorded. The measurement bandwidth is then progressively narrowed, and the received power level is recorded as a function of the bandwidth. The end result is a graph or table showing measured power as a function of measurement system bandwidth. The appropriate measurement bandwidth will be the bandwidth where the first reduction of the full power level is observed. If a reduction in power level is observed immediately, then the widest available measurement bandwidth should be used.

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[1] In all cases, if the above derived measurement bandwidth is greater than 1 MHz, then the corrections described in § 3.2 should be used.

Video bandwidth ≥ measurement system bandwidth.

Detector positive peak.

3.1 Measurements within the out-of-band domain

Within the out-of-band (OoB) domain, the limits given in Recommendation ITU-R SM.1541 are defined in dBpp. This is a relative power measurement and an IF bandwidth leading to a measurement bandwidth less than the reference bandwidth should be used. Even if the measurement bandwidth is less than the reference bandwidth no correction needs to be done, since both the peak of the spectrum and the data points within the OoB domain are measured using the same measurement bandwidth B_m.

Measurements should generally be made using a bandwidth that is close to but less than the specified reference bandwidth. This approach will minimize the measurement time but it also causes some broadening of the measured spectrum. Thus in marginal situations, where measurement of the true close in spectrum shape may be important, it is recommended that the close-in region within the OoB domain should be re-measured using a maximum bandwidth of $0.2/T$ or $0.2/t$ as appropriate.

3.2 Measurements within the spurious domain

3.2.1 Correction of the measurement within the spurious domain

Where the measurement bandwidth, B_m, differs from the reference bandwidth, B_{ref}, a correction factor needs to be applied to the measurements conducted within the spurious domain to express the results in the reference bandwidth. Then the following correction factor should be applied:

$$\text{Spurious level, } B_{ref} = \text{Spurious level (measured in } B_m) + 10 \times \log(B_{ref}/B_m)$$

NOTE 1 – This correction factor should be used except where it is known that the spurious is not noise-like, where a factor between 10 and 20 $\log(B_{ref}/B_m)$ may apply and may be derived by measurements in more than one bandwidth. In all cases the most precise result will be obtained using a measurement bandwidth (B_m) equal to the reference bandwidth. For radars operating above 1 GHz the reference bandwidth (B_{ref}) is 1 MHz.

3.2.2 Correction of the measurement data to the peak envelope power

Within the spurious domain, the limits given in RR Appendix 3 are defined in a reference bandwidth, B_{ref}, with respect to the peak envelope power (PEP). Data recorded in dBpp within the spurious domain must be referenced to the PEP (and not the spectrum peak observed in dBpp).

The PEP is approximated using the following correction formulae:

For continuous wave (CW) and phase coded pulses:

$$PEP = P_{meas} + 20 \times \log(B_{pep}/B_m) \qquad \text{for } B_{pep} > B_m$$

For swept-frequency (FM or chirp) pulsed radars:

$$PEP = P_{mes} + 10 \times \log(B_c / (B_m^2 \times T)) \qquad \text{for } (B_m^2 T) / B_c < 1$$

where:

PEP: peak envelope power;

P_{meas}: spectrum peak power (B_m);

B_{pep}: bandwidth calculated according to the following:

– for fixed-frequency, non-pulse-coded radar, one divided by the radar pulse length (s) (e.g. if the radar pulse length is 1 μs, then B_{pep} is 1/1 μs = 1 MHz);

– for fixed-frequency, phase coded pulsed radar, one divided by the phase chip length (s) (e.g. if the phase coded chip is 2 μs long, then B_{pep} is 1/2 μs = 500 kHz);

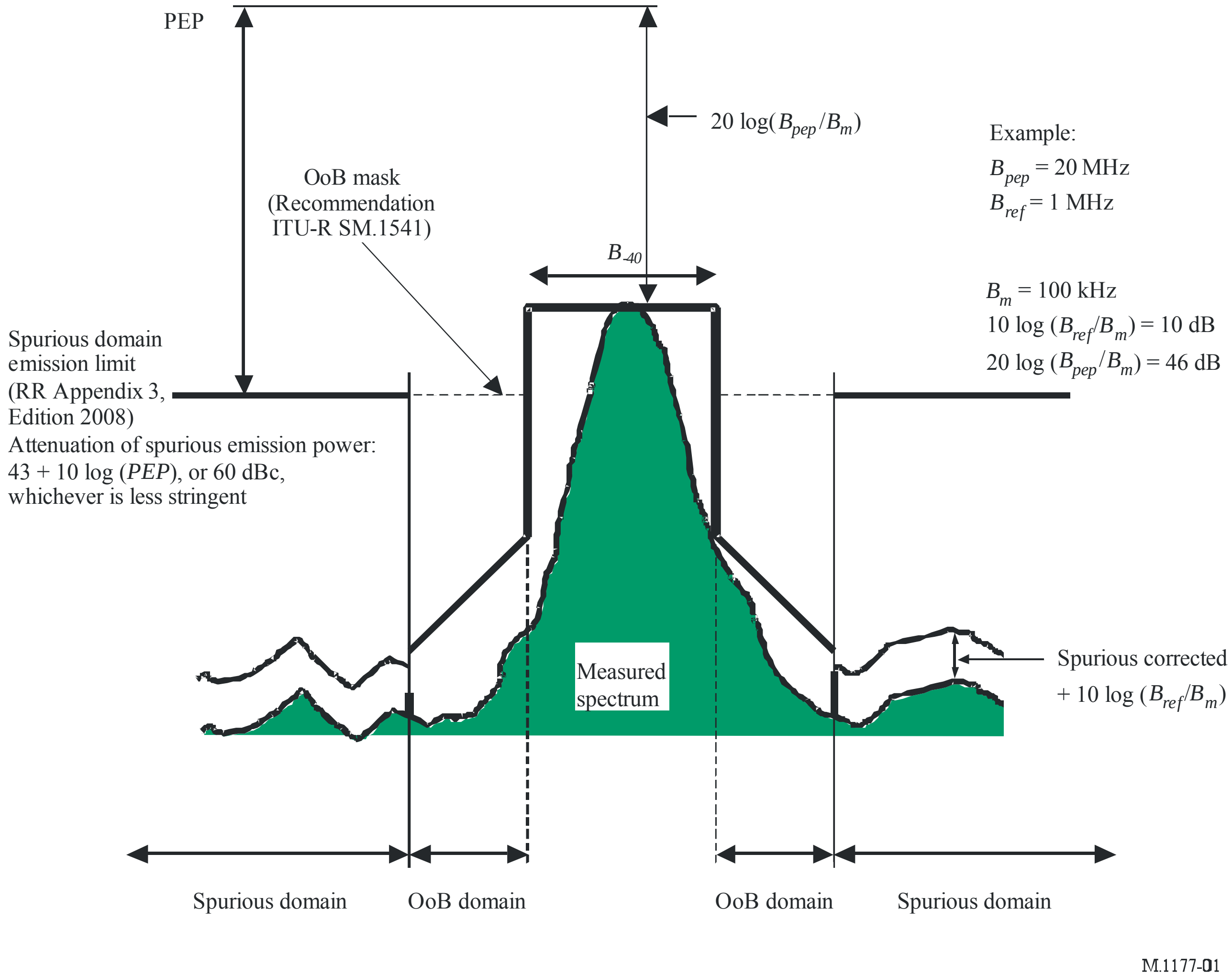
– for FM or chirped radar, the square root of the quantity obtained by dividing the chirp bandwidth in MHz by the pulse length (μs) (e.g. if the FM is from 1 250 MHz to 1 280 MHz or 30 MHz during the pulse of 10 μs, then B_{pep} is $(30\ \text{MHz}/10\ \mu\text{s})^{1/2} = 1.73$ MHz);

– for radars operating with multiple waveforms B_{pep} is determined empirically from observations of the radar emission. The empirical observation is performed as follows: the measurement system receiver is tuned to one of the fundamental frequencies of the radar, or is tuned to the centre frequency within the chirp range of the radar. The measurement system bandwidth is set to the widest available value, and the received power level from the radar in this bandwidth is recorded. The measurement bandwidth is then progressively narrowed, and the received power level is recorded as a function of the bandwidth. The end result is a graph or table showing measured power as a function of measurement system bandwidth. The required bandwidth is the smallest bandwidth in which the full power level is still observed and B_{pep} can be calculated from a knowledge of the impulse response of the measurement receiver using the criteria described below. If a reduction in power level is observed immediately, then the widest available bandwidth should be used. The corrections described in § 3.2 are illustrated graphically in Fig. 1.

As can be seen in Fig. 1, the OoB mask and the measured spectrum have been referenced to the equivalent PEP level by using the factor $20 \log(B_{pep}/B_m)$. The Figure shows that the measured spurious is shifted upwards by an amount equal to the correction factor described in § 3.2.1 (here taken as $10 \log(B_{ref}/B_m)$). In this example, a measurement bandwidth of 100 kHz was chosen only for illustrative purposes, even though a bandwidth close to 1 MHz is recommended in this case. Also for illustrative purposes, the mask is shown offset in frequency as permitted in Recommendation ITU-R SM.1541.

FIGURE 1

Graphical illustration of the correction described in § 3.2



4 Measurements for multiple pulse or multimode radars

For radars with multiple pulse waveforms, the $B_{–40}$ dB bandwidth should be calculated for each individual pulse type and the maximum $B_{–40}$ dB bandwidth obtained shall be used to establish the shape of the emission mask (see Recommendation ITU-R SM.1541, Annex 8).

For radars with multiple pulse width settings, that can be selected individually, the setting which results in the widest calculated $B_{–40}$ dB bandwidth (see Recommendation ITU-R SM.1541, Annex 8) should be used. Emission measurements only need to be carried out for this pulse width setting.

For radars using elevation beam scanning, measurements normally need only be made in the azimuth plane.

5 Dynamic range of the measurement system

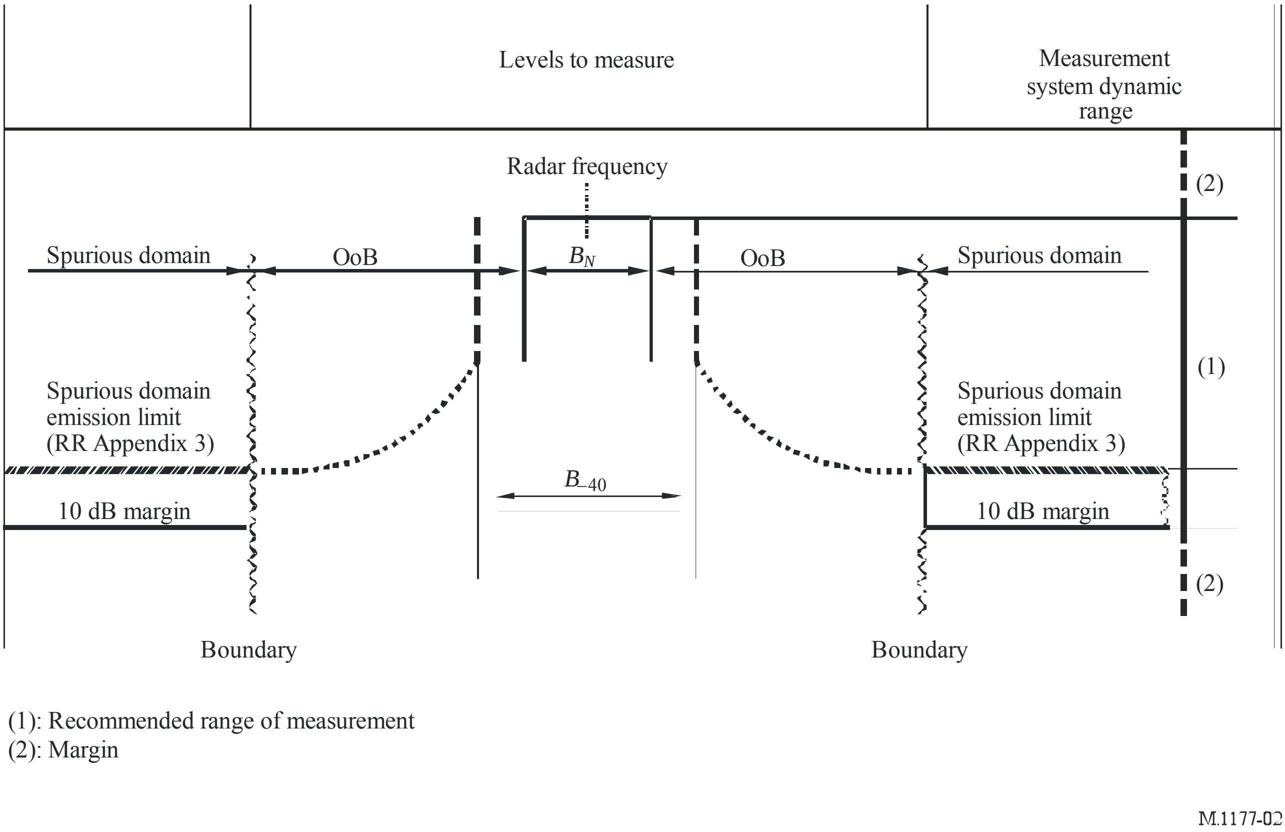
The measurement system should be able to measure levels of unwanted emissions as given in RR Appendix 3. To obtain a complete picture of the spectrum especially in the spurious emissions domain, it is recommended to be able to measure levels of emissions 10 dB below the levels given in RR Appendix 3.

For a high level of confidence in the results, the measurement dynamic range of the system should be significantly higher than the required range of measurement (margin (2) in Fig. 2).

The link between the required range of measurement and the recommended dynamic range of the measurement system is given in Fig. 2.

FIGURE 2

Relation between the required range of measurement and the recommended dynamic range of the measurement system



NOTE 1 – It should be noted that Recommendation ITU-R SM.329 recommends, under category B limits, more stringent limits than those given within RR Appendix 3 in some cases. This should be taken into account when evaluating the required range of measurement and the recommended dynamic range of the measurement system.

6 Direct methods

Two direct methods described below can be used to measure unwanted emissions (OoB and spurious) from radar systems. The first method is manually controlled and the second method is automatically controlled. These two methods have been used to measure the emission characteristics of radar systems operating at frequencies up to 24 GHz, transmitter output powers of several megawatts, and e.i.r.p. levels in the gigawatt range. Taking safety aspects into account, these methods may also be carried out in an anechoic chamber.

6.1 Measurement environment conditions

Regarding the measurement distance, either near field or far field measurements can be made. Variation of the peak received signal should be made less than 3 dB using the absorber when the receiving antenna is moved $\lambda D/2H$ horizontally or vertically away from the point where maximum signal is received (H: height of the transmitting point, D: measurement distance, λ: transmitting wave length).

Regarding the measurement site, it is preferable to locate the transmitting and receiving antennas in a fairly high position such as on towers. Note that the height should be determined considering the vertical beam width of the radar and measurement antennas, and no reflective objects should be between the antennas.

6.2 Measurement hardware and software

Block diagram of the type of measurement system required for the two direct methods are shown in Fig. 3 (manual method) and Fig. 4 (automatic method). The first element to be considered in the system is the receive antenna. The receive antenna should have a broadband frequency response, at least as wide as the frequency range 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 measurement; the narrow antenna beamwidth provides discrimination against other signals in the area; the narrow beamwidth minimizes problems with multipath propagation from the radar under measurement; and spectrum data collected with a parabolic antenna require a minimum of post-measurement correction, as discussed in the next paragraph. 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*. The antenna polarization may be tested by rotating the feed (if linear polarization is used) or by exchanging left and right-hand polarized feeds, if circular polarization is being used.

Corrections for variable antenna gain as a function of frequency should be considered. Antenna gain levels are usually specified relative to that of a theoretically perfect isotropic antenna (dBi). The effective aperture of an isotropic antenna decreases as 20 log(f), where f is the frequency being measured. This means that, if the measurement antenna has a constant effective aperture (that is, has an isotropic gain that increases as 20 log(f)), no corrections for variable antenna gain need be performed. This requirement is met by a theoretically perfect parabolic reflector antenna, and is one of the reasons that such an antenna is preferred for a broadband radar spectrum measurement.

Conversely, to the extent to which the gain of the measurement antenna deviates from a 20 log(f) curve (including a less-than-ideal parabolic antenna), the resulting measurements must be corrected for such deviation.

The cable connecting the measurement antenna to the measurement system should also be considered. A length of low-loss RF cable (which will vary depending upon the circumstances of measurement system geometry at each measurement radar site) connects the antenna to the RF front-end of the measurement system. As losses in this piece of line attenuate the received radar signal, it is desirable to make this line length as short, and as low-loss, as possible.

FIGURE 3

Bloch diagram for measurement of radiated unwanted emissions from radars using the manually controlled direct method

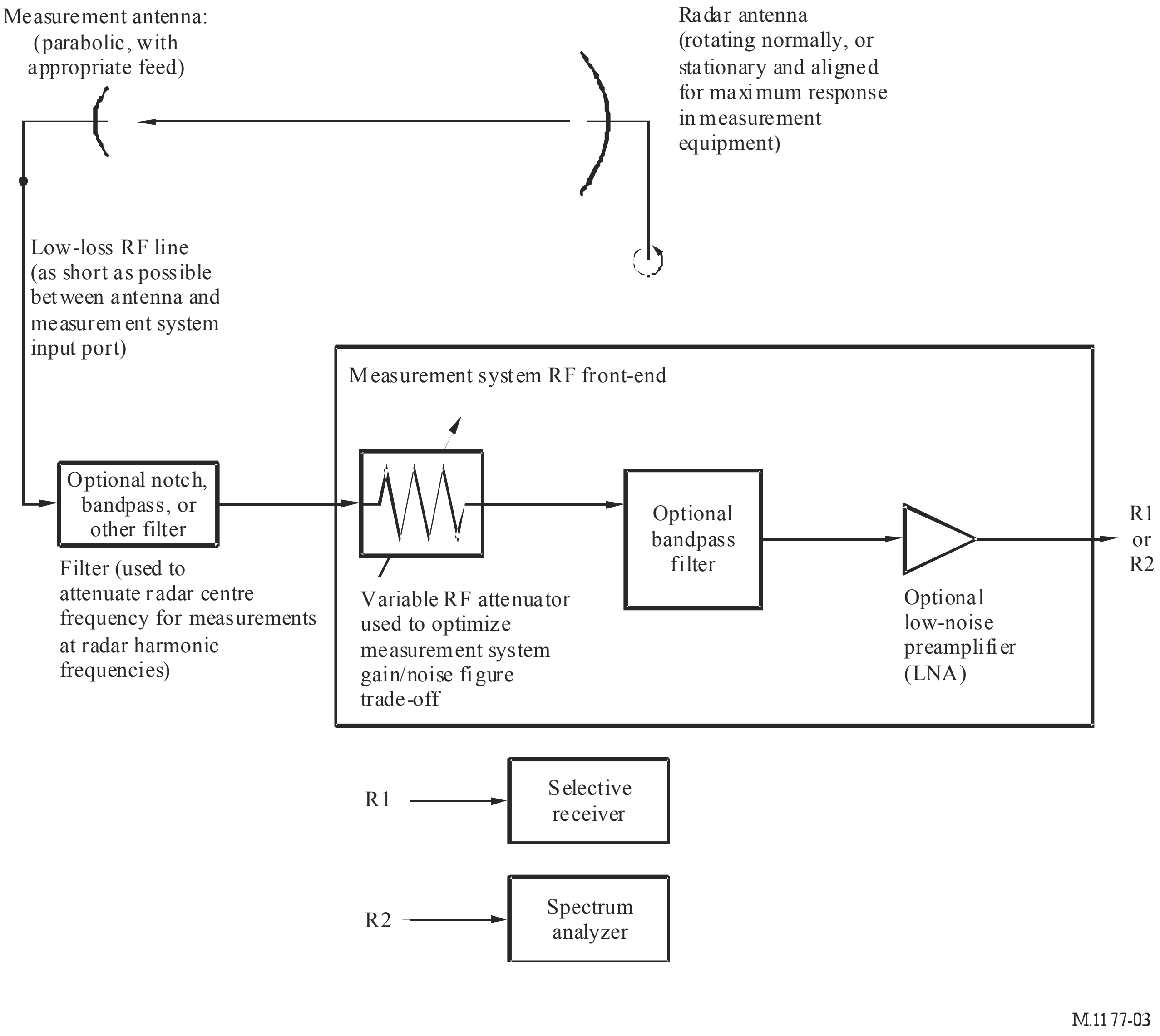
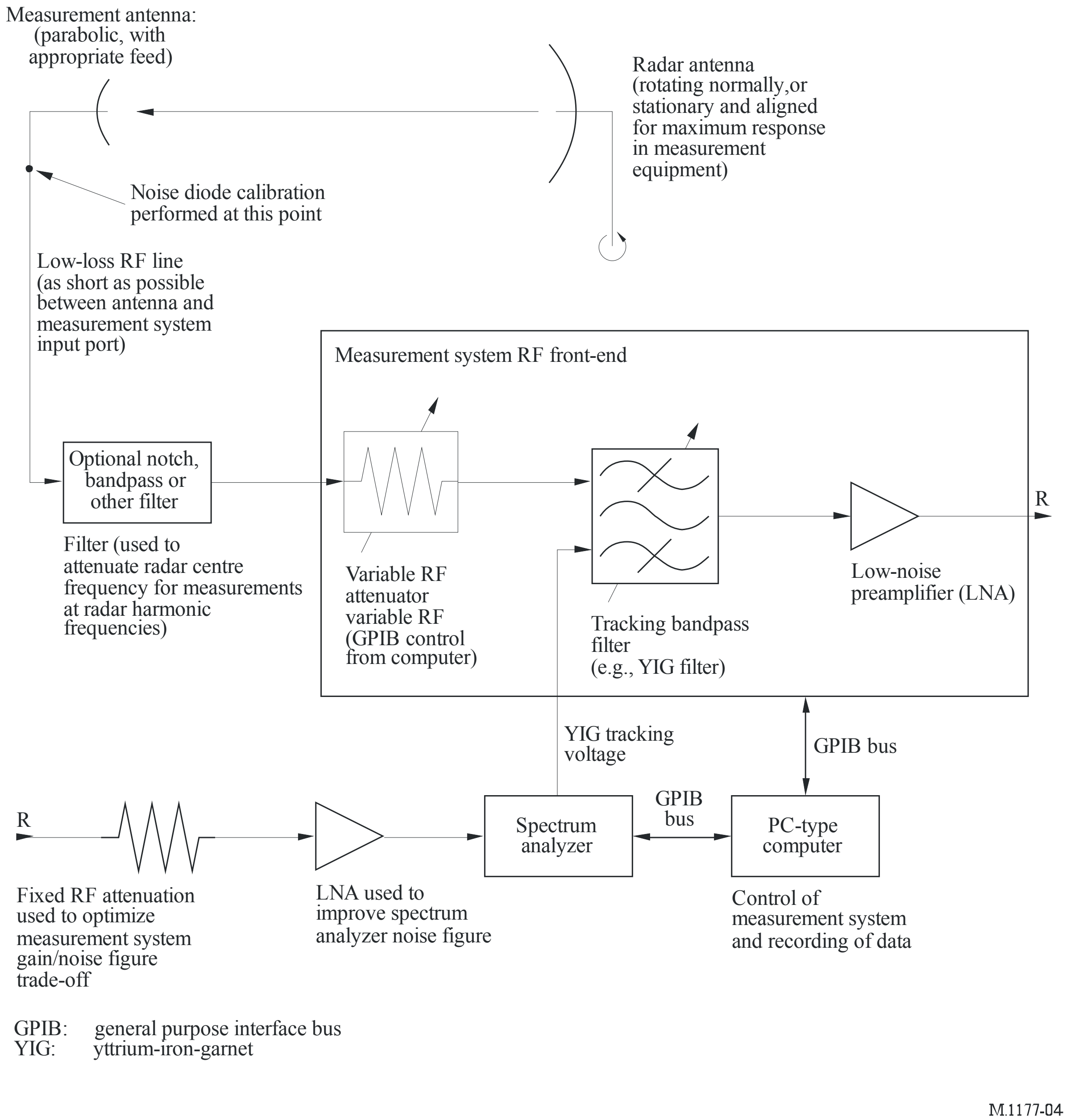


FIGURE 4

Block diagram from measurement of radiated unwanted emissions from radars using the automatically controlled direct method



The RF front-end is one of the most critical parts of the entire measurement system. It performs three vital functions. The first is control and extension of measurement system dynamic range through the use of variable RF attenuation. The second is bandpass filtering (preselection) to prevent overload of amplifiers by high-amplitude signals that are not at the tuned frequency of the measurement system. The third is low-noise preamplification to provide the maximum sensitivity to emissions that may be as much as 130 dB below the peak measured level at the radar fundamental.

Each of these sections in the RF front-end is considered below.

The RF attenuator is the first element in the front-end. It 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 dynamic range of the measurement system by the maximum amount of attenuation available (e.g. 70 dB for a 0-70 dB attenuator).

6.2.1 Manually controlled measurement system

The manually controlled measurement consists of sweeping across the spectrum in fixed increments (equal to the span value). At each frequency sweep, the attenuator is adjusted to keep the radar peak power within the dynamic range of the other elements in the measurement system (often the front-end amplifier and the spectrum analyzer log amplifier are the limiting elements). With the front-end RF attenuator properly adjusted at each sweep, a measurement of the radar power at that frequency is performed.

A manually controlled bandpass filter can be used at this point to avoid overloading the preamplifier (and thus causing gain-compression), if it is necessary to measure very low spurious emissions (i.e. level of fundamental emissions – level of spurious emissions > instantaneous measurement dynamic range).

The final element in the RF front-end is an LNA. An LNA is installed as the next element in the signal path after the preselector. The low-noise input characteristic of the LNA provides high sensitivity to low-amplitude spurious radar emissions, and its gain allows for the noise figure of the rest of the measurement system (e.g. a length of transmission line and a spectrum analyzer).

The sensitivity and dynamic range of the measurement system are optimized by proper selection of LNA gain and noise figure characteristics. It is desirable to minimize noise figure while providing enough gain to allow for all measurement circuitry after the LNA (essentially the RF line loss after the front-end, plus the noise figure of the spectrum analyzer circuitry). Ideally, the sum of the LNA gain and noise figure (which is the excess noise produced by the LNA with a 50 Ω termination on its input) should be approximately equal to the noise figure of the remaining measurement system.

Typical spectrum analyzer noise figures are 25-45 dB (varying as a function of frequency), and transmission line losses may typically be 5-10 dB, depending upon the quality and the length of the line. As a result of the variation in measurement system noise figure as a function of frequency, a variety of LNAs used in frequency octaves (e.g. 1-2 GHz, 2-4 GHz, 4-8 GHz, 8-18 GHz, 18-26 GHz and 26-40 GHz) may be required. Each LNA can be optimized for gain and noise figure within each frequency octave. This also helps match LNAs to octave breaks between various YIG filters (e.g. 0.5-2 GHz, 2-18 GHz, etc.). Use of an LNA after the preselector (and, if required, a cascaded LNA at the spectrum analyzer input) may reduce the overall measurement system noise figure to about 10-15 dB. This noise figure range has been found to be adequate for the measurement of broadband radar emission spectra over a range as large as 130 dB.

The remainder of the RF measurement system is expected to be essentially a commercially available spectrum analyzer or a spectrum analyzer with a preselector or a selective receiver. Any equipment, which can receive signals over the frequency range of interest, can be used.

6.2.2 Automatically controlled measurement system

The key to using the RF front-end attenuator effectively in a radar measurement, as shown in Fig. 3, is to tune the measurement system in fixed-frequency increments (e.g. 1 MHz), called steps, rather than to sweep across the spectrum, as is more conventionally done with manually controlled spectrum analyzers. At each fixed-frequency step, the attenuator is adjusted to keep the radar peak power within the dynamic range of the other elements in the measurement system (often the front-end amplifier and the spectrum analyzer log amplifier are the limiting elements). With the front-end RF attenuator properly adjusted at each step, a measurement of the radar power at that frequency is performed. In this way, a nominal 60 dB dynamic range for the measurement system is extended by as much as 70 dB, to a total resulting dynamic range of 130 dB. To minimize measurement time, this attenuator and the stepped-frequency measurement algorithm that it necessitates can be controlled by computer.

The next element in the front-end, the tunable bandpass filter preselector is necessary if it is needed to measure low-power spurious emission levels at frequencies that are adjacent to much higher-level fundamental emissions (e.g. 130 dB below fundamental). For example, it may be necessary to measure spurious emissions from an air traffic control radar at 2 900 MHz that are at a level of –120 dBm in the measurement circuitry, while the fundamental emission level is at +10 dBm and is only 150 MHz away in frequency (at 2 750 MHz). The measurement system requires an unattenuated LNA to measure the spurious emission at 2 900 MHz, but the amplifier will be overloaded (and thus gain-compressed) if it is exposed to the unattenuated fundamental emission at 2 750 MHz. For this reason, attenuation that has frequency-dependence is required in the front-end at a position before the LNA input. In practice, this tunable bandpass filtering is effectively provided by varactor technology (below 500 MHz) and by YIG technology (above 500 MHz). The applicable filters may be procured commercially, and should be designed to automatically track the tuned frequency of the measurement system.

The final element in the RF front-end is an LNA. An LNA is installed as the next element in the signal path after the preselector. The low-noise input characteristic of the LNA provides high sensitivity to low-amplitude spurious radar emissions, and its gain allows for the noise figure of the rest of the measurement system (e.g. a length of transmission line and a spectrum analyzer).

Considerations for the sensitivity and dynamic range of the measurement system, as well as for typical spectrum analyzer noise figures, are the same as stated in § 6.2.1.

Another option for LNA configuration is one in which LNAs are cascaded. The first LNA is placed between two stages within the YIG or varactor bandpass preselector filter. It has a low noise figure, but only enough gain to allow for the insertion loss of the second YIG stage. A second (possibly lower-performance) LNA is placed immediately after the YIG. This option will provide somewhat lower overall system noise figure because the second stage of the YIG is allowed for by the first LNA. However, this option may require more advanced design and engineering modifications to the preselector filter than an administration may deem practical.

A third option for the measurement system LNA configuration, and one not requiring any redesign or retrofitting of the front-end preselector filter, is to place a lower-gain LNA in the front-end and a second LNA at the spectrum analyzer signal input. The first LNA is selected to have very low noise figure and just enough gain to allow for the RF line loss and the noise figure of the spectrum analyzer LNA. The spectrum analyzer LNA, in turn, is selected for a gain characteristic that is just adequate to allow for the spectrum analyzer's noise figure in the appropriate frequency range of the radar measurement. This set of two cascaded LNAs may be more easily acquired than a single, extremely high-performance LNA, and will typically be less susceptible to overload as the 1 dB compression points can be expected to be higher than those for individual high-performance LNAs.

The remainder of the RF measurement system is expected to be essentially a commercially available spectrum analyzer. Any spectrum analyzer 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 analyzers must be allowed for 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 or equivalent) that is compatible with the computer controller and interface card(s) 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 analyzer 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. While the development of software requires a significant resource expenditure, practical experience with such systems has shown such an investment to be worthwhile if radar emission measurements are to be performed on a frequent and repeatable basis.

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 or other components should fail during the measurement.

6.3 Measurement system calibration

6.3.1 Manual direct method

The manually controlled method requires either calibration of all the measuring components individually or of the whole measuring set with a calibrated generator (substitution method).

6.3.2 Automatic direct method

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) (where *ENR* = (effective temperature (K), of noise diode/ambient temperature (K)) 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 factor, *Y*, measurement, as described in Appendix 2 to Annex 1, 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. Appendix 2 to Annex 1 describes the calibration procedure in more detail.

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

6.4 Measurement procedure

6.4.1 Manual method

Appendix 1 to Annex 1 describes the direct method in detail; this section provides a summary of the method.

Prior to measurement, a spectrum analyzer is used to detect the presence of signals not emitted by the radar: if there are emissions corrupting the measurement, appropriate filters must be used.

Max-Hold function

Spectrum analyzer 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 analyzer centre frequency would be 2 GHz).
Spectrum analyzer frequency span	=	10, 20, 50, 100, or 500 MHz.
Spectrum analyzer sweep time	>	automatic sweep time

Time	>	record signal during a minimum of 3 radar beam rotation intervals. (e.g. if radar rotates at 40 r.p.m. or 1.5 s per rotation, then duration should be > 3 × 1.5 s; 4.5 s would be a reasonable selection). Record signal for a sufficient time for spectrum to form. Radar antenna may be held stationary and aligned for the maximum measurement system response.

NOTE 1 – The setting of the spectrum analyzer sweep time and the signal record duration should be validated.

The second measurement point is taken by tuning the measurement system to the next frequency band to be measured. This frequency is optimally equal to the first measured frequency band plus the measured span.

In the case where the measurement instrument is a selective receiver, the measurement is done point by point according to the recommended bandwidth.

6.4.2 Automatic method

Appendix 1 to Annex 1 describes the direct method in detail; this section provides a summary of the method. In addition to the parameters listed in § 2, the spectrum analyzer should be set up as follows:

Spectrum analyzer 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 analyzer centre frequency would be 2 GHz).
Spectrum analyzer frequency span	=	0 Hz (analyzer is operated as a time-domain instrument).
Spectrum analyzer step time	>	radar beam rotation interval (e.g. if radar antenna rotates at 40 r.p.m. or 1.5 s/rotation, then step time should be > 1.5 s; 2 s would be a reasonable selection). For frequency agile radars or radars with vertical scanning antenna beams, the step time may have to be several antenna rotation periods. For these more complex radar systems, the step time should be determined empirically.

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 (step time) slightly longer than that of the radar antenna rotation period, or for a longer step time for complex radar systems. This time-display of the radar antenna beam rotation will be displayed on the spectrum analyzer 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 stepping process consists of a series of individual amplitude measurements made at predetermined (fixed-tuned) frequencies across a spectrum band of interest. The frequency change between steps is optimally equal to the measurement system IF bandwidth. For example, measurements across 200 MHz of spectrum might use 200 steps at a 1 MHz step interval and a 1 MHz IF bandwidth. The step interval may be set wider in the spurious emission domain to expedite the overall measurement. However, at frequencies that are integral multiples (e.g. 2, 3, 4) of the fundamental radar emission, the maximum step interval should again be about equal to the measurement system IF bandwidth.

The measurement system remains tuned to each frequency for a specified measurement interval. The interval is called step time, or dwell. The dwell for each step is specified by the measurement system operator, and is normally slightly longer than the radar beam scanning interval.

Computer control of the measurement system is desirable if this process (step, tune, measure, correct for gain, and repeat) is to be performed with efficiency and accuracy. In order to correctly measure the peak of the fundamental emission it may be required to use a smaller step interval of the order of half or less of the measurement bandwidth over this region.

The stepped time technique is required to enable 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 that might occur in the spectrum.

It is 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.

These measurements may be performed without the radar beam being scanned in space, but only if it is verified that the direction of the radar beam relative to the mechanical axis of the antenna does not vary across the frequency range of the measurement.

6.4.3 Indirect method

Figure 5 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 Ro-Jo with a feeder (as shown in Fig. 6).

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. 7).

FIGURE 5

Typical radar system

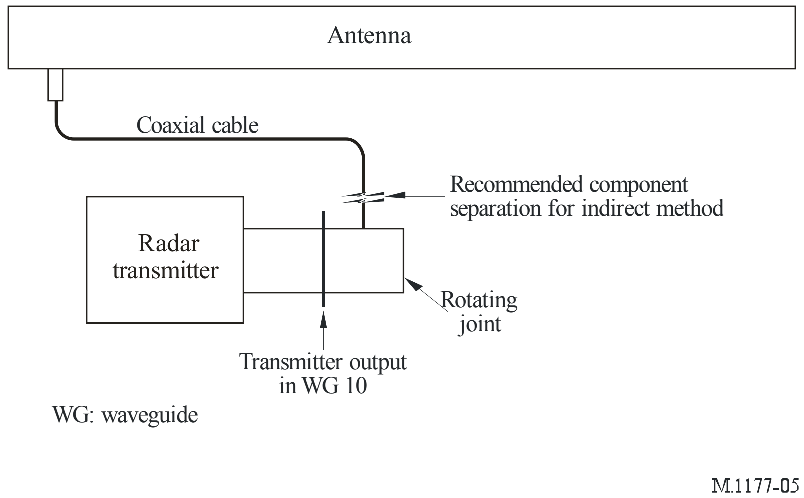
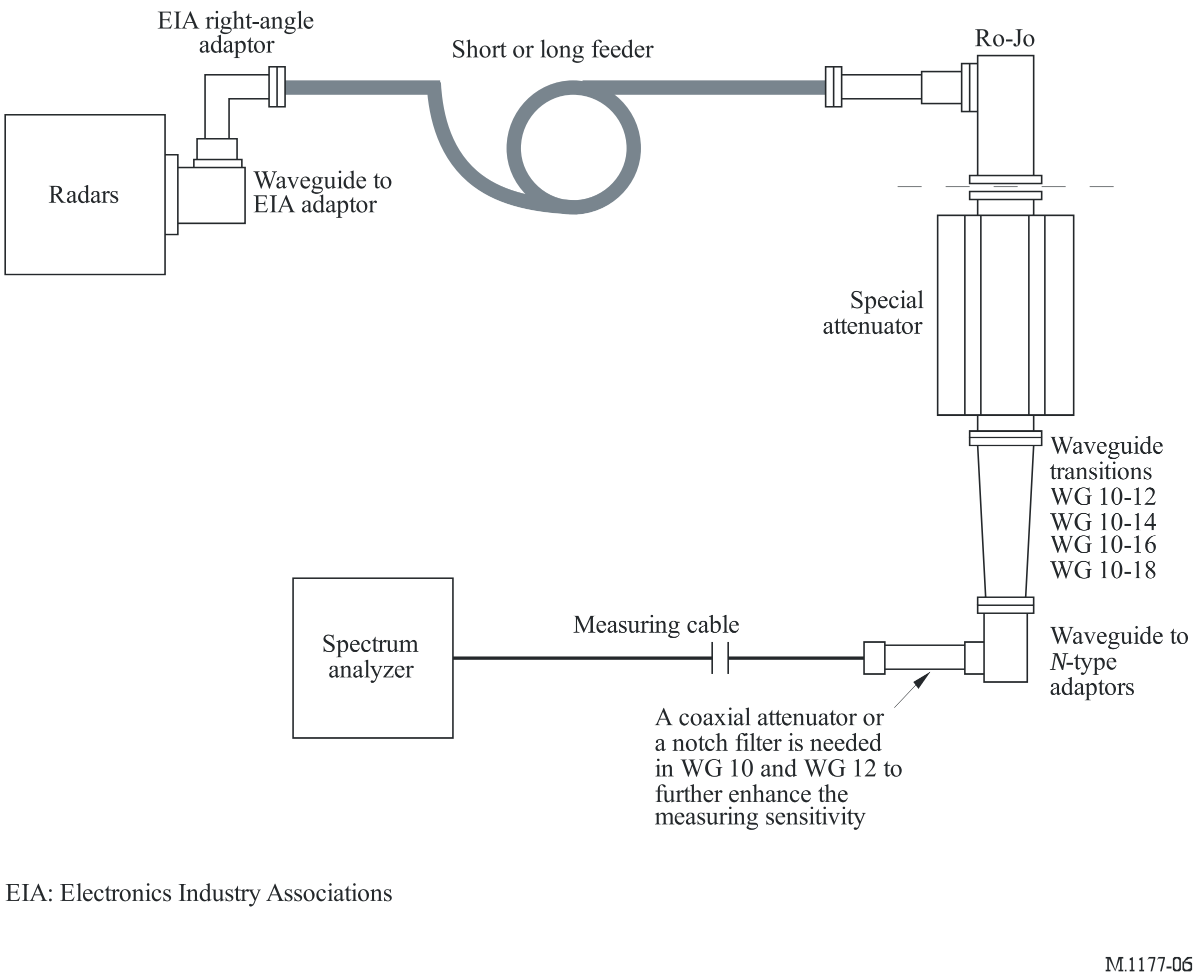


FIGURE 6

Measurement at the Ro-Jo part



Step 3: Correct the measured gains with an appropriate correction factor (using a software program or model of the known antenna performance. In the simplest cases it may be possible to use the software programme, given in Appendix 4 to Annex 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 effective e.i.r.p. radiation at the observed unwanted emission frequencies.

6.4.3.1 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 must be such that it attenuates the powerful fundamental signal sufficiently to protect the measuring equipment, whilst at other frequencies offers a negligible attenuation and energy is being measured in the TE_{10} mode.

It should be recognized that, the spurious frequency emissions of the transmitter output could be in higher order modes and this possibility should be considered when setting up the measurement system. For simple radars however this will rarely be of significance as such higher order modes are generally 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).

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

This measuring system allows the accurate measurement of low levels of emissions 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.

6.4.3.3 Results of measurement at the Ro-Jo port

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

6.4.3.4 Measurement uncertainty in a waveguide

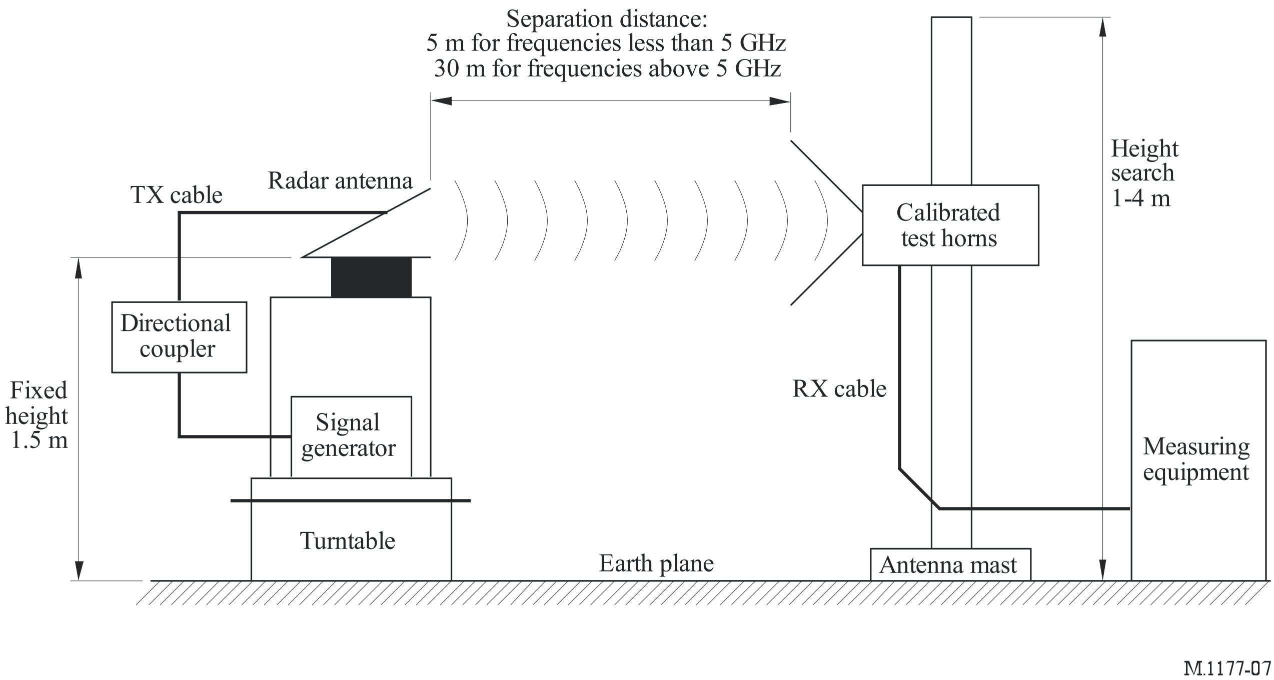
The system has a measurement accuracy of ±1.3 dB across the frequency band 2 to 18.4 GHz for the waveguide port. Total uncertainties with a confidence level of not less than 95% can be calculated to be ±3.4 dB for the waveguide port including the spectrum analyzer.

6.4.3.5 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. 7.

FIGURE 7

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



6.4.3.6 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 OoB frequencies measured or identified, using the method specified in § 6.4.3. 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 analyzer 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 4 to Annex 1
- S: measured spectrum analyzer level (dBm)
- G_r: gain of the receiving test horn antenna (dBi)
- d: measuring distance (m)
- λ: wavelength of a frequency of interest (m).

6.4.3.7 Gain correction and reduction factors

The software program given in Appendix 4 to Annex 1 gives the far field correction factors from a near field measurement for a very simple case. 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. Thus a more complex software model or data derived using the direct method may be required to achieve accurate results in such cases.

6.4.3.8 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 analyzer, 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.

6.4.3.9 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 a 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.

6.4.3.10 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 and the measurement frequency range can easily be extended to 40 GHz or higher. It can also usefully be used in conjunction with the direct method to assess incremental changes in a given radar system that has been previously measured.

Appendix 1
to Annex 1

Direct method detailed description of procedures and software

The direct method assumes that the following conditions can be met:

– the far field radiation zone of a radar can be accessed by a measurement system as described in the body of this Annex;

– unwanted feed-through of radar signals directly into the measurement system hardware (i.e. bypassing the measurement system antenna) can be minimized to a sufficiently low level to ensure that measurement results are accurate.

The direct method does not require that the radar operation be coordinated with the measurement system, although in some cases cooperative operation may be beneficial in expediting the measurement.

The direct method process is as follows:

Step 1: determine a measurement location

The measurement location should be within or as near as possible to the radar main radiation beam. For surface search radars and some other radar types, this may be relatively easy, as the radar beam will sweep across the surface, and the measurement system need only be placed within this area. For many air search radars, however, the main beam does not directly illuminate the ground. For these radars, the measurement system should be located within the maximum coupling zone on the surface. This zone may be determined by tuning the measurement system to the radar fundamental frequency and then driving the measurement system in a vehicle from a position close to the radar to a position far (on the order of a few kilometres) from the radar. The measurement system is used to monitor received signal level as a function of position. This can be done by running a spectrum analyzer in a zero frequency span with a sweep time of 500 s, and watching the peak level every few seconds when the radar sweeps past the vehicle. The result is a time display that shows the maximum coupling location(s).

Any place within the maximum coupling zone should be adequate. In practice, this zone has been found to begin no closer than about 0.75 km from air search radars, and to extend to no further than about 2 km from the same radars. There is usually no sharply defined point where maximum coupling occurs, but rather a broad zone within these limits.

The question of multipath should be considered. Multipath effects have been observed very rarely. When they have been observed, it has been in cases in which the radar and the measurement system were separated by calm, smooth water surfaces. In other cases, irregular intervening terrain and the use of parabolic reflector antennas by the measurement system minimize multipath effects to an extent that makes them negligible. Multipath effects can be checked by repeating the radar measurement at a second location and comparing the results from the two measurement locations. Multipath is also believed to be minimized by raising the measurement antenna on a telescoping mast to a height of about 10 m above the ground. This also provides a better line-of-sight between the radar and the measurement system.

Step 2: set up the measurement system and check for unwanted feed-through signals

The measurement system is configured with a parabolic reflector antenna at the top of a 10 m mast (optional), or at a height of at least a few metres above the ground, to avoid multipath effects and provide reasonably good line-of-sight propagation. The measurement system should be tuned to the radar fundamental frequency or maximum emission frequency, if it is chirped or frequency-hopping.

It is necessary to check for unwanted feed-through (i.e. the unwanted reception of radar energy within the measurement equipment, bypassing the measurement antenna). Feed-through is checked by disconnecting the measurement antenna and terminating the input line with a 50 Ω load. If feed-through is present, the following options may be exercised:

– check to ensure measurement equipment racks (if any) are sealed;

– check connectors for firm fittings;

– move the radar measurement system to an alternative location, in which the measurement equipment is shielded from the radar by buildings or foliage, and in which the antenna is raised above these obstacles on the telescoping mast;

– move the radar measurement system to a larger distance from the radar.

A well-designed measurement system should minimize the possibility of unwanted feed-through.

Step 3: determine radar emissions parameters

The parameters that are most critical to determine before the measurement begins are beam scanning interval and effective emission bandwidth. Beam scanning interval and other characteristics are acquired by tuning the spectrum analyzer in a zero span mode and a sweep time interval of several seconds, and then observing the beam scanning of the radar.

Determination of the emission bandwidth is accomplished as described in the main body of this Annex, with the spectrum analyzer tuned to the radar fundamental frequency in a zero span mode, and the IF and video bandwidths initially set to their widest available values. The IF bandwidth is then reduced each time the radar beam swings past the measurement system, and the bandwidth at which the received power level drops is noted. This is the widest available measurement bandwidth that is less than the radar emission bandwidth. This will be the measurement bandwidth used, unless circumstances such as a need to observe the radar in a particular receiver bandwidth dictate otherwise.

Additional radar emission parameters that should be noted are: pulse repetition rate, pulse jitter (if any), pulse stagger (if any), and pulse width. The first three of these parameters may be measured on an oscilloscope connected to the spectrum analyzer's video output. The RF pulse width (50% voltage points) and rise time (10-90% voltage points) should be measured with a peak power meter or suitable wideband RF detector diode, operated in the square-law region. It should be properly matched to an oscilloscope having a sufficient bandwidth to enable display of the pulse waveform without distortion associated with limited detector bandwidth.

Step 4: calibrate the measurement system

Manually controlled direct method:

– The manually controlled method requires calibration of all the measuring components individually or calibration of the whole measuring set.

Automatically controlled direct method:

– See Appendix 2 of Annex 1. Noise diode calibration is recommended, although alternative methods using signal generators can be used.

Step 5: configure measurement system software (automatic method only)

The measurement software must be configured to the desired start frequency (MHz), stop frequency (MHz), step size (MHz), step interval (MHz), IF bandwidth (MHz), video bandwidth (≥ IF bandwidth), detector (positive peak), spectrum analyzer reference level (usually –10 dBm), initial attenuation at the start frequency (usually 0 dB), and additional data regarding the location (such as radar name, project name for the measurement, etc.).

Step 6: check for linearity during the measurement

It is critical to maintain the integrity of the measurement by checking for linearity as the measurement progresses. When measuring, both at the fundamental frequency and in the spurious emissions, system linearity should be checked by periodically inserting 10 dB of RF attenuation at the RF front-end, ahead of the LNA. The result should always be a 10 dB drop in measured signal level. If other than a 10 dB drop is observed either front-end overload or unwanted feed-through may be occurring. Good system design will minimize these potential problems. If they do occur, it may alternatively be necessary to either take additional steps to shield the measurement system, or else to move to another location, as described in Step 2, above.

Step 7: measure the radar in more than one IF bandwidth (recommended but not required)

It may be useful to measure radar emissions in several bandwidths. Such measurements provide an unequivocal indication of the variation in measured radar power as a function of receiver bandwidth at any given frequency in the spectrum.

Appendix 2
to Annex 1

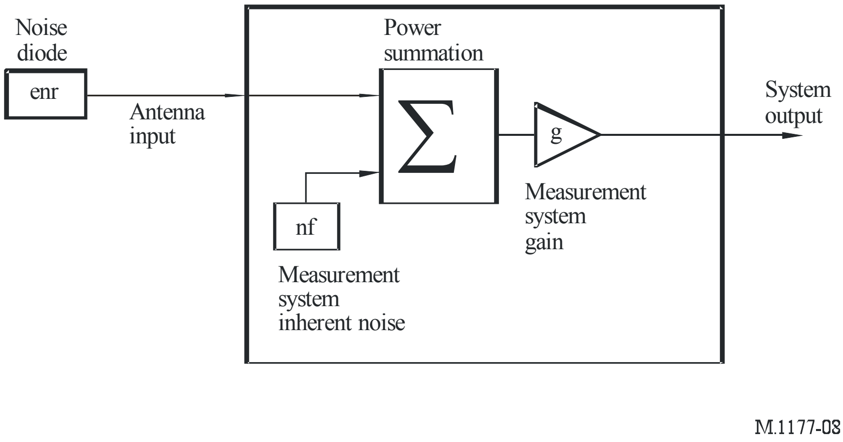
Gain and noise figure calibration using a noise diode

Measurement system calibration should be performed prior to every radar emission spectrum measurement. As measurements are performed, gain corrections may be added automatically to every data point. For measurement system noise figures of 20 dB or less, noise diode factor, *Y*, calibration (as described below) may be used. This Appendix describes the theory and procedure for such calibration.

The noise diode calibration of a receiver tuned to a particular frequency may be represented in lumped-component terms as shown in Fig. 8. In this diagram, the symbol Σ represents a power-summing function that linearly adds any power at the measurement system input to the inherent noise power of the system. The symbol g represents the total gain of the measurement system. The measurement system noise factor is denoted by nf, and the noise diode has an excess noise ratio denoted as enr. (In this Appendix, all algebraic quantities denoted by lower-case letters, such as “g”, represent linear units. All algebraic quantities denoted by upper case letters, such as “G”, represent decibel units.)

FIGURE 8

Lumped component diagram of noise diode calibration



Noise factor is the ratio of noise power from a device, n_{device} (W), and thermal noise:

$$\frac{n_{device}}{k\ T\ B}$$

where:

- k: Boltzmann's constant (1.38×10^{-23} J/K)
- T: system temperature (K)
- B: bandwidth (Hz).

The excess noise ratio is equal to the noise factor minus one, making it the fraction of power in excess of $k\,T\,B$. The noise figure of a system is defined as 10 log (noise factor). As many noise sources are specified in terms of excess noise ratio, that quantity may be used.

In noise diode calibration, the primary concern is the difference in output signal when the noise diode is switched on and off. For the noise diode = on condition, the power, P_{on} (W), is given by:

$$p_{on} = (nf_s + enr_d) \times g\,k\ T\ B$$

where:

- nf_s: system noise factor
- enr_d: noise diode enr.

When the noise diode is off, the power, P_{off} (W), is given by:

$$p_{off} = (nf_s) \times g\,k\ T\ B$$

The ratio between P_{on} and P_{off} is the Y factor:

$$y = \left(\frac{p_{on}}{p_{off}} \right) = \frac{(nf_s + enr_d)}{nf_s}$$

$$Y = 10\ \log(y) = 10\ \log \left(\frac{p_{on}}{p_{off}} \right) = P_{on} - P_{off}$$

Hence the measurement system noise factor can be solved as:

$$nf_s = \frac{enr_d}{y-1}$$

The measurement system noise figure is:

$$NF_s = 10 \log \left(\frac{enr_d}{y-1} \right) = ENR_d - 10 \log (y-1) = ENR_d - 10 \log (10^{Y/10} - 1)$$

Hence:

$$g = \frac{p_{on} - p_{off}}{enr_d \times k\, T\, B}$$

$$G = 10 \log (p_{on} - p_{off}) - 10 \log (enr_d \times k\, T\, B)$$

or

$$G = 10 \log \left(10^{P_{on}/10} - 10^{P_{off}/10} \right) - ENR_d - 10 \log (k\, T\, B)$$

In noise diode calibrations, the preceding equation is used to calculate measurement system gain from measured noise diode values.

Although the equation for NF_s may be used to calculate the measurement system noise figure, software may implement an equivalent equation:

$$nf_s = \frac{p_{off}}{g\, k\, T\, B}$$

$$NF_s = 10 \log (p_{off}) - 10 \log (g\, k\, T\, B) = P_{off} - G - 10 \log (k\, T\, B)$$

and substituting the expression for gain into the preceding equation yields:

$$NF_s = P_{off} + ENR_d - 10 \log \left(10^{P_{on}/10} - 10^{P_{off}/10} \right)$$

The gain and noise figure values determined with these equations may be stored in look-up tables. The gain values are used to correct the measured data points on a frequency-by-frequency basis.

Excluding the receive antenna, the entire signal path is calibrated with a noise diode source prior to a radar spectrum measurement. A noise diode is connected to the input of the first RF line in place of the receiving antenna. The connection may be accomplished manually or via an automated relay, depending upon the measurement scenario. The noise level in the system is measured at a series of points across the frequency range of the system with the noise diode turned on. The noise measurement is accomplished with the IF bandwidth set to 1 MHz and the video bandwidth set to 1 kHz. The noise diode is then turned off and the system noise is measured as before, at the same frequencies. The measurement system computer thus collects a set of P_{on} and P_{off} values at a series of frequencies across the band to be measured. The values of P_{on} and P_{off} are used to solve for the gain and noise figure of the measurement system in the equations above.

Appendix 3
to Annex 1

Measurement of pulse width and pulse rise/fall times

1 Introduction

This Appendix is intended to provide guidance for measuring radar pulse parameters needed in applying the emission mask for the OoB domain. Recommendation ITU-R SM.1541, Annex 8, addresses unwanted emissions in the OoB domain for radar systems. To determine the necessary bandwidth, B_n, and the 40 dB bandwidth, $B_{–40}$, the pulse width, t, and the rise time, t_r, of pulsed radars must be measured[2].

Pulse width, t, is measured at the –6 dB points (50% voltage points) of a radar pulse. The rise time, t_r, or fall time, t_f, is measured between the –0.9 dB and –20 dB (10%-90% voltage points) on a pulse's leading or trailing edge, respectively. For coded pulses, t_r and t_f are the rise/fall times of a sub-pulse. If sub-pulses are not discernable, then it may be assumed that t_r is 40% of the time to switch from one phase or sub-phase to the next.

For some radar designs, pulse width and rise or fall time may be measured via a hardline connection to a directional coupler. However, radiated pulse characteristics may differ somewhat from those measured from directional couplers. Moreover, some radar designs do not provide a directional coupler. For these radars, pulse width and rise or fall time can be measured via radiated energy if the measurement system has sufficient bandwidth (that is, exceeding $(10/t_r)$ or a bandwidth that can be adequately corrected to determine the true rise time). A potential impediment to measuring pulse width via radiation is the effect of multipath energy, which causes a stair-step fall-off on the trailing edge of each radiated pulse. This effect can be minimized by the use of a parabolic reflector antenna on the measurement system. If the effect of multipath can be suppressed enough for the first trailing edge stair step to occur more than 6 dB below the nominal pulse level, then a radiated measurement of pulse width is possible if the bandwidth requirement is met[3]. A broadband diode detector is required to achieve sufficient bandwidth.

2 Measurements for conventional radars

2.1 Hardline-coupled pulse measurements

For hardline-coupled measurements of pulse characteristics, the measurement setup is shown in Fig. 9. A coaxial cable of appropriate impedance is connected between the directional coupler output and the input of a wideband (bandwidth exceeding $(1/t_r)$) crystal detector. A variable attenuator (0-70 dB, for example) is inserted between the coupler and the detector. Prior to connecting the detector, the attenuator is initially set to a sufficiently high level as to protect the

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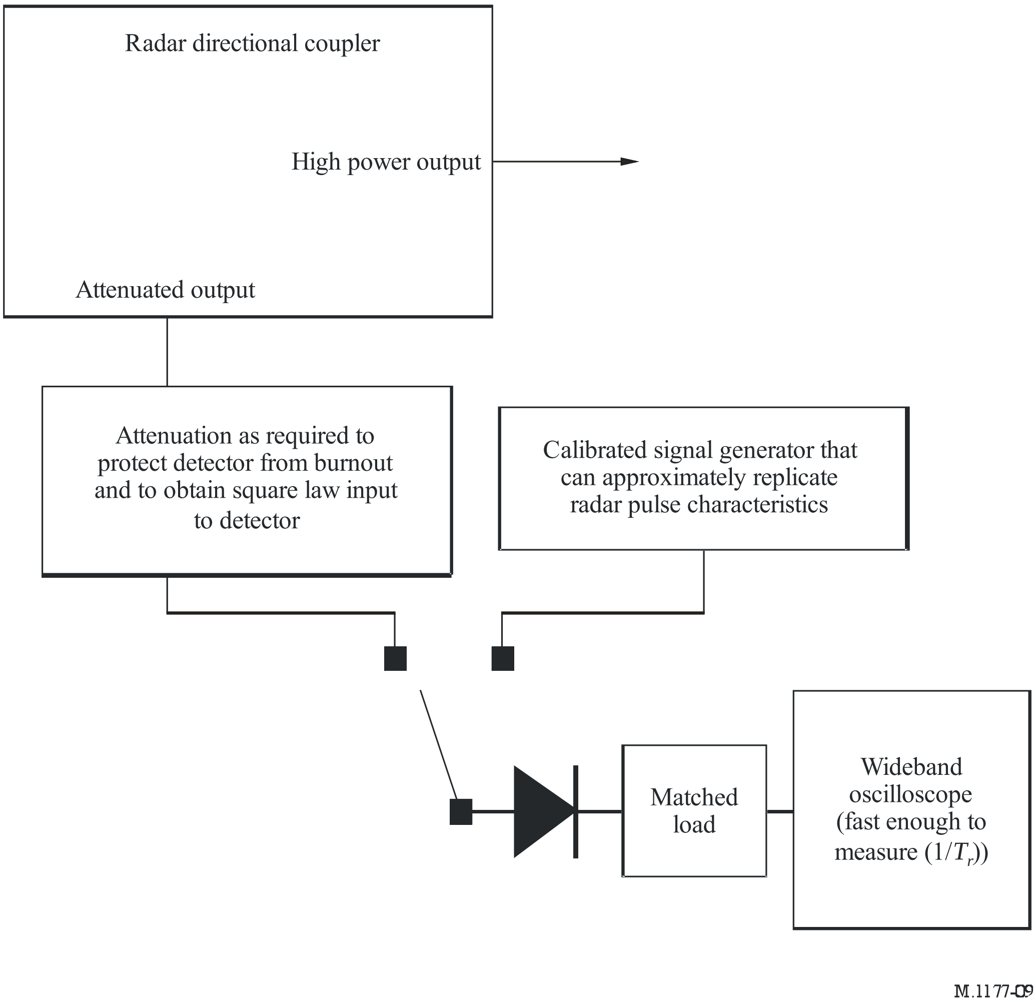
[2] When the fall time, t_f, of the radar pulse is less than the rise time, t_r, it should be used in place of the rise time in applying equations in Recommendation ITU-R SM.1541.

[3] For example, a 1 µs pulse might have a rise time of less than 0.1 µs. This t_r would require bandwidth in excess of 10 MHz for accurate measurement. Oscilloscopes are available with bandwidths of up to 2 GHz. For purposes of measuring radar rise/fall times, oscilloscopes with at least 500 MHz should be used. The bandwidth must be available in a single-shot (not repetitively sampled) mode, as the measurements are made on single radar pulses.

crystal from damage[4]. The maximum permissible detector input level may be assumed to be +20 dBm, if other data are lacking.

FIGURE 9

Block diagram schematic for measuring radar pulse width and rise time (or fall time) parameters via a hardline connection to a directional coupler



The detector output is connected to an oscilloscope having bandwidth that exceeds (1/t_r). Impedances should be matched appropriately; most modern oscilloscopes having selectable input impedance values. 50 Ω is typically correct. DC coupling should be used on the oscilloscope input.

The oscilloscope is adjusted to display and record[5] radar pulse envelopes. The setting of the variable attenuator is noted by measurement personnel.

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[4] The initial attenuator setting may be derived from the radar's peak power level and the specified insertion loss of the directional coupler.

[5] Most oscilloscopes can record data to either an internal disk or to an external computer via an IEEE-488 (GPIB) bus. Recording may also be achieved by photographing the oscilloscope screen with a digital still-frame camera.

Next, the line from the radar directional coupler is disconnected from that device. It is reconnected to the output of a calibrated signal generator that is capable of producing pulses of approximately the same width as measured from the radar. The signal generator output is adjusted to generate an amplitude response on the oscilloscope that is the same for both envelopes, preferably about +10 dBm.

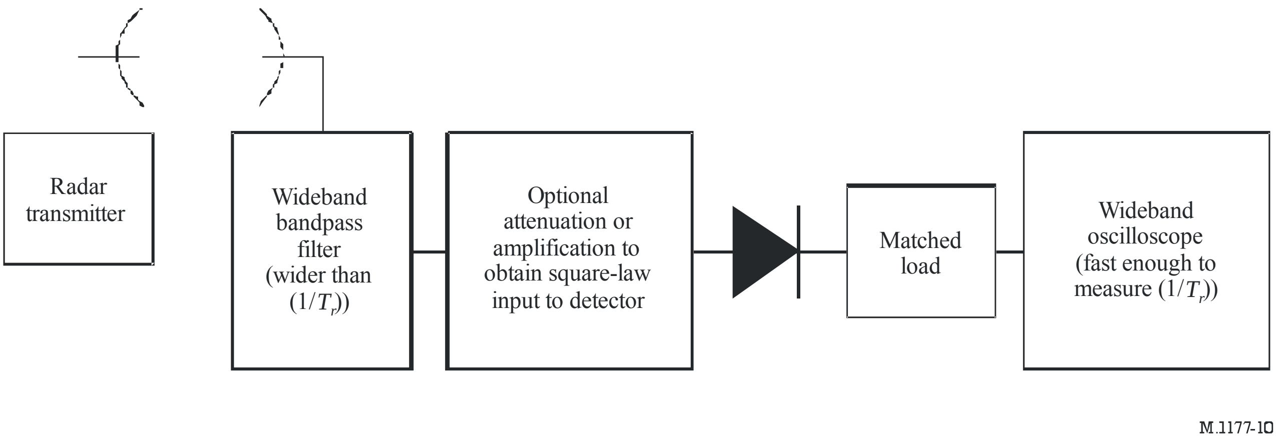
With this adjustment made, the response of the crystal detector can be calibrated as follows. The signal generator output is decreased by, successively, 0.9 dB, 6 dB and 20 dB[6]. At each of these levels, vertical markers are placed on the measured pulse envelope. The resulting time intervals between the vertical markers provide the pulse width (Δ between the 6 dB points), the rise time (Δ between the 0.9 dB and 20 dB points on the leading edge), and the fall time (Δ between the 0.9 dB and 20 dB points on the trailing edge).

2.2 Radiated coupled pulse measurements

For radars that do not incorporate directional couplers, pulse characteristics can only be measured through radiated measurements. Figure 10 shows the measurement hardware configuration for measuring radiated pulses.

FIGURE 10

Block diagram schematic for measuring radar pulse width and rise time (or fall time if shorter) parameters via radiated pulses



The procedure that should be used is as follows:

Step 1: Position the measurement system at a location with clear line-of-sight path to the radar transmitter antenna, and as close as possible without suffering degradation to the measurement system performance (e.g. feed-through), losing power from the radar by passing underneath the main beam, or being within the near-field distance of either the radar antenna or the measurement antenna.

Step 2: Use a high-gain antenna (e.g. a 1 m diameter or larger parabolic at microwave frequencies) on the measurement system to receive pulses from the radar at the highest possible amplitude and to discriminate against signals from other transmitters.

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6 Crystal detector outputs are not necessarily linear; therefore the 10%, 50% and 90% voltage points for the RF signal may not appear to be 10%, 50%, and 90% voltage points at the DC output of the detector. A calibrated signal generator is needed to determine the actual DC output voltages for these input voltages.

Step 3: At the measurement antenna input, install a bandpass filter that will pass the radar fundamental-frequency energy and that has bandwidth that exceeds $(1/t_r)$ of the radar pulses to be measured. Following the bandpass filter, install a diode detector that has bandwidth and rise time response speed that exceeds $(1/t_r)$ of the radar pulses to be measured[7].

Step 4: Connect the detector output to the input of an oscilloscope. The output impedance of the detector must be matched to the input impedance of the oscilloscope. The oscilloscope must have single-shot bandwidth exceeding $(1/t_r)$ of the radar pulses to be measured. Set the oscilloscope to a single-sweep mode, with a trigger threshold low enough to ensure that radar pulses are captured. Wait until a series of pulses are recorded. Elevate the trigger threshold and wait for another set of pulses to activate the trigger. Continue this process until the threshold is sufficiently high that no more pulses are recorded. Reduce the trigger threshold slightly, and wait for a sequence to be recorded. This pulse sequence shows the pulse repetition rate.

Step 5: Measure the pulse width and rise time or fall time on the oscilloscope using criteria specified above for hard-line coupled measurements.

2.3 Notes on the radiated pulse measurement procedure

By positioning the measurement system in close proximity to the radar, with clear line-of-sight, multipath problems are minimized and the received power in the pulses is maximized. Use of a high-gain measurement antenna further mitigates the multipath problem and increases the received pulse power level.

Care must be taken to ensure that all elements in the measurement system have bandwidth and time response characteristics that are sufficient to measure radar pulse rise time. Diode detectors with fast response characteristics are probably necessary to meet this requirement.

In multi-radar environments, or environments with strong ambient non-radar signals that are in or near the edges of the spectrum band of the radar being measured, it may be necessary to take steps to isolate the pulses of the radar being measured from other signals. The use of a parabolic antenna for microwave-frequency radars, and also a bandpass filter at the measurement antenna terminals will help to isolate the desired pulse waveforms. If these items are not adequate to isolate the desired pulses, then amplitude-dependent triggering should provide the necessary isolation, assuming that pulses from the radar being measured have higher amplitude in the measurement system than any other signals in the environment.

3 Measurements for advanced technology radars

3.1 Hardline coupled pulse measurements

In this context, advanced radars are those that utilize pulse modulation. Either frequency or phase may be modulated. If FM (chirping) is being utilized, then the same measurement techniques may be used as specified above. But the measurement bandwidth must equal or exceed the total chirped-frequency range. In practice this may require the use of a broadband diode detector.

Measurements of rise time on chirped pulses are the same as for non-chirped pulses; the same procedure as specified above may be used.

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[7] The peak input power to the detector should fall within the square-law response region. To obtain the appropriate power input level, it may be necessary to install either an attenuator or an amplifier between the bandpass filter and the diode detector.

Pulse compression ratio (FM pulse systems): Measurements to determine pulse compression are described below. This approach is adequate for determination of pulse compression for all radars, including advanced systems.

For phase-coded radar pulses, the measurement of pulse width is also performed as specified above. But measuring the rise time of the individual phase segments (chips) may be difficult. The first difficulty arises with ordinary phase coding, in which a phase change of π may occur between each chip. Although the phase is shifted, the squared value of the waveform is observed at the output of the detector, erasing phase information. This makes the edges of the chips unobservable, in principle, with a detector of any sort.

In application, transients may occur at the phase transitions between the chips, and these transients are visible on an oscilloscope. But the observation of the chip transitions does not result in a measurement of the chip rise time.

Total number of subpulses within each pulse (phase-coded systems): Radars employing conventional phase-shifting with instantaneous switching of ±180° will normally exhibit transients that can be observed in the envelopes of the detected pulses. In this manner, the number of chips in each pulse can be determined. However, for radar systems employing minimum shift keying (MSK) or other phase-shifting technologies that eliminate such transients, it is impossible to determine the number of chips within each pulse by measuring the detected pulse envelope. For these radars, if a pair of hardline connections to monitor the I and Q channels are not available, the number of chips can only be determined by using reference materials such as technical manuals, operating manuals and specification sheets.

Chip rise time measurement: For ordinary phase-coded pulses, the chip rise time may be measured directly only if the waveform is sampled prior to detection. This may be done by connecting an IF output[8] from a spectrum analyzer to a vector signal analyzer or similar digital signal processing device.

Advanced phase-coded pulses do not employ discontinuous phase changes between chips. Instead they use MSK. With MSK modulation, the requirement for observation of chip rise time is to separate the I and Q components of the pulse, and observe the rise time of each component individually. This can be accomplished with an appropriately programmed vector signal analyzer (VSA) (or dedicated digital signal processor (DSP) or field programmable gate array (FPGA)) that is fed the IF output from a spectrum analyzer.

If a measurement organization does not have available the phase-sensitive equipment described above (VSA, DSP or FPGA with appropriate software installed), a pulse rise time measurement may be performed on the rising edge of the pulse instead of a direct chip rise time measurement. The rise time measurement is performed as described above. If this is done, the fact should be noted in the resulting data set.

3.2 Radiated coupled pulse measurements

In advanced radars that lack a directional coupler (such as systems employing multiple transmitter modules), pulse characteristics must be measured radiatively, as described above. Care must be taken to maintain adequate bandwidth for measurement of pulse rise time, and the diode detector input should be at an amplitude that is in the square-law response of the detector.

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[8] The IF output is assumed to be coupled from the spectrum analyzer prior to the detection and resolution bandwidth stages, so that adequate bandwidth is maintained for a pulse rise time measurement.

3.3 Use of reference materials to determine pulse characteristics

Operations manuals, specification sheets and other radar-specific references may be presumed to be reasonably accurate for the aggregate set of all radars within a particular model production line or series, although it must be recognized that any individual radar may vary somewhat from the production average. Such variation presumably occurs as a result of both quality variation in manufacturing and the maintenance that the radar receives in the field. If one or more of the required pulse characteristics cannot be measured directly, the parameter values that are quoted in such references may be used for emission mask computations.

Appendix 4
to Annex 1

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

```
********************************************************************************
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 radians”
'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
```

Annex 2

Measurement of unwanted emissions of radar systems as detailed in *recommends* 2 and 3

1 Introduction

The techniques recommended are termed direct and indirect. The direct measurement method accurately measures unwanted emissions from radars (as detailed in *recommends* 2 and 3) through free space measurement of the radiated signals. The indirect method measures the signals at transmitter output then combines it with models of the subsequent system to estimate the free space field strengths. Comparison of the two techniques has shown very close agreement; to within 2 dB.

2 Reference bandwidth

In general the rules for determining reference bandwidth for higher frequency radar (see Annex 1) apply to lower frequency radar with suitable scaling of the waveform parameters.

For radar systems, the reference bandwidth, B_{ref}, used to define unwanted emission limits (Recommendations ITU-R SM.329 and ITU-R SM.1541, and RR Appendix 3) should be calculated for each particular radar system. For the three general types of radar pulse modulation utilized for long wavelength radionavigation, radiolocation, acquisition, tracking and other radiodetermination functions, the reference bandwidth values are determined using the following formulas:

– for fixed-frequency, non-pulse-coded radar, one divided by the radar pulse length, in seconds (e.g. if the radar pulse length is 100 μs, then the reference bandwidth is 1/100 μs = 10 kHz);

– for fixed-frequency, phase coded pulsed radar, one divided by the phase chip length (s) (e.g. if the phase coded chip is 200 μs long, then the reference bandwidth is 1/200 μs = 5 kHz);

– for FM or chirped radar, the square root of the quantity obtained by dividing the chirp bandwidth (MHz) by the pulse length (μs) (e.g. if the FM is from 1 250 MHz to 1 251 MHz or 10 kHz during the pulse of 20 ms, then the reference bandwidth is $(10 \text{ kHz}/20 \text{ ms})^{1/2}$ = 700 Hz).

In cases, where the above calculated bandwidths are greater than 1 MHz, then a reference bandwidth, B_{ref}, of 1 MHz should be used.

3 Measurement bandwidth and detector parameters

The measurement bandwidth, B_m, is defined as the impulse bandwidth of the receiver and is greater than the IF bandwidth, B_{if}, (sometimes referred to as resolution bandwidth for spectrum analyzers). The measurement bandwidth, B_m, may be derived from the following equation:

$$B_m = B_{if} \times MBR$$

The MBR needs to be determined for the measurement receiver being used. MBR is approximately 3/2 for a –3 dB IF bandwidth Gaussian filter as typically used in many commercial spectrum analyzer receivers.

NOTE 1 – In some instruments the IF bandwidth is defined at the –6 dB point.

An appropriate receiver IF bandwidth should be selected to give one of the following recommended measurement bandwidths. (In general, the rules for determining measurement bandwidth for higher frequency radars (see Annex 1) apply to lower frequency radar with suitable scaling of the waveform parameters.)

Measurement bandwidth[9]

≤ $(1/T)$ for fixed-frequency, non-pulse-coded radars, where T is the pulse length (e.g. if radar pulse length is 100 μs, then the measurement IF bandwidth should be ≤ 1/(100 μs) = 10 kHz).

≤ $(1/t)$ for fixed-frequency, phase-coded pulsed radars, where t is the phase-chip length (e.g. if radar transmits 260 μs pulses, each pulse consisting of 13 phase coded chips that are 20 μs in length, then the measurement IF bandwidth should be ≤ 1/(20 μs) = 50 kHz).

≤ $(B/T)^{1/2}$, for swept-frequency (FM or chirp, or FMCW) radars, where B is the range of frequency sweep during each pulse and T is the pulse length (e.g. if radar sweeps (chirps) across frequency range of 1 250-1 251 MHz (= 10 kHz of spectrum) during each chirp, and if the chirp length is 20 ms, then the measurement IF bandwidth should be ≤ $(10 \text{ kHz}/20 \text{ ms})^{1/2} = \sqrt{0.5}$ kHz ≈ 700 Hz).

4 Dynamic range of the measurement system

The measurement system should be able to measure levels of unwanted emissions as given in RR Appendix 3. To obtain a complete picture of the spectrum especially in the spurious emissions domain, it is recommended to be able to measure levels of emissions 10 dB below the levels given in RR Appendix 3.

For a high level of confidence in the results, the measurement dynamic range of the system should be significantly higher than the required range of measurement (margin (2) in Fig. 2).

The link between the required range of measurement and the recommended dynamic range of the measurement system is given in Fig. 2.

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9 The corrections associated with measurement bandwidth transforms to reference and PEP bandwidths discussed in § 3 of Annex 1, also apply to long wavelength radars described here in Annex 2.

5 Direct method

A direct method, described below, can be used to measure unwanted emissions (OoB and spurious) from long wavelength radar systems, which allow easy access to the main beam of the radar. For instance where the antenna or array is situated on the ground and is vertically polarized. This method has been used to measure the emission characteristics of long wavelength radar systems operating at frequencies up to 45 MHz, and e.i.r.p.s in the megawatt range.

5.1 Measurement hardware and software

5.1.1 Antenna

A block diagram of the type of measurement system required for the two direct methods are shown in Fig. 11. The first element to be considered in the system is the receive antenna. The receive antenna should have a broadband frequency response, at least as wide as the frequency range to be measured. This may require the use of ground screens. Gain is not usually a problem and so a simple whip antenna with a ground screen is adequate. Calibration of the antenna gain may be required for broadband measurement. This can be achieved using a reference source and a second short (poorly matched) antenna feeding into a power meter.

The antenna should be located in the far field if practical, for example at 20 MHz, more than 1 km away, although measurement of spectral characterization has shown no discernible difference in far field and near field measurements. Many long wavelength radars are arrays which synthesize a beam that is electronically steerable. In this case the beam should be steered or measurement antenna positioned such that the measurement antenna is as close as possible to the peak of the main beam.

The antenna polarization is selected to maximize response to the radar signal.

The cable connecting the measurement antenna to the measurement system may be normal coaxial cable.

5.1.2 Clear channel advisor

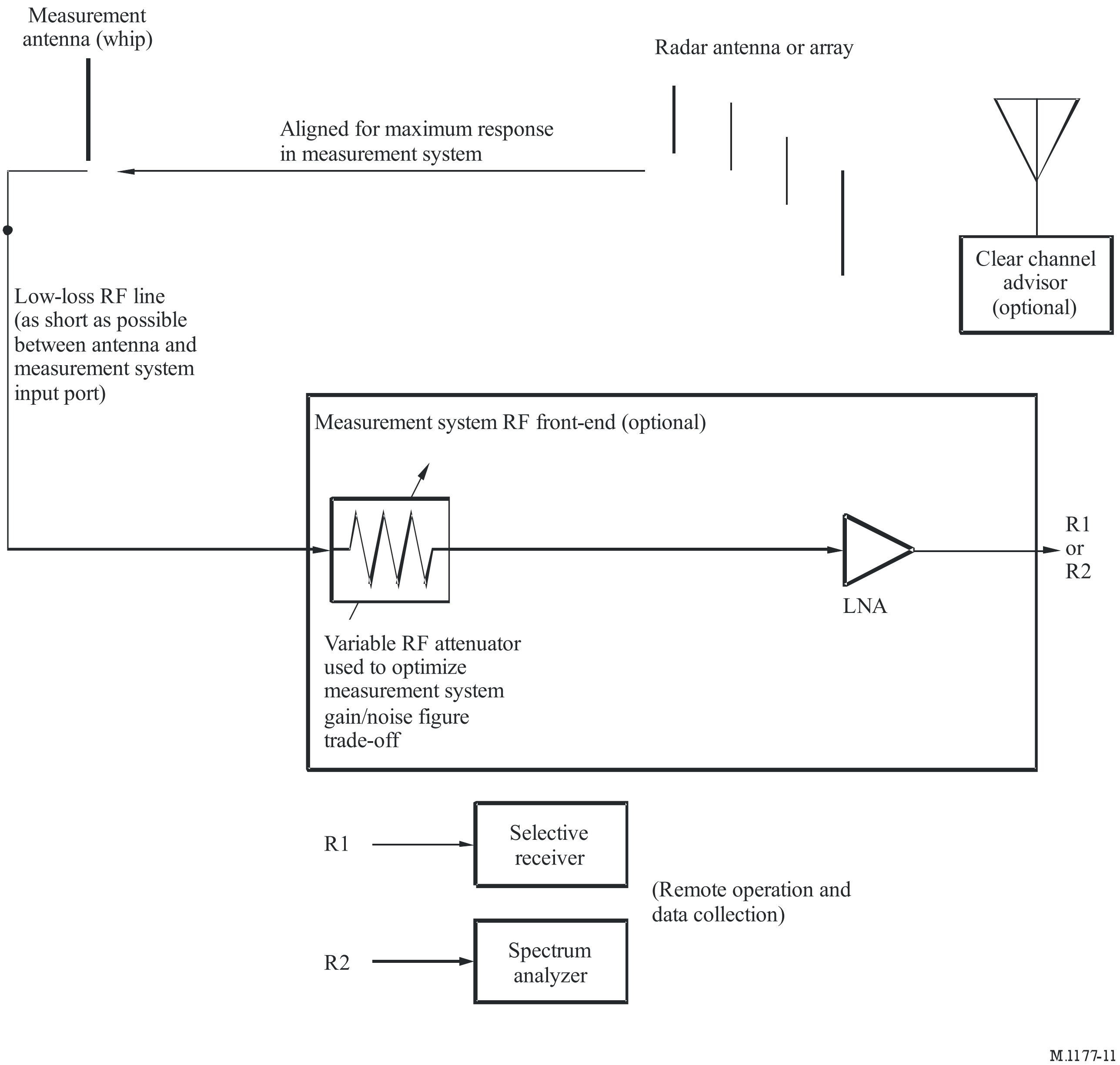
Because of ionospheric propagation long wavelength transmissions can travel large distances, and so much of the spectrum that is measured by the test antenna will, in general, be exposed to external signals. It is therefore important to have a device advising of occupied channels, preferably one that can capture this data and give some indication of the signal strength. The spectrum measuring system can be used for this, or an independent receiving system. This data can be used to reconcile any unwanted emissions that may have been caused by external sources. It should also be used to detect a clear channel for the testing of within the in-band B_{-40} and OoB domains.

5.1.3 RF front-end

The RF front-end performs two functions. The first is to protect the front-end of the detection system through the use of variable RF attenuation. The second is low-noise preamplification to provide the maximum sensitivity to low power emissions. The RF attenuator is the first element in the front-end. It provides variable attenuation (e.g. 0-70 dB) in fixed increments (e.g. 10 dB/attenuator step).

FIGURE 11

Block diagram for measurement of radiated unwanted emissions from radars using the manually controlled direct method



5.1.4 Manually controlled measurement system

The manually controlled measurement consists of sweeping across the spectrum in fixed increments (equal to the measurement bandwidth). At each frequency sweep, the attenuator may be adjusted to keep the radar peak power within the dynamic range of the measurement system (often the front-end amplifier and the spectrum analyzer log amplifier are the limiting elements). With the front-end RF attenuator properly adjusted at each sweep, a measurement of the radar power at that frequency is performed.

The final element in the RF front-end is an LNA. An LNA is installed as the next element in the signal path after the preselector. The low-noise input characteristic of the LNA provides high sensitivity to low-amplitude spurious radar emissions, and its gain accommodates the noise figure of the rest of the measurement system (e.g. a length of transmission line and a spectrum analyzer/selected receiver).

The sensitivity and dynamic range of the measurement system are optimized by proper selection of LNA gain and noise figure characteristics. It is desirable to minimize noise figure while providing enough gain to accommodate all measurement circuitry after the LNA (essentially the RF line loss after the front-end, plus the noise figure of the spectrum analyzer/selected receiver circuitry). Ideally, the sum of the LNA gain and noise figure (which is the excess noise produced by the LNA with a 50 Ω termination on its input) should be approximately equal to the noise figure of the remaining measurement system. For example, assume that the spectrum analyzer noise figure is 25 dB and the RF line loss between the RF front-end and the analyzer is 5 dB. Thus the front-end LNA must accommodate a total noise figure of 30 dB. The sum of the LNA gain and noise figure should therefore be approximately 30 dB in this example. A combination for such an LNA would be 3 dB noise figure and 27 dB gain.

The remainder of the RF measurement system is expected to be essentially a commercially available spectrum analyzer or a spectrum analyzer with a pre-selector or a selective receiver. Any equipment, which can receive signals over the frequency range of interest, can be used. Measurements have been performed with modern digital receivers which easily accommodate the frequency and dynamic range requirements, largely obviating the need for any attenuation or gain in the front-end.

6 Indirect method

In the indirect method, measurements are made by coupling from the output of each transmitter. The measurement apparatus is similar to the direct method from that point. If there are multiple transmitters, then the complex amplitude must be recorded; then the signals must be combined together in software taking account of beam steering array weighting and feeder delays.

Data capture can be readily achieved by connection of the spectrum analyzer or receiver to a laptop PC through a GPIB or equivalent interface.