Chapter 7

RF emissions measurements

One of the aspects of electromagnetic compatibility that is most difficult to grasp is the raft of techniques that are involved in making measurements. EMC phenomena extend in frequency to well beyond 1GHz and this makes techniques established for low frequency and digital work, quite irrelevant. Development and test engineers must appreciate the basics of high frequency measurements in order to perform, or at least understand, the EMC testing that will be demanded of them. This chapter and the next will serve as an introduction to the equipment, the test methods and some of the causes of error and uncertainty that attend high frequency EMC testing.

For ease of measurement and analysis, in the commercial tests radiated emissions are assumed to predominate above 30MHz and conducted emissions are assumed to predominate below 30MHz. There is of course no magic changeover at 30MHz. But typical cable lengths tend to resonate above 30MHz, leading to anomalous conducted measurements, while measurements of radiated fields below 30MHz will of necessity be made in the near field if closer to the source than $\lambda/2\pi$ (see section 11.1.4.2), which gives results that do not necessarily correlate with real situations. In practice, investigations of interference problems have found that controlling the noise voltages developed at the mains terminals has been successful in alleviating radio interference in the long, medium and short wave bands [89]. At higher frequencies, mains wiring becomes less efficient as a propagation medium, and the dominant propagation mode becomes radiation from the equipment or wiring in its immediate vicinity. If you are considering military, aerospace or automotive tests, the supply wiring is relatively less important as a principal route, and both conducted and radiated emissions tests are performed over a wider and overlapping frequency range.

Emissions testing requires that the equipment under test (EUT) is set up within a controlled electromagnetic environment under its normal operating conditions. If the object is to test the EUT alone, rather than as part of a system, its ancillary support equipment (if any) must be separately screened from the measurement (see section 10.2.4.4). Any ambient signals should be well below the levels to which the equipment will be tested.

7.1 Emissions measuring instruments

7.1.1 Measuring receiver

Conformance test measurements are normally taken with a measuring receiver, which is optimized for the purpose of taking EMC measurements. Typical costs for a complete receiver system to cover the range 10kHz to 1GHz can be anywhere between £15,000–£60,000.

7.1.1.1 Spot frequency receiver

Early measuring receivers were manually tuned and the operator had to take readings from the meter display at each frequency that was near to the limit line. This was a lengthy procedure and prone to error. The current generation of receivers are fully automated and can be software controlled via either Ethernet, USB or an IEEE-488 standard bus; this allows a PC-resident program to take measurements with the correct parameters over the full frequency range of the test, in the minimum time consistent with gap-free coverage. Results are stored in the PC's memory and can be processed or plotted at will.

The distinguishing features of a measuring receiver compared to a spectrum analyser are:

- the instantaneous receiver output is provided at a spot frequency, although high-end units can also provide a spectrum display;
- very much better sensitivity, allowing signals to be discriminated from the noise at levels much lower than the emission limits;
- robustness of the input circuits, and resistance to overloading;
- intended specifically for measuring to CISPR standards, with bandwidths, detectors and signal circuit dynamic range tailored for this purpose;
- frequency and amplitude accuracy is better than low-cost spectrum analysers;
- may be split into two units, one covering up to 30MHz and the other covering from 30MHz upwards, potentially to tens of GHz; although there are models available which cover the full frequency range from a few Hz to 40GHz, if you have particularly deep pockets.

7.1.1.2 FFT/time domain receiver

The Fast Fourier Transform (FFT) is an algorithmic implementation of the Fourier Transform which acts on discrete samples of a time domain waveform. The transformed time domain data gives a frequency domain representation of the captured signal spectrum. The Nyquist-Shannon sampling theorem states that the signal can be completely reconstructed as long as the sampling frequency $1/t_S$ is greater than twice the maximum signal bandwidth. Measuring receivers are now available which have a fast enough A-D converter and enough memory to take a "chunk" of spectrum, usually from their first IF (intermediate frequency) amplifier, store this over a period of perhaps a few seconds, and then perform the FFT on the result.

Once a segment is captured, any resolution bandwidth and any detector function can be applied retrospectively to the analysis, as long as there are enough time samples in the segment, approx. 2/RBW (narrow RBWs require longer time captures, i.e. more memory for given segment width), and enough time to ensure detector settling. The principal advantages are that the measurement time can be significantly shortened, particularly for narrow bandwidths, which for the classical spot frequency receiver require a slow step rate and small step size; and that the probability of catching short duration narrowband signals is considerably improved.

There are artefacts and disadvantages with the FFT:

- transient signals may give different results depending on the (unsynchronised) time relationship between the capture window and the transient duration

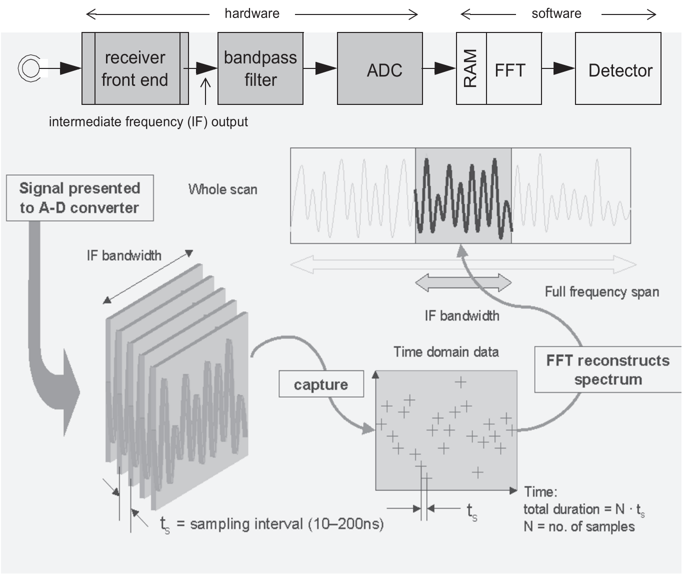


Figure 7.1 FFT receiver implementation

- finite capture periods result in "leakage" (frequencies in the output that are not present in the input spectrum)
- inadequate bandwidth filtering before the ADC can give rise to aliasing (input frequencies above the sampling frequency are folded into the output spectrum)
- the dynamic range is fixed for each captured segment, although different segments can use auto-ranging

But top-end receivers are available which adequately address these issues, and this can be expected to improve test labs' capability to carry out efficient emissions testing within reasonable timescales. The use of FFT receivers is explored further in section 7.4.2.3.

7.1.2 Spectrum analyser

A fairly basic spectrum analyser can be cheaper than a measuring receiver (typically £5,000–£15,000, but there are some good value units around the £1000 mark) and is widely used for "quick-look" testing and diagnostics. The instantaneous spectrum display is extremely valuable for confirming the frequencies and nature of offending emissions, as is the ability to narrow-in on a small part of the spectrum. When combined with a tracking generator, a spectrum analyser is useful for checking the HF response of circuit networks.

Basic spectrum analysers are not an alternative to a measuring receiver in a full compliance set-up because of their limited sensitivity and dynamic range, and susceptibility to overload. Figure 7.2(a) shows the block diagram of a typical spectrum analyser. The input signal is fed straight into a mixer which covers the entire frequency range of the analyser with no advance selectivity or preamplification. The consequences of this are threefold: firstly, the noise figure is not very good, so that when the attenuation due to the transducer and cable is taken into account, the sensitivity is hardly enough to discriminate signals from noise at the lower emission limits (see section 7.2.1.1 later). Secondly, the mixer is a very fragile component and is easily damaged by momentary transient signals or continuous overloads at the input. If you take no precautions to protect the input, you will find your repair bills escalating quickly. Thirdly, the energy contained in broadband signals can overload the mixer and drive it into non-linearity even though the energy within the detector bandwidth is within the instrument's apparent dynamic range; this means you could be making an artificially low measurement, due to overloading, without realizing it.

One point to remember when using a spectrum analyser is that its display combines both frequency domain *and time domain* information. This is because it takes time to sweep across the frequency range shown on the display. Therefore it's possible for broadband short pulses to appear as if they were at discrete frequencies. If you are operating the analyser in real time this is a valuable diagnostic feature, but it means that looking at a printed plot, either from an analyser or measuring receiver, can lead you to false conclusions.

7.1.2.1 Preselector

You can find instruments which offer a performance equivalent to that of a measuring receiver, but the price then becomes roughly equivalent as well. This is because the spectrum analyser's front-end performance has been enhanced with a tracking preselector. The preselector (Figure 7.2(b)) contains input protection, preamplification and a swept tuned filter which is locked to the unit's local oscillator. The preamplifier improves the system noise performance to that of a test receiver. Equally importantly, the input protection allows the instrument to be used safely in the presence of gross out-of-band overloads, and the filter reduces the energy content of broadband signals that the mixer sees, which improves the effective dynamic range.

7.1.2.2 Tracking generator

Including a tracking generator with the spectrum analyser greatly expands its measuring capability without greatly expanding its price. With it, you can make many frequency-sensitive measurements which are a necessary feature of a full EMC test facility.

The tracking generator (Figure 7.2(c)) is a signal generator whose output frequency is locked to the analyser's measurement frequency and is swept at the same rate. The output amplitude of the generator is maintained constant within very close limits, typically less than ±1dB over 100kHz to several GHz. If it provides the input to a network whose output is connected to the analyser's input, the frequency–amplitude response of the network is instantly seen on the analyser. Whilst it is not as capable as a proper vector network analyser, it gives some of the same functions at a fraction of the cost. The dynamic range could be theoretically equal to that of the analyser (up to 120dB), but in practice it is limited by stray coupling which causes feedthrough in the test jig.

You can use the tracking generator/spectrum analyser combination for several tests related to EMC measurements:

- characterize the loss of RF cables. Cable attenuation versus frequency must be accounted for in an overall emissions measurement;
- perform open site attenuation calibration (section 7.3.1.2). The site loss

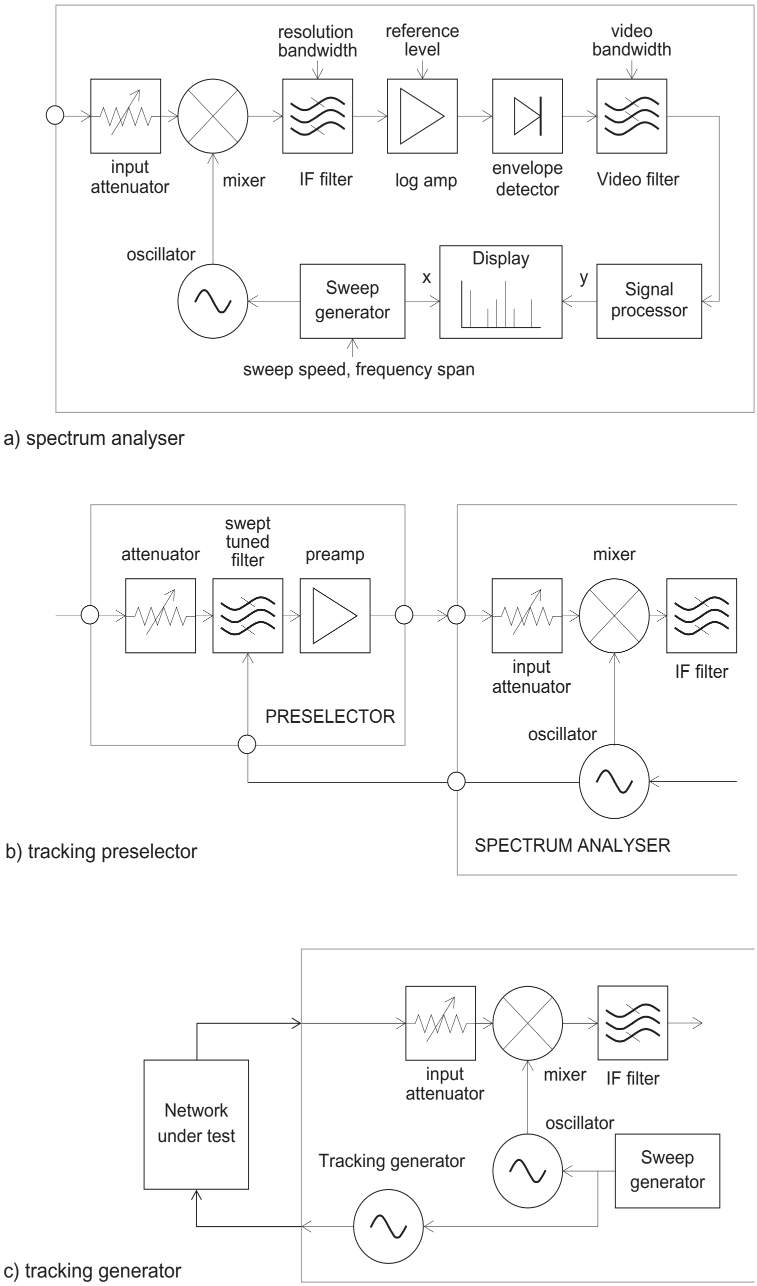


Figure 7.2 Block diagram of spectrum analyser

between two calibrated antennas versus frequency is an essential parameter for open area test sites;

- characterize components, filters, attenuators and amplifiers. This is a vital tool for effective EMC remedies;
- make tests of shielding effectiveness of cabinets or enclosures;
- determine structural and circuit resonances.

7.1.3 Receiver specifications

Whether you use a measuring receiver or spectrum analyser, there are certain requirements laid down in the relevant standards for its performance. The "relevant standards" are CISPR 16-1-1 for CISPR-related tests, and MIL-STD-461G or DEF STAN 59-411 for military tests.

7.1.3.1 Bandwidth

The actual value of an interference signal that is measured at a given frequency depends on the bandwidth of the receiver and its detector response. These parameters are rigorously defined in CISPR publication 16-1-1 [180], which is referenced by all the commercial emissions standards that are based on the work of CISPR. CISPR 16-1-1 splits the measurement range of 9kHz to 18GHz into five bands, and defines a measurement bandwidth which is constant over each of these bands (Table 7.1). The military requirements don't reference CISPR directly; the receiver specifications here are embedded in DEF STAN 59-411 and MIL-STD-461G.

Sources of emissions can be classified into *narrowband*, usually due to oscillator and signal harmonics, and *broadband*, due to discontinuous switching operations, commutator motors and digital data transfer. The actual distinction between narrowband and broadband is based on the bandwidth occupied by the signal compared with the bandwidth of the measuring instrument. A broadband signal is one whose occupied bandwidth exceeds that of the measuring instrument. Thus a signal with a bandwidth of 30kHz at 20MHz (CISPR band B) would be classed as broadband, while the same signal at 50MHz (band C) would be classed as narrowband.

CISPR band			A	B	C, D	E
Band edge (CISPR)			9–150kHz	0.15–30MHz	30MHz–1GHz	1–18GHz
Band edge (Military)	20Hz–1kHz	1–10kHz				
Bandwidth at -6dB points						
CISPR	N/A	N/A	200Hz	9kHz	120kHz	1MHz
Military	10Hz	100Hz	1kHz	10kHz	100kHz	
Quasi-peak detector						
Charge time constant, ms			45	1	1	N/A
Discharge time constant, ms			500	160	550	
Overload factor, dB			24	30	43.5	

Table 7.1 Receiver bandwidths and CISPR quasi-peak detector

Noise level versus bandwidth

The indicated level of a broadband signal changes with the measuring bandwidth. As the measuring bandwidth increases, more of the signal is included within it and hence the indicated level rises. The indicated level of a narrowband signal is not affected by measuring bandwidth. Random (thermal) noise, of course, is inherently broadband, and therefore there is a direct correlation between the "noise floor" of a receiver or spectrum analyser and its measuring bandwidth: minimum noise (maximum sensitivity) is obtained with the narrowest bandwidth. The relationship between noise and bandwidth is given by equation (7.1):

$$\text{Noise level change (dB)} = 10\log_{10}(BW_1/BW_2) \qquad (7.1)$$

For instance, a change in bandwidth from 10 to 120kHz would increase the noise floor by 10.8dB.

7.1.3.2 Detector function

There are three kinds of detector in common use in RF emissions measurements: peak, quasi-peak and average. The characteristics are defined in CISPR 16-1-1 and are different for the different frequency bands.

Interference emissions are rarely continuous at a fixed level. A carrier signal may be amplitude modulated, and either a carrier or a broadband emission may be pulsed. The measured level which is indicated for different types of modulation will depend on the type of detector in use. Figure 7.3 shows the indicated levels for the three detectors with various signal modulations.

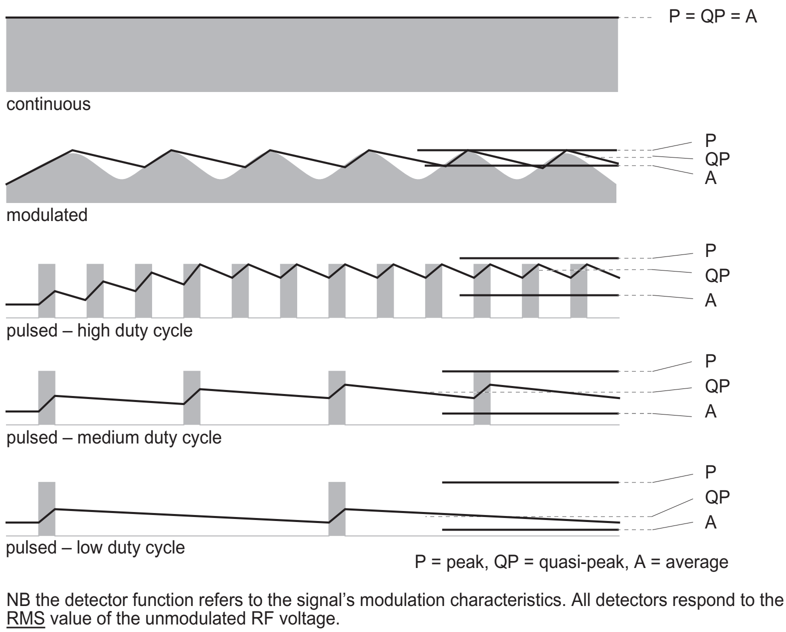


Figure 7.3 Indicated level versus modulation waveform for different detectors

Peak

The peak detector responds near-instantaneously to the peak value of the signal and discharges fairly rapidly. If the receiver dwells on a single frequency the peak detector output will follow the "envelope" of the signal, hence it is sometimes called an envelope detector. Military specifications make considerable use of the peak detector, but CISPR emissions standards do not require it at all for frequencies below 1GHz. However its fast response makes it very suitable for diagnostic or "quick-look" tests, and it can be used to speed up a proper compliance measurement as is outlined in section 7.4.2.

Average

The average detector, as its name implies, measures the average value of the signal. For a continuous signal this will be the same as its peak value, but a pulsed or modulated signal will have an average level lower than the peak. The main CISPR standards call for an average detector measurement on conducted emissions, with limits which are 10–13dB lower than the quasi-peak limits. The effect of this is to penalize continuous emissions with respect to pulsed interference, which registers a lower level on an average detector [90]. A simple way to make an average measurement on a spectrum analyser is to reduce the post-detector "video" bandwidth to well below the lowest expected modulation or pulse frequency [96].

Quasi-peak

The quasi-peak detector is a peak detector with weighted charge and discharge times (Table 7.1) which correct for the subjective human response to pulse-type interference. Interference at low pulse repetition frequencies (PRFs) is said to be subjectively less annoying on radio reception than that at high PRFs. Therefore, the quasi-peak response de-emphasizes the peak response at low PRFs, or to put it another way, pulse-type emissions will be treated more leniently by a quasi-peak measurement than by a peak measurement. But to get an accurate result, the measurement must dwell on each frequency for substantially longer than the QP charge and discharge time constants.

Since CISPR-based tests have historically been intended to protect the voice and broadcast users of the radio spectrum, they lay considerable emphasis on the use of the QP detector. There is a point of view which suggests that with the advent of digital telecommunications and broadcasting this will change, since digital signals are affected by impulsive interference in a quite different way.

RMS-average detector

A new addition to CISPR 16-1-1 is a weighting detector which is a combination of an RMS detector (for pulse repetition frequencies above a corner frequency f_c) and the average detector (for pulse repetition frequencies below the corner frequency f_c), which achieves a pulse response curve with the following characteristics: 10dB/decade above the corner frequency and 20dB/decade below the corner frequency. The draft which introduced this detector [187] goes on to say:

> Nowadays the majority of disturbance sources may not contain repeated pulses, but still a great deal of equipment contains broadband emissions (with repeated pulses) and pulse modulated narrowband emissions. In addition, the transition from analog radiocommunication services to digital radiocommunication services has happened to a great deal and is partially still going on. The introduction of a new detector type may follow the transition from analog to digital radiocommunication systems. This transition may be regarded as a matter of frequency ranges: above 1 GHz, the use of digital radiocommunication systems is more frequent than below.

This RMS-average detector, though now defined, has yet to appear as a requirement in most CISPR-based standards, CISPR 13 (due to be superseded) being an exception.

7.1.3.3 Overload factor

A pulsed signal with a low duty cycle, measured with a quasi-peak or average detector, should show a level that is less than its peak level by a factor which depends on its duty cycle and the relative time constants of the quasi-peak detector and PRF. To obtain an accurate measurement the signal that is presented to the detector must be undistorted at very much higher levels than the output of the detector. The lower the PRF, the higher will be the peak value of the signal for a given output level (Figure 7.4). Conventionally, the input attenuator is set to optimize the signal levels through the receiver, but the required pulse response means that the RF and IF stages of the receiver must be prepared to be overloaded by up to 43.5dB (for CISPR bands C and D) and remain linear. This is an extremely challenging design requirement and partially accounts for the high cost of proper measuring receivers, and the unsuitability of spectrum analysers for pulse measurements.

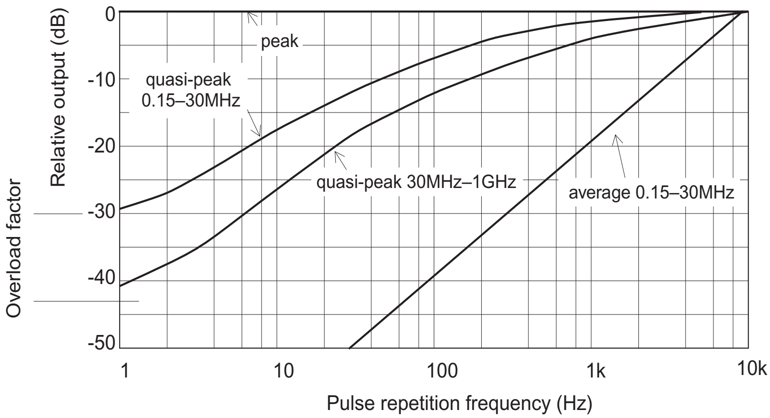


Figure 7.4 Relative output versus PRF for CISPR 16-1 detectors

The same problem means that the acceptable range of PRFs that can be measured by an average detector is limited. The overload factor of receivers up to 30MHz is only required to be 30dB, and this degree of overload would be reached on an average detector with a pulsed signal having a PRF of less than 300Hz. But average limits are set such that compliance with the QP detector applies to impulsive interference, and the average detector only applies to continuous signals to allow for modulation or the presence of broadband noise (see next section).

7.1.3.4 Measurement time

Both the quasi-peak and the average detector require a relatively long time for their output to settle on each measurement frequency. This time depends on the time constants of each detector and is measured in hundreds of milliseconds. When a range of frequencies is being measured, the conventional method is to step the receiver at a step size of around half its measurement bandwidth, in order to cover the range fully without gaps (for the specified CISPR filter shape, the optimum step size is around 0.6 times the bandwidth, to give the largest step size consistent with maintaining the accuracy of measurement of any signal). For a complete measurement scan of the whole frequency range, as is required for a compliance test, the time taken is given by:

$$T = (\text{frequency span/step size}) \cdot \text{dwell time per spot frequency} \tag{7.2}$$

If the dwell time is restricted to three QP time constants, the time taken to do a complete quasi-peak sweep from 150kHz to 30MHz turns out to be 53 minutes. For an average measurement the scan time would be even longer, were it not for the way in which the average limit is applied. The difference between the quasi-peak and average limits is at most 13dB (in CISPR 22, Class A) and this difference occurs at a PRF of 1.8kHz. The decisive value for lower PRFs is always the QP indication. Therefore the average indication only has to be accurate for modulated or pulsed signals above this PRF, and this can be ensured with only a short dwell time, such as 1ms.

But if you were to sweep with the quasi-peak detector, the dwell time would have to be increased to ensure that the peaks are captured and indicated correctly, without specialized signal processing algorithms in the receiver. It should be at least 1 second, if the signals to be measured are unknown. This has repercussions on the test method, as is discussed later in section 7.4. It places correspondingly severe restrictions on the sweep rate when you are using a spectrum analyser [39].

7.1.3.5 Input VSWR

For any RF measuring instrument, the input impedance is crucial since amplitude accuracy depends on the maximum power transfer from the antenna, through the connecting cable to the receiver input. Invariably the system impedance is specified as 50Ω. As long as the receiver input is exactly 50Ω resistive, all the power is transferred without loss and hence without measurement error. Any departure from 50Ω causes some power to be reflected and there is said to be a "mismatch error".

In practice the receiver input impedance cannot maintain a perfect 50Ω across the whole frequency range, and the degree to which it departs from this is called its VSWR (Voltage Standing Wave Ratio, see appendix D section D.2.4 and section 7.5.2.1). VSWR can also be expressed differently as return loss or input reflection coefficient. A VSWR of 1:1 means no mismatch; CISPR 16-1-1 requires the receiver to have better than 2:1 VSWR with no input attenuation, and better than 1.2:1 with 10dB or greater input attenuation (3:1 or 2:1 above 1GHz). There is a trade-off between input attenuation and sensitivity. As far as possible, receivers should be operated with at least 10dB input attenuation since this gives a better match and greater accuracy, but this will bring the noise floor closer to the limit line, which may degrade accuracy. The EMC test engineer has to apply receiver settings which balance these two aspects, and may require different settings at different frequencies. Both sources of error should be accounted for in the measurement uncertainty budget, as discussed in section 7.5.

7.1.3.6 Instrumentation above 1GHz

At microwave frequencies, the sensitivity of the receiving system deteriorates. Measurements are often taken with spectrum analyser/preamplifier combinations, sometimes with the addition of preselection or filtering. The field strength is calculated by adding the antenna factor, cable loss, and any other gain or attenuation to the measured voltage at the receiver/spectrum analyser. The receiver noise floor, determined by the thermal noise generated in the receiver's termination, therefore sets a lower bound on the field strength that can be measured (see Figure 7.8).

The standard measurement bandwidth above 1GHz is normally 1MHz as a compromise between measurement speed and noise floor. A typical microwave spectrum analyser with a mixer front-end may have a noise floor at a resolution bandwidth of 1MHz ranging from approximately 25 dBμV at 1GHz to 43 dBμV at

22GHz. You can use a low noise preamplifier to improve this poor noise performance. The noise figure of a two-stage system is given by the following equation:

$$\text{Total NF} = NF_1 + (NF_2 - 1)/G1, \tag{7.3}$$

where NF_1 is the preamplifier noise figure, G1 is the preamplifier gain, and NF_2 is the noise figure of the spectrum analyser (all in linear units, not dB).

This shows that the overall system noise figure is dominated by the first stage's noise figure and gain. A preamplifier is virtually a necessity for these measurements; it should be located very close to the measuring antenna with a short low-loss cable connecting the two, since any loss here will degrade the system noise performance irretrievably, while loss incurred after the preamp has much less effect.

7.1.3.7 Other measuring instruments

Instruments have appeared on the market which fulfil some of the functions of a spectrum analyser or receiver at a much lower price. These may be units which convert an oscilloscope into a spectrum display, or which act as add-ons to a PC that performs the majority of the signal processing and display functions. Such devices are useful for diagnostic purposes provided that you recognize their limitations – typically frequency range, stability, bandwidth and/or sensitivity. The major part of the cost of a spectrum analyser or receiver is in its bandwidth-determining filters and its local oscillator. Cheap versions of these simply cannot give the performance that is needed of an accurate measuring instrument – although improvements in technology have seen some very good low-cost instruments appear on the market. A careful perusal of the specifications is necessary to be sure of performance adequate to your purposes.

Even for diagnostic purposes, frequency stability and accuracy are necessary to make sense of spectrum measurements, and the frequency range must be adequate (150kHz–30MHz for conducted, 30MHz to more than 1GHz for radiated diagnostics). Sensitivity matching that of a spectrum analyser will be needed if you are working near to the emission limits. The inflexibility of the cheaper units soon becomes apparent when you want to make detailed tests of particular emission frequencies.

7.2 Transducers

For any RF emissions measurement you need a device to couple the measured variable into the input of the measuring instrumentation. Measured variables take one of four forms:

- radiated electric field
- radiated magnetic field
- conducted cable voltage
- conducted cable current

and the transducers for each of these forms are discussed below.

7.2.1 Antennas for radiated field

7.2.1.1 VHF-UHF antennas

The basics of electromagnetic fields are outlined in section 11.1.4.1. Radiated field measurements can be made of either electric (E) or magnetic (H) field components. In the far field the two are equally representative of the power in the field, and are related by the impedance of free space:

$$E/H = Z_o = 120\pi = 377\Omega \tag{7.4}$$

but in the near field their relationship is complex and generally unknown. In either case, an antenna is needed to couple the field to the measuring receiver. Electric field strength limits are specified in terms of volts (or microvolts) per metre at a given distance from the EUT, whilst measuring receivers are calibrated in volts (or microvolts) at the 50Ω input. The antenna must therefore be calibrated in terms of volts output into 50Ω for a given field strength at each frequency; this calibration is known as the *antenna factor*.

CISPR 16-1-4 defines transducers for radiated measurements. Historically its reference antenna has been a tuned dipole, but it also allows the use of broadband antennas, which remove the need for retuning at each frequency. Up until the mid-1990s the two most common broadband devices were the biconical, for the range 30–300MHz, and the log periodic, for the range 300–1000MHz (some examples have different frequency ranges).

However, it is possible to combine a biconical and a log periodic to cover the range 30–1GHz or even up to 3GHz. The two structures have been amalgamated with a means of ensuring that the feed is properly defined over the whole frequency range, and this type, originally designed at York University in the UK, is now available commercially. It is known, unsurprisingly, as the BiLog. Its major advantage, particularly appreciated by test houses, is that an entire radiated emissions (or immunity) test can be done without changing antennas, with a consequent improvement in speed and reliability. This has meant that the type is now almost universally used for commercial testing – the military standards are prescriptive and the BiLog has never made it into this sector – and versions are available from all the main EMC antenna manufacturers.

Figure 7.5 The BiLog

The advantage of the tuned dipole is that its performance can be accurately predicted, but because it can only be applied at spot frequencies it is not used for everyday measurement but is reserved for calibration of broadband antennas, site surveys, site attenuation measurements and other more specialized purposes.

Antenna factor

Those who use antennas for radio communication purposes are familiar with the specifications of gain and directional response, but these are of only marginal importance for EMC emission measurements. The antenna is always oriented for maximum response. Antenna factor is the most important parameter, and each calibrated broadband antenna is supplied with a table of its antenna factor (in dB/m, for E-field antennas) versus frequency. Antenna calibration is treated in more detail in section 7.5.2.3. Typical antenna factors for a biconical, a log periodic and two varieties of BiLog are shown in Figure 7.6. From this you can see that there is actually very little difference for the log periodic section (above 300MHz) in particular: any LP design with the same dimensions will give substantially the same performance. The biconical (30–300MHz) section can be "tweaked" but again, antennas with the same basic dimension give largely similar performance. This has the particular consequence that if all labs use pretty much the same design of antenna (which they do), the inter-lab variations in radiated field measurement due to the antenna itself are minimized.

To convert the measured voltage at the instrument terminals into the actual field strength at the antenna you have to add the antenna factor and cable attenuation (Figure 7.7). Cable attenuation is also a function of frequency; it can normally be regarded as constant with time, although long cables exposed to wide temperature variations, such as on open sites, may suffer slight variations of loss with temperature.

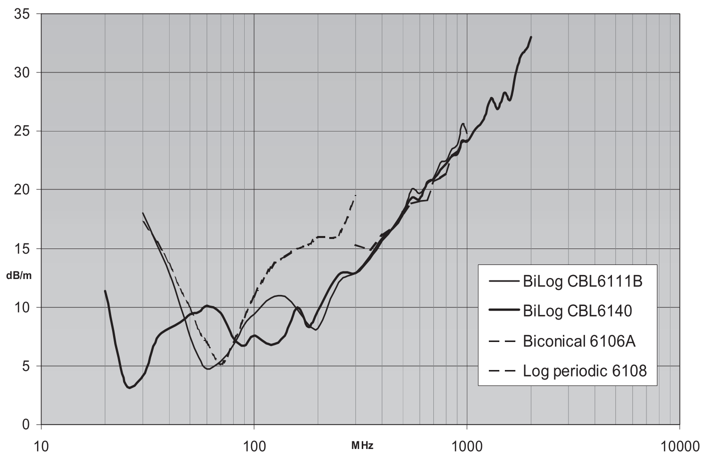


Figure 7.6 Typical antenna factors

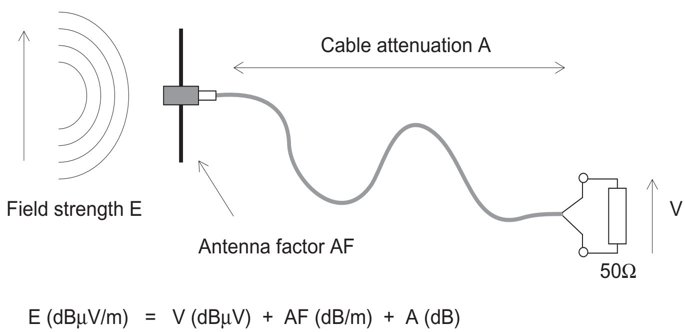


Figure 7.7 Converting field strength to measured voltage

System sensitivity

A serious problem can arise when using an antenna with a spectrum analyser for radiated tests. Radiated emission compliance tests can be made at 10m distance and the

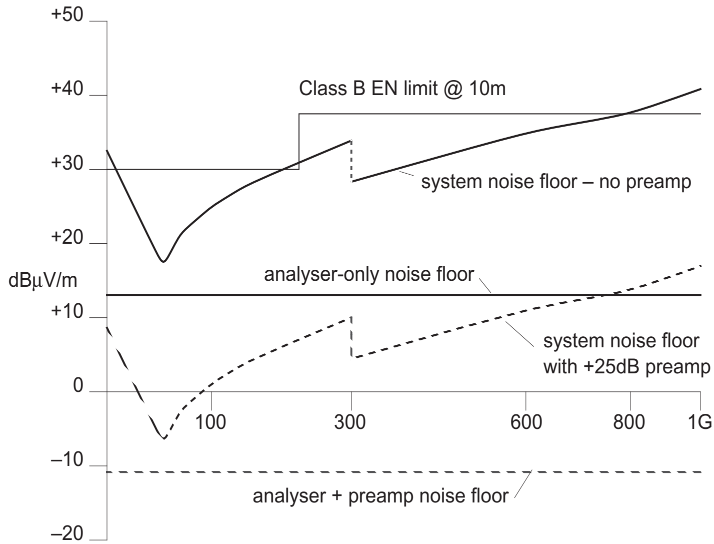


Figure 7.8 Typical system sensitivity (separate biconical and log periodic)

most severe limit in the usual commercial standards is the CISPR/EN Class B level, which is 30dBµV/m below 230MHz and 37dBµV/m above it. The minimum measurable level will be determined by the noise floor of the receiver or analyser (see section 7.1.3.1), which for an analyser with 120kHz bandwidth is typically +13dBµV. To this must be added the antenna factor and cable attenuation in order to derive the overall measurement system sensitivity. Taking the antenna factors already presented, together with a typical 3dB at 1GHz due to cable attenuation, the overall system noise floor rises to 41dBµV/m at 1GHz as shown in Figure 7.8, which is 4dB *above* the limit line.

The CISPR 16-1-1 requirement on sensitivity is that the noise contribution should affect the accuracy of a compliant measurement by less than 1dB. This implies a noise floor that is below the measured value by at least 6dB.

Thus fully compliant Class B radiated measurements *cannot be made with a spectrum analyser alone*. Three options are possible: reduce the measuring distance to 3m, which may raise the limit level by 10.5dB, but this increases the measurement uncertainty and still gives hardly enough margin at the top end; or, use a preamplifier or preselector to lower the effective system noise floor, by a factor equal to the preamp gain less its noise figure, typically 20–25dB; or use a test receiver, which has a much better inherent sensitivity.

Polarization

In the far field the electric and magnetic fields are orthogonal (Appendix D, section D.3.8). With respect to the physical environment each field may be vertically or horizontally polarized, or in any direction in between. The actual polarization depends on the nature of the emitter and on the effect of reflections from other objects. An antenna will show a maximum response when its plane of polarization aligns with that of the incident field, and will show a minimum when the planes are at right angles. The plane of polarization of biconical, log periodic and BiLog is in the plane of the elements. CISPR emission measurements must be made with "substantially plane polarized" antennas; circularly polarized antennas, such as the log spiral, a broadband type once favoured for military RF immunity testing, are outlawed.

7.2.1.2 The loop antenna

The majority of radiated emissions are measured in the range 30 to 1000MHz. A few CISPR standards call for radiated measurements below 30MHz. In these cases the magnetic field strength is measured, using a loop antenna. Measurements of the magnetic field give better repeatability in the near field region than do measurements of the electric field, which is easily perturbed by nearby objects. The loop (Figure 7.9(a)) is merely a coil of wire which produces a voltage at its terminals proportional to frequency, according to Faraday's law:

$$E = 4\pi \cdot 10^{-7} \cdot N \cdot A \cdot 2\pi F \cdot H \tag{7.5}$$

where N is the number of turns in the loop
A is the area of the loop, m^2
F is the measurement frequency, Hz
H is the magnetic field, Amps/metre

The low impedance of the loop does not match the 50Ω impedance of typical test instrumentation. Also, the frequency dependence of the loop output makes it difficult to measure across more than three decades of frequency, typically 9kHz to 30MHz. Passive loops deal with this latter problem by switching in different numbers of turns to cover smaller sub-ranges in frequency, but naturally this does not lend itself to test automation.

These disadvantages are overcome by including as part of the antenna a preamplifier which corrects for the frequency response and matches the loop output to 50Ω. The preamp can be battery powered or powered from the test instrument. Such an "active" loop has a flat antenna factor across its frequency range. Its disadvantage by comparison with a passive loop is that it can be saturated by large signals, and some form of overload indication is needed to warn of this.

The Van Veen loop

A disadvantage of the loop antenna as it stands is its lack of sensitivity at low frequencies. An alternative method [31] is to actually surround the EUT with the loop; in its practical realization, three orthogonal loops of 2–4m diameter are used with the current induced in each being sensed by a current transformer, and the three signals are measured in turn by the test receiver. This is the large loop antenna (LLA) or Van Veen loop, named after its inventor, and it is specified in CISPR 15/EN 55015, the standard for lighting equipment.

The MIL-STD loop

Another design of loop antenna is used for low frequency military emissions tests. This is sometimes called a "search coil" as it is used in a different manner, being swept over the surfaces of the EUT at a fixed distance of 7cm. The standard design has 36 turns and a diameter of 13.3 cm. The method is described in MIL-STD-461G RE101 and DEF STAN 59-411 DRE02. It is considerably more complicated: measurements are made by searching for the highest levels across the frequency range (20Hz–100kHz for DRE02) around each face of the EUT; if the limit is exceeded at 7cm, the further distance at which it *is* achieved has to be reported.

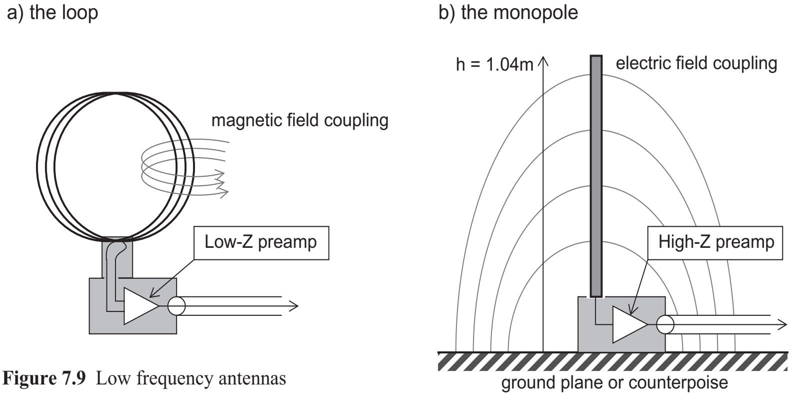


Figure 7.9 Low frequency antennas

7.2.1.3 The electric monopole

The complementary antenna to the loop is the monopole (Figure 7.9(b)). Covering the frequency range again typically up to 30MHz, the monople is simply a single vertical rod of length 1.04m (41") referenced against a ground plane or "counterpoise", and it measures the electric field in vertical polarization. It's not used in many CISPR-based tests, only the automotive emissions standards CISPR 12 and CISPR 25 call it up, but it is used fairly widely in military testing to DEF STAN 59-411 and its American equivalent, MIL-STD-461G. These tests require low frequency measurement of both the E-field and the H-field strengths.

The monopole is electrically short (its length is much less than a wavelength) and its source impedance looks like a capacitance of a few pF. So just as with the loop it is not suitable for connecting directly to a 50 ohm measuring system, and it should be fitted with a high impedance pre-amplifier to give impedance matching and to give a flat antenna factor. This makes it sensitive to damage and to electrical overload by large signals during the measurement – including the all-pervasive 50Hz mains E-field – so again it needs an overload indicator, and a high-pass filter to remove the mains field. Because the near electric field can be affected by the presence of virtually any conducting object, the accuracy and repeatability of measurements made with this antenna is poor even by the standards of EMC testing.

7.2.1.4 Antennas for > 1GHz

Dipole-type antennas become very small and insensitive as the frequency increases above 1GHz. They have a smaller "aperture", which describes the area from which energy is collected by an antenna. It is possible to get log periodics up to 2 or even 3GHz, and the BiLog types can also go this high, but above this it is normal to use a horn antenna. The horn is explicitly specified in the MIL-STD-461G radiated emissions test for the range 1–18GHz (and a larger one is also required by this standard for the range 200MHz–1GHz). This type converts the 50 ohm coax cable impedance directly to a plane wave at the mouth of the horn, and depending on construction can have either a wide bandwidth or a high gain and directivity, though it is rare to get both together. As with the dipole and monopole types, it is calibrated for the electric field.

The high gain gives the best system noise performance, but the directivity can be both a blessing and a curse. Its advantage is that it gives less sensitivity to off-axis reflections, so that the anechoic performance of a screened room or the effect of reflection from dielectric materials – which worsens at these higher frequencies – becomes less critical; but it will also cover less area at a given distance, so large EUTs cannot be measured in one sweep but must have the antenna trained on different parts in consecutive sweeps.

7.2.2 LISNs and probes for cable measurements

7.2.2.1 Artificial mains network

To make conducted voltage emissions tests on the mains port, you need an Artificial Mains Network (AMN) or Line Impedance Stabilizing Network (LISN) to provide a defined impedance at RF across the measuring point, to couple the measuring point to the test instrumentation and to isolate the test circuit from unwanted interference signals on the supply mains. The most widespread type of LISN is defined in CISPR 16-1-2 and presents an impedance equivalent to 50Ω in parallel with 50μH + 5Ω across each line to earth (Figure 7.10). This is termed a "V-network" since for a single-phase supply the impedance appears across each arm of the V, where the base of the V is the reference earth.

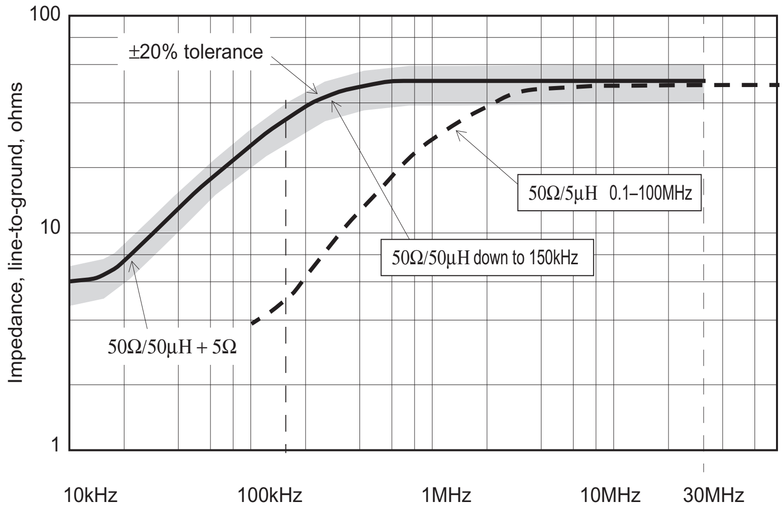


Figure 7.10 LISN impedances versus frequency

Note that its impedance is not defined above 30MHz, partly because commercial mains conducted measurements are not required above this frequency (although military and automotive standards are) but also because component parasitic reactances make a predictable design difficult to achieve. An alternative 50Ω/5μH network is available in the CISPR specification, and a similar version is widely used in military and automotive tests according to DEF STAN 59-411 and MIL-STD-461G. Since it uses a smaller inductor, it can carry higher currents and its impedance can be controlled up to 100MHz and beyond. The military LISN's impedance is specified down to 1kHz and up to 400MHz. It is principally intended to simulate DC supplies but can also be used for mains tests when higher current ratings, typically above 50A, are needed.

CISPR 16-1-2 includes a suggested circuit (Figure 7.11) for each line of the LISN, but it only actually *defines* the impedance characteristic. The main impedance determining components are the measuring instrumentation input impedance, the 50µH inductor and the 5Ω resistor. The remaining components serve to decouple the incoming supply. The 5Ω resistor is only effective at the bottom end of the frequency range, and in fact a "cut-down" version of LISN is defined which omits it and the 250µH inductor but is restricted to frequencies above 150kHz. Most commercial LISNs, though, include the whole circuit and cover the range down to 9kHz. A common addition is a high-pass filter between the LISN output and the receiver, cutting off below 9kHz, to prevent the receiver from being affected by high-level harmonics of the mains supply itself. Of course, this filter has to maintain the 50Ω impedance and have a defined (preferably 0dB) insertion loss at the measured frequencies.

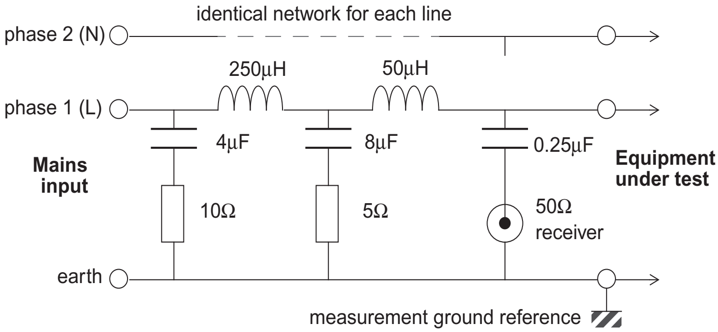


Figure 7.11 LISN circuit per line

An extension to the LISN specification was introduced in an amendment to CISPR 16-1-2 [185]. This tightens various aspects of the impedance requirement, in particular that it should have a phase angle tolerance of better than ±11.5° across the whole frequency range, even up to 30MHz. This requirement can be difficult to meet for some LISNs, particularly larger ones at the high frequency end, because of stray capacitance. The justification for it is that if you are going to calculate a complete measurement uncertainty budget for the conducted emissions test, a boundary needs to be placed on the possible range of impedance in both magnitude and phase presented by the LISN, otherwise the uncertainty due to impedance variations is unknown. It seems, though, debatable whether the greater complexity in calibration will be worthwhile when other, larger sources of uncertainty in what is already a reasonably well-specified test remain unaddressed (section 7.5.2.2).

Current rating

For the user, the most important parameter of the LISN is its current rating. Since the inductors are in series with the supply current, their construction determines how much current can be passed; if they are air cored, then magnetic saturation is not a problem but the coils may still overheat with too much current. Most LISNs use air cored coils, but if magnetic cores are used (typically iron powder) for a smaller construction then you also need to be concerned about saturation, which will affect the impedance characteristic of the device.

Another effect of the impedance of the inductors is the voltage drop that may appear between the supply feed and the EUT terminals. At 50Hz the total in-line inductance of

600µH gives an impedance of about 0.2Ω, which may itself give a significant voltage drop, added to the resistance through the unit, at high currents; but if, as may happen with an electronic power supply, your unit draws substantial harmonics of 50Hz (see section 11.4), then the inductive impedance of a few ohms at a few hundred Hz can give a much greater voltage drop with attendant waveform distortion. This in turn could affect the functional performance of the EUT.

Limiter

The spectrum analyser's input mixer is a very fragile component. As well as being affected by high-level continuous input signals it is also susceptible to transients. Unfortunately the supply mains is a fruitful source of such transients, which can easily exceed 1kV on occasion. These transients are attenuated to some extent by the LISN circuitry but it cannot guarantee to keep them all within safe limits. More importantly, switching operations within the EUT itself are likely to generate large transients due to interruption of current through the LISN chokes, and these are fed directly to the analyser without attenuation.

For this reason it is essential to include a transient limiter in the signal cable between the LISN and the spectrum analyser. This adds an extra 10dB loss (typically) in the signal path which must be added to the LISN's own transducer factor, since the limiting devices need to be fed from a well-defined impedance, but this can normally be tolerated and is a much cheaper option than expensive repair bills for the analyser front end. The limiter circuit generally uses a simple back-to-back diode clipping scheme; some limiters also incorporate a filter to restrict the frequency range transmitted to the analyser.

A limiter is less necessary, though still advisable, when a measuring receiver is used since the receiver's front end should be already protected. The limiter does have one particular danger: low frequency signals that are outside the measurement range and therefore not subject to limits may legitimately have amplitudes of volts, which will drive the limiter into continuous clipping and create harmonics which are then incorrectly measured as in-band signals. If you suspect such an eventuality, be prepared to place extra attenuation or high-pass filtering before the limiter to check.

Earth current

A large capacitance (in total around 12µF) is specified between line and earth, which when exposed to the 230V line voltage results in around 0.9A in the safety earth. This level of current is lethal, and the unit must therefore be solidly connected to earth for safety reasons. If it is not, the LISN case, the measurement signal lead and the equipment under test (EUT) can all become live. As a precaution, you are advised to bolt your LISN to a permanent ground plane and not allow it to be carried around the lab! A secondary consequence of this high earth current is that LISNs cannot be used directly on mains circuits that are protected by earth leakage or residual current circuit breakers. Both of these problems can be overcome by feeding the mains to the LISN through an isolating transformer, provided that this is sized adequately, bearing in mind the extra voltage drop through the LISN itself.

Diagnostics with the LISN

As it stands, the LISN does not distinguish between differential mode (line-to-line) and common mode (line-to-earth) emissions (see section 11.2.2); it merely connects the measuring instrument between phase and earth. A modification to the LISN circuit (Figure 7.12) allows you to detect either the sum or the difference of the live and neutral voltages, which correspond to the common mode and differential mode voltages respectively [118]. This is not required for compliance measurements but is very useful when making diagnostic tests on the mains port of a product. Transformers TX1 and 2, which can be nothing more than 50 ohm 1:1 broadband balun parts, are switched to add or subtract the two signals. (Or see page 355 for a quick and dirty check.)

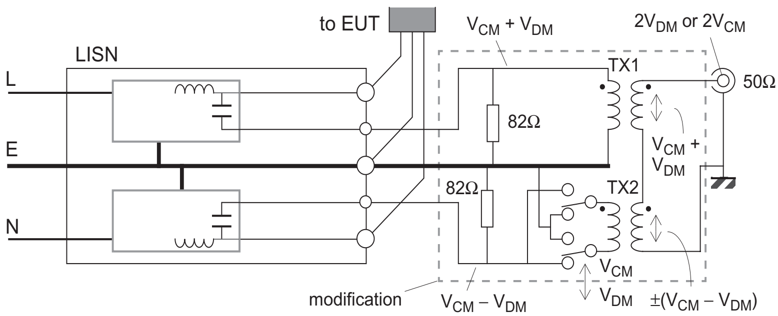


Figure 7.12 Modifying the LISN to measure differential or common mode

7.2.2.2 *Artificial hand*

A minor accessory which should be used for conducted testing in some circumstances is the artificial hand. This is specified in CISPR 16-1-2, and it is for application to EUTs which have no safety earth and are hand-held in normal use, to simulate the influence of the user's hand on the measurement. Typical EUTs are power tools, food mixers, telephone handsets or keyboards. The artificial hand is a strip of metal foil, typically 6cm wide, connected through a 1m length of wire to a series RC element of 220pF and 510Ω, which in turn is grounded to the reference earth of the LISN. The foil is placed on or wrapped around that part of the EUT normally touched or held by the user's hand.

7.2.2.3 *Absorbing clamp and CMAD*

As well as measuring the emissions above 30MHz directly as a radiated field you can also measure the disturbances that are developed in common mode on connected cables. Standards which apply primarily to small apparatus connected only by a mains cable – notably CISPR 14-1/EN 55014-1 – specify the measurement of interference power present on the mains lead. This has the advantage of not needing a large open area for the tests, but it should be done inside a fairly large screened room and the method is somewhat clumsy. The transducer is an absorbing device known as a ferrite clamp.

The ferrite absorbing clamp (often referred to as the MDS-21 clamp, and different from the EM-clamp used in immunity tests despite its similar appearance) consists of a current transformer using two or three ferrite rings, split to allow cable insertion, with a coupling loop (Figure 7.13). This is backed by further ferrite rings forming a power absorber and impedance stabilizer, which clamps around the mains cable to be measured. The device is calibrated in terms of output power versus input power, i.e. insertion loss. The purpose of the ferrite absorbers is to attenuate reflections on the lead under test downstream of the current transformer; this is not 100% effective, and a full compliance test requires the clamp to be traversed for a half wavelength along the cable, i.e. 5m, to find a maximum. The lead from the current transformer to the measuring instrument is also sheathed with ferrite rings to attenuate screen currents on this cable. Because the output is proportional to current flowing in common mode on the measured cable, it can be used as a direct measure of noise power, and the clamp can be calibrated as a two-port network in terms of output power versus input power.

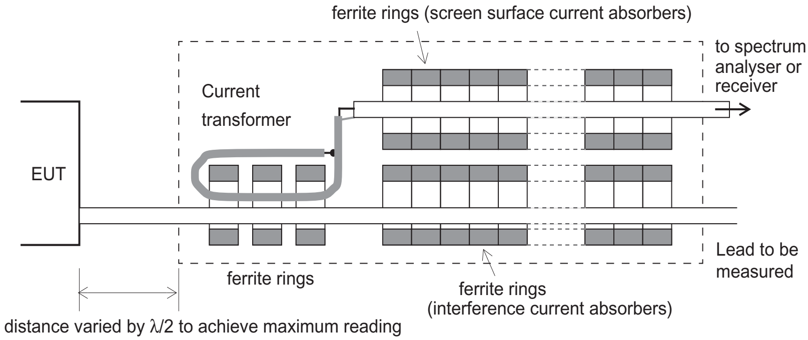


Figure 7.13 The ferrite absorbing clamp

CISPR 16-1-3 specifies the construction, calibration and use of the ferrite clamp. As well as its use in certain compliance tests, it also lends itself to diagnostics as it can be used for repeatable comparative measurements on a single cable to check the effect of circuit changes.

The CMAD

A further common use for the clamp is to be applied to the further end of connected cables, both in radiated emissions and immunity tests, to damp the cable resonance and reduce variations due to cable termination. The clamp output is not connected when it is used in this way. Although this is a convenient method if a clamp is already to hand, using a string of 6–10 large snap-on ferrite sleeves is almost as effective. Alternatively, you can obtain commercially a unit known as a “Common Mode Absorbing Device” (CMAD) which is the same thing. Amendment A1 to the third edition of CISPR 22 specified such a device to be applied to cables leaving the radiated emissions test site, whose purpose was simply to stabilize the far-end cable impedance and therefore make for a more repeatable test.

Despite this worthy aim, the amendment sparked such a howl of protest that it was abandoned and later editions of the standard make no reference to cable common mode impedance stabilization. Many of the reasons against using CMADs in this way demonstrated a lack of understanding of the purpose of the amendment: for instance it was claimed that such clamps would never be used in real installations and therefore the test would not be representative; but there is really no way that such test set-ups can ever be both truly representative *and* repeatable. The merit of the CMAD is that it would ensure a high impedance at a fixed distance from the EUT and therefore improve repeatability, and at the same time represent one installation condition where such an impedance did occur.

A more reasonable objection to the amendment was that at the time, no method was published for verifying the impedance of the CMAD. This has now been addressed and CISPR 16-1-4 edition 3 includes such a method. This author is wholeheartedly in favour of using some kind of CMAD to control the cable impedances in the radiated tests; even if the compliance test stubbornly refuses to address the issue, your pre-compliance measurements will be easier to repeat if you do.

7.2.2.4 Current probe

Also useful for diagnostics is the current probe, which does the same thing as the absorbing clamp except that it doesn't have the absorbers. It is simply a clamp-on, calibrated wideband current transformer. Military specifications call for its use on individual cable looms, and later editions of CISPR 22/EN 55022 giving test methods for telecoms ports also requires a current probe for some versions of the tests. CISPR 16-1-2 includes a specification for the current probe. Because the current probe does not have an associated absorber, the RF common mode termination impedance of the line under test should be defined by an impedance stabilizing network, which must be transparent to the signals being carried on the line.

Both the ferrite clamp and the current probe have the great advantage that no direct connection is needed to the cable under test, and disturbance to the circuit is minimal below 30MHz since the probe effect is no more than a slight increase in common mode impedance. But at higher frequencies the effect of the common mode coupling capacitance between probe and cable becomes significant, as does the exact position of the probe along the cable, because of standing waves on the line. Your test plan and report should note this position exactly, along with the method of bonding the current probe case to the ground plane, which controls the stray capacitance.

7.2.2.5 ISNs and other methods for telecom port conducted emissions

Later editions of CISPR 22/EN 55022 have provisions for tests on telecommunications ports. The preferred method uses a particular variant of impedance stabilizing network (ISN, also referred to as Asymmetrical Artificial Network, AAN) which is designed to mimic the characteristics of balanced, unscreened ISO/IEC 11801 data cables. This network has a common mode impedance of 150Ω and a carefully controlled longitudinal conversion loss (LCL, see section 14.1.9.1), that is, the parameter which determines the conversion from differential mode signal to common mode interference currents. Both current and voltage limits are published, related by the 150Ω impedance.

The telecom port test has been controversial since the third edition was published. The basic problem is that, since it applies to ports such as Local Area Network (LAN) interfaces, the signal that is intended to be passed through the port – data up to, say, 100Mb/s – is in the same frequency range as the interference to be measured. The

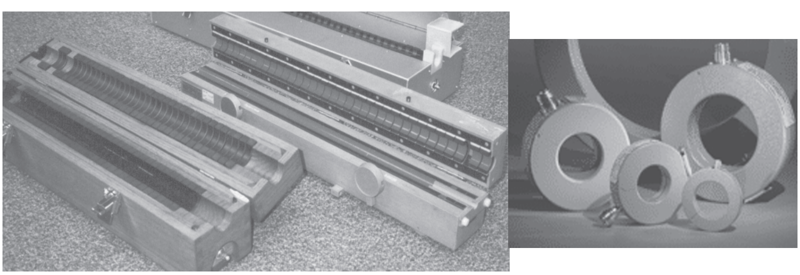


Figure 7.14 Absorbing clamps and current probes

wanted signal is in differential mode while the interference is in common mode. Therefore, for a given data amplitude as determined by the network in use, such as Ethernet, the interference you measure is at least partly determined by the LCL of the network that is used for the measurement to represent a particular type of cable. There will be two components to the measurement:

- the wanted data converted from differential to common mode by the LCL;
- any extraneous common mode noise added by imperfections in the design of the port.

Of course, the second of these must be controlled, and so the test is necessary, but the first should not be allowed to spoil the measurement unnecessarily. Hence a need for a very careful specification of the LCL of the impedance stabilizing network, since all other parameters are invariant. The initial version of the standard paid insufficient attention both to this question and to the proper calibration of the ISN, and it took some time for the issue to be sorted out. The fifth edition of EN 55022 corrected the problems and its values of LCL are shown graphically in Figure 7.15, but in the meantime earlier versions were not acceptable for full compliance purposes in respect of the telecom port test, and for that reason their dates of mandatory implementation kept being postponed.

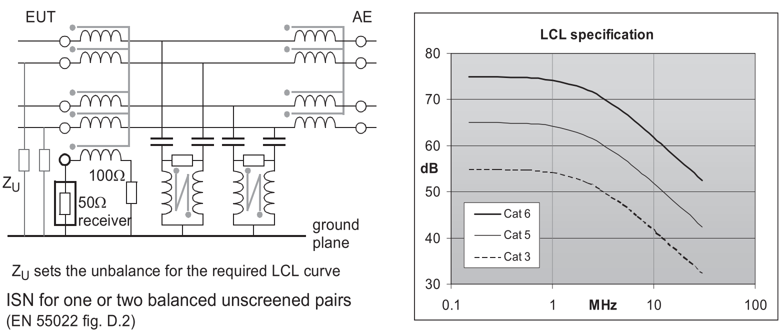


Figure 7.15 An example ISN circuit and the LCL specification

As well as using ISNs with specified parameters for signal lines with balanced, unscreened pairs, the telecom port test is also applied to signal lines that use other kinds of cable. It is not always possible to specify an ISN for every one of these, and so alternative and preferably non-invasive methods of measurement have been and still are needed. These are described in Annex C of CISPR 22/EN 55022 Ed. 5 and include:

- using alternative ISNs, such as the CDNs used for conducted immunity tests to IEC 61000-4-6 (section 8.1.4), as long as the EUT can operate normally with this inserted, and as long as the CDN has a calibrated minimum LCL (C.1.1);
- for shielded cables, using a 150Ω load to the outside surface of the shield in conjunction with a ferrite decoupler (C.1.2);
- using a combination of current probe and capacitive voltage probe, and comparing the result to both current and voltage limits (C.1.3);

- using a current probe only, but with the common mode impedance on the ancillary equipment side of the probe explicitly set to 150Ω at each test frequency with a ferrite decoupler (C.1.4).

The various methods are illustrated in Figure 7.16. In the 5th edition improvements were made over the original, although even so the method of C.1.4 is so cumbersome that the standard itself said “If the method in C.1.4 is combined with the method of C.1.3, it is possible to use the advantages of both methods, without suffering too much from the disadvantages” and in fact it is wise to avoid it if at all possible. Edition 6 of the standard dispensed with C.1.4 altogether. Its successor standard CISPR 32 is more prescriptive; it has a table (Table C.1) which specifies which procedure to use for particular types of cable port. These are updated versions of C1.1, 1.2 and 1.3 below, C.1.4 is nowhere to be seen. C.1.3 has a quirk in that both current and voltage measurements are compared to the limits, and the voltage measurement is adjusted depending on the current measurement. The reference to CDNs as alternative ISNs according to IEC 61000-4-6 is no longer present, although it would be possible to use these CDNs in some circumstances.

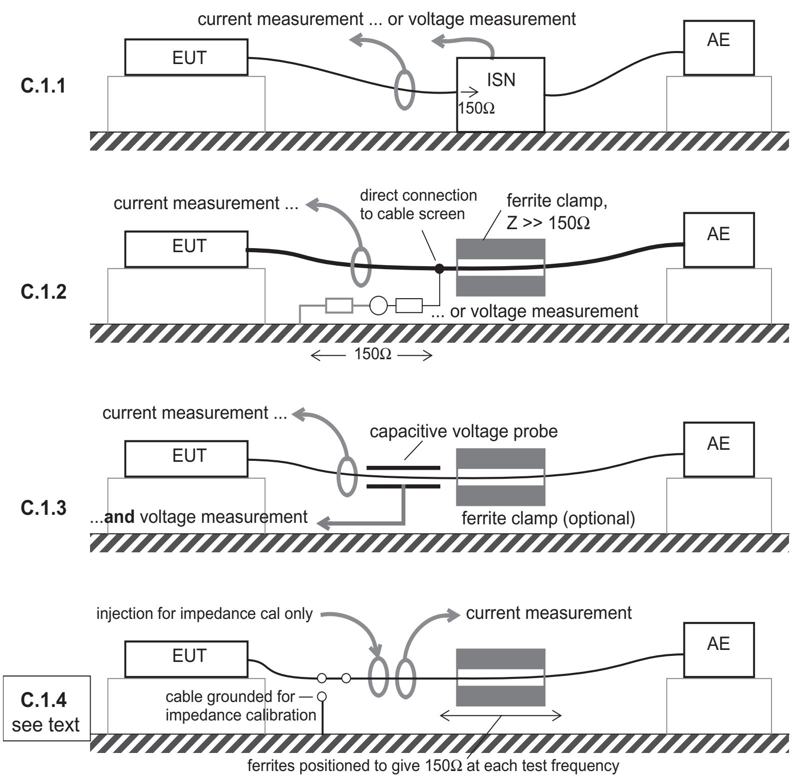


Figure 7.16 Alternative telecom port measurement methods (CISPR 22 Ed 5)

7.2.3 Near field probes

Very often you will need to physically locate the source of emissions from a product. A set of near field (or "sniffer") probes is used for this purpose. These are so-called because they detect field strength in the near field, and therefore two types of probe are needed, one for the electric field (short rod construction) and the other for the magnetic field (loop construction). It is simple enough to construct adequate probes yourself using coax cable (Figure 7.17), or you can buy a calibrated set. The "improved" H-field probe shown in the figure has its screen balanced to reduce E-field pickup. A probe can be connected to a spectrum analyser for a frequency domain display, or to an oscilloscope for a time domain display, although for reasonable sensitivity the E-field probe must go into a high impedance input.

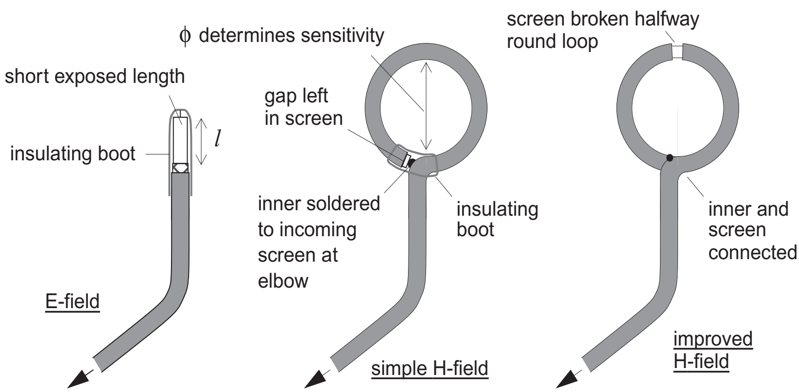


Figure 7.17 Do-it-yourself near field probes

Probe design is a trade-off between sensitivity and spatial accuracy. The smaller the probe, the more accurately it can locate signals but the less sensitive it will be. You can increase sensitivity with a preamplifier if you are working with low-power circuits. A good magnetic field probe is insensitive to electric fields and vice versa; this means that an electric field probe will detect nodes of high dv/dt but will not detect current paths, while a magnetic field probe will detect paths of high di/dt but not voltage points.

Near field probes can be calibrated in terms of output voltage versus field strength – for a loop the voltage is given by Faraday's Law, $V = A \cdot dB/dt$, and for a rod the conversion is effectively the length l of the element divided by 1m, in series with the capacitance between the element and the item being probed (which is generally unknown). But these figures should be used with care. Measurements cannot be directly extrapolated to the far field strength (as on an open site) because in the near field one or other of the E or H fields will dominate depending on source type. The sum of radiating sources will differ between near and far fields, and the probe will itself distort the field it is measuring. Perhaps more importantly, you may mistake a particular "hot spot" that you have found on the circuit board for the actual radiating point, whereas the radiation is in fact coming from cables or other structures that are coupled to this point via an often complex path. Probes are best used for tracing and for comparative rather than absolute measurements.

7.2.3.1 Near field scanning devices

A particular implementation of a near field probe is the planar scanning device, one example of which is the EMSCAN. This was developed and patented at Bell Northern Research in Canada and is now marketed by EmScan Corporation of Canada. In principle it is essentially a planar array of tiny near field current probes arranged in a grid form on a multilayer PCB [26]. The output of each current probe can be switched under software control to a spectrum analyser, whose output in turn provides a graphical display on the controlling workstation.

An alternative method uses a single probe positioned by stepper motors, in the same way as an X-Y plotter; an example of this is marketed by Detectus of Sweden. This has the advantage that it can carry any type of probe (including, for instance, a thermal probe) and can move in three dimensions, but because it relies on physical positioning it is much slower.

The device is used to provide a near-instantaneous two-dimensional picture of the RF circulating currents within a printed circuit card placed over the scanning unit. It can provide either a frequency versus amplitude plot of the near field at a given location on the board, or an x-y co-ordinate map of the current distribution at a given frequency. For the designer it can quickly and repeatably show the effect of remedial measures on the PCB being investigated, while for production quality assurance it can be used to evaluate batch samples which can be compared against a known good standard.

7.2.4 The GTEM for emissions tests

Use of the GTEM for radiated RF immunity testing is covered in section 8.1.1.5. It can also be used for emissions tests with some caveats. The GTEM is a special form of enclosed TEM (transverse electromagnetic mode) transmission line which is continuously tapered and terminated in a broadband RF load. This construction prevents resonances and gives it a flat frequency response from DC to well beyond 1GHz. An EUT placed within the transmission line will couple closely with it, and its radiated emissions can be measured directly at the output of the cell. Since far field conditions also describe a TEM wave, any test environment that provides TEM wave propagation should be acceptable as an alternative. The great advantages of this technique are that no antenna or test site is needed, the frequency range can be covered in a single sweep, and ambients are eliminated.

However, compliance tests demand a measure of the radiated emissions as they would be found on an OATS (see next section). This requires that the GTEM measurements are correlated to OATS results. This is done in software and the model was originally described in [155]. In fact, three scans are done with the EUT in orthogonal orientations within the cell. The software then derives at each frequency an equivalent set of elemental electric and magnetic dipole moments, and then re-calculates the far field radiation at the appropriate test distance from these dipoles.

The limitation of this model is that the EUT must be "electrically small", i.e. its dimensions are small when compared to a wavelength. Connected cables pose a particular problem since these often form the major radiating structure, and are of course rarely electrically small, even if the EUT itself is. Good correlation has been found experimentally for small EUTs without cables [40][116], but the correlation worsens as larger EUTs, or EUTs with connected cables, are investigated.

There is now a standard for measurements of both emissions and immunity in TEM cells, IEC 61000-4-20 [172]. This expands on the OATS correlation and gives a detailed description of the issues involved in using any kind of TEM cell, including the GTEM, for radiated tests, but its limitation is apparent in Clause 6:

> **6.1 Small EUT**
>
> An EUT is defined as a small EUT if the largest dimension of the case is smaller than one wavelength at the highest test frequency (for example, at 1 GHz λ = 300 mm), and if no cables are connected to the EUT. All other EUTs are defined as large EUTs.
>
> **6.2 Large EUT**
>
> An EUT is defined as a large EUT if it is
>
> • a small EUT with one or more exit cables,
>
> • a small EUT with one or more connected non-exit cables,
>
> • an EUT with or without cable(s) which has a dimension larger than one wavelength at the highest test frequency,
>
> • a group of small EUTs arranged in a test set-up with interconnecting non-exit cables, and with or without exit cables.

For “guidance purposes” on emissions tests, it then goes on to state that “for compliance testing of large EUTs the following procedure has been proposed” (without then saying that the following procedure is accepted): the procedure involves making a statistical comparison between multiple OATS and TEM cell measurements on a “particular EUT type” and, if the comparison shows correlation of better than 3dB, accepting the TEM cell method for that type. Hardly surprisingly, few test labs regard this as a practical way of declaring compliance. In other words virtually all real EUTs cannot be treated under the current version.

In practice the GTEM is a useful device for testing small EUTs without cables, and can be applied in a number of specialized applications such as for measuring direct emissions from integrated circuits. As a basic standard, IEC 61000-4-20 does not specify the tests to be applied to any particular apparatus or system. Instead it is meant to provide a general reference for all interested product committees, and its popularity will depend on it being referenced widely in conventional product emissions standards. The OATS correlation is limited in its full applicability to only a few types of EUT, and the likelihood that the GTEM will inhabit more than a restricted niche in EMC testing is small. Meanwhile, the National Physical Laboratory Electromagnetic Metrology Group has published a Best Practice Guide [110] for the GTEM which expands on the practicalities of IEC 61000-4-20 measurements. Anybody who uses a GTEM should have both of these documents as a reference.

7.3 Sites and facilities

7.3.1 Radiated emissions

7.3.1.1 The CISPR OATS

For CISPR-based standards, the reference for radiated emissions compliance testing is an Open Area Test Site (OATS). The characteristics of a minimum standard OATS are defined in CISPR 22/EN 55022 and CISPR 16-1-4 and some guidance for construction is given in ANSI C63.7 [228]. Such a site offers a controlled RF attenuation characteristic between the emitter and the measuring antenna (known as “site attenuation”). To avoid influencing the measurement there should be no objects that could reflect RF within the vicinity of the site. The original CISPR test site dimensions are shown in Figure 7.18.

The ellipse defines the area which must be flat and free of reflecting objects, including overhead wires. In practice, for good repeatability between different test sites a substantially larger surrounding area free from reflecting objects is advisable. This means that the room containing the control and test instrumentation needs to be some distance away from the site. An alternative is to put this room directly below the ground plane, either by excavating an underground chamber (as long as your site's water table will allow it) or by using the flat roof of an existing building as the test site. Large

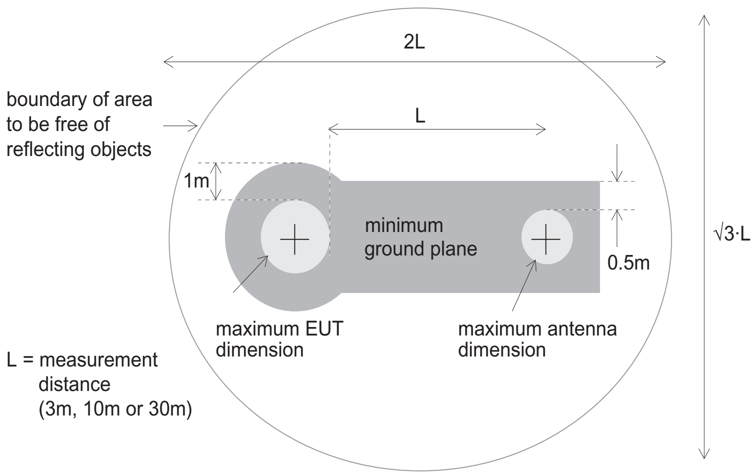


Figure 7.18 The CISPR OATS

coherent surfaces will be a problem, but not smaller pieces of metal for door hinges, door knobs, light fixtures at ground level, bolts, and metal fittings in primarily non-conductive furniture. Don't put your site right next to a car park!

Ground plane

Because it is impossible to avoid ground reflections, these are regularized by the use of a ground plane. The minimum ground plane dimensions are also shown in Figure 7.18. Again, an extension beyond these dimensions will bring site attenuation closer to the theoretical; scattering from the edges contributes significantly to the inaccuracies, although these can be minimized by terminating the edges into the surrounding soil [97]. Close attention to the construction of the ground plane is necessary. It should preferably be solid metal sheets welded together, but this may be impractical over the whole area. Bonded wire mesh is suitable, since it drains easily and resists warping in high temperatures if suitably tensioned. For RF purposes it must not have voids or gaps that are greater than 0.1λ at the highest frequency (i.e. 3cm for 1GHz). Ordinary wire mesh is unsuitable unless each individual overlap of the wires is bonded. CISPR 16-1-4 suggests a ground plane surface roughness of better than 4.5cm. The surface should not be covered with any kind of lossy dielectric – floor paint is acceptable, but nothing much more than that.

Measuring distance

The measurement distance d between EUT and receiving antenna determines the overall dimensions of the site and hence its expense. There are three commonly specified distances: 3, 10 and 30m, although 30m is rarely used in practice. In CISPR 22/EN 55022 and related standards the measuring distance is defined between the boundary of the EUT and the reference point of the antenna. Although the limits are usually specified at 10m distance, tests can be carried out on a 3m range, on the assumption that levels measured at 10m will be 10.5dB lower (field strength should be proportional to 1/d). This assumption is not entirely valid at the lower end of the frequency range, where 3m separation is approaching the near field, and indeed experience from several quarters shows that a linear 1/d relationship is more optimistic than is found in practice. Nevertheless because of the expense of the greater distance, especially in an enclosed chamber, 3m measurements are widely used.

Weather proofing

The main environmental factor that affects open area emissions testing, particularly in Northern European climates, is the weather. Some weatherproof but RF-transparent structure is needed to cover the EUT to allow testing to continue in bad weather. The structure can cover the EUT alone, for minimal cost, or can cover the entire test range; a half-and-half solution is sometimes adopted, where a 3m range is wholly covered but the ground plane extends outside and the antenna can be moved from inside to out for a full 10m test. Fibreglass is the favourite material. Wood is not preferred, because the reflection coefficient of some grades of wood is surprisingly high [99] and varies with moisture content, leading to differences in site performance between dry and wet weather. You may need to make allowance for the increased reflectivity of wet surfaces during and after precipitation, and a steep roof design which sheds rain and snow quickly is preferred.

7.3.1.2 Validating the site: NSA

Site attenuation is the insertion loss measured between the terminals of two antennas on a test site, when one antenna is swept over a specified height range, and both antennas have the same polarization. This gives an attenuation value in dB at each frequency for which the measurement is performed. Transmit and receive antenna factors are subtracted from this value to give the Normalized Site Attenuation (NSA), which should be an indication only of the performance of the site, without any relation to the antennas or instrumentation.

NSA measurements are performed for both horizontal and vertical polarizations, with the transmit antenna positioned at a height of 1m (for broadband antennas) and the receive antenna swept over the appropriate height scan. CISPR standards specify a height scan of 1 to 4m for 3m and 10m sites. The purpose of the height scan, as in the test proper (section 7.4.2), is to ensure that nulls caused by destructive addition of the direct and ground reflected waves are removed from the measurement. Note that the height scan is *not* intended to measure or allow for elevation-related variations in signal emitted directly from the source, either in the NSA measurement or in a radiated emissions test.

Figure 7.19 shows the geometry and the basic method for an NSA calibration. Referring to that diagram, the procedure is to record the signal with points [1] and [2] connected, to give V_{DIRECT}, and then via the antennas over the height scan, to give V_{SITE}. Then NSA in dB is given by

$$\text{NSA} = V_{DIRECT} - V_{SITE} - A_{FT} - A_{FR} \tag{7.6}$$

where A_{FT} and A_{FR} are the antenna factors

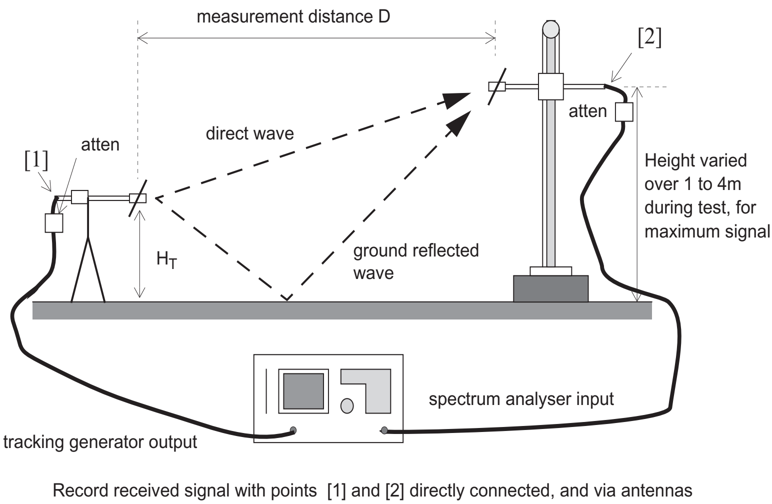


Figure 7.19 Geometry and set-up for an NSA measurement

CISPR 16-1-4, and related standards, includes the requirement that

> A measurement site shall be considered acceptable when the measured vertical and horizontal NSAs are within ±4dB of the theoretical normalized site attenuation

and goes on to give a table of theoretical values versus frequency for each geometry and polarization (the values differ between horizontal and vertical because of the different ground reflection coefficients). This is the yardstick by which any actual site is judged; the descriptions in 7.3.1.1 above indicate how this criterion might be achieved, but as long as it *is* achieved, any site can be used for compliance purposes. Vice versa, a site which does not achieve the ±4dB criterion cannot be used for compliance purposes no matter how well constructed it is. Note that the deviation from the theoretical values cannot be used as a "correction factor" to "improve" the performance of a particular site. This is because the NSA relates to a specific emitting source, and the site attenuation characteristics for a real equipment under test may be quite different.

In choosing the ±4dB criterion, it is assumed by CISPR that the instrumentation uncertainties (due to antenna factors, signal generator and receiver, cables, etc.) account for three-quarters of the total and that the site itself can be expected to be within ±1dB of the ideal. This has a crucial implication for the method of carrying out an NSA measurement. If you reduce the instrumentation uncertainties as far as possible you can substantially increase the chances of a site being found acceptable. Conversely, if your method has greater uncertainties than assumed, *even a perfect site will not meet the criterion*. Clearly, great attention must be paid to the method of performing an NSA calibration. The important aspects are:

- antenna factors – suitable for the geometry of the method, not free-space;
- antenna balance and cable layout – to minimize the impact of the antenna cables;

- impedance mismatches – use attenuator pads on each antenna to minimize mismatch error.

7.3.1.3 Radiated measurements in a screened chamber

Open area sites have two significant disadvantages, particularly in a European context – ambient radiated signals, and bad weather. Ambients are discussed again in section 7.5.2.5. These disadvantages create a preference for using sheltered facilities, and in particular screened chambers.

Alternative sites to the standard CISPR open area test site are permitted provided that errors due to their use do not invalidate the results. As you might expect, their adequacy is judged by performing an NSA measurement. However, an extra requirement is added, which is to insist that the NSA is checked over the *volume* to be occupied by the largest EUT. This can require up to 20 separate NSA sweeps – five positions in the horizontal plane (centre, left, right, front and back) with two heights and for two polarizations each. As before, the acceptability criterion is that none of the measurements shall exceed ±4dB from the theoretical.

The problem with untreated screened chambers for radiated measurements is that reflections occur from all six surfaces and will substantially degrade the site attenuation from EUT to measuring antenna [83]. For any given path, significant nulls and peaks with amplitude variations easily exceeding 30dB will exist at closely spaced frequency intervals. Equally importantly, different paths will show different patterns of nulls and peaks, and small changes within the chamber can also change the pattern, so there is no real possibility of correcting for the variations. If you have to look for radiated emissions within an unlined screened chamber, do it on the basis that you will be able to find frequencies at which emissions exist, but will not be able to draw any firm conclusions as to the amplitude of those emissions.

To be able to make anything approaching *measurements* in a screened chamber, the wall and ceiling reflections must be damped. The floor remains reflective, since the test method relies on the ground plane reflection, and so this kind of chamber is called “semi-anechoic”. This is achieved by covering all surfaces except the floor with radio absorbing material (RAM). RAM is available as ferrite tiles, carbon loaded foam pyramids, or a combination of both, and it is quite possible to construct a chamber using these materials which meets the volumetric NSA requirement of ±4dB. Enough such chambers have been built and installed that there is plenty of experience on call to ensure that this is achieved. The snag is that either material is expensive, and will at least double the cost of the installed chamber. A comparison between the advantages and disadvantages of the three options is given in Table 7.2.

Partial lining of a room is possible but produces partial results [27][59]. It may, though, be an option for pre-compliance tests. Figure 7.20 shows an example of a chamber NSA which falls substantially outside the required criterion but is still quite a lot better than a totally unlined chamber.

The FAR

So far, we have discussed chambers which mimic the characteristics of an open area site, that is they employ a reflective ground plane and a height scan. This makes them a direct substitute for an OATS, allows them to be used in exactly the same way for the same standards, and generally avoids the question of whether the OATS is the optimum method for measuring radiated emissions.

In fact, it isn’t. It was originally proposed as a means of dealing with the unavoidable proximity of the ground in practical test set-ups, in the USA, where

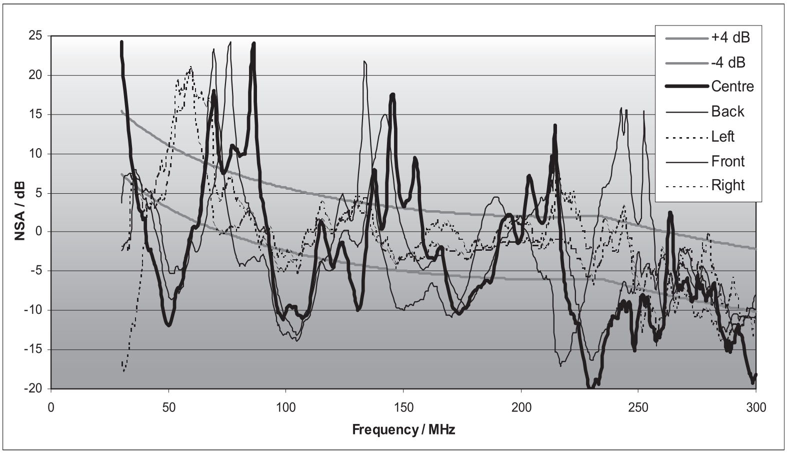


Figure 7.20 Example of a poor chamber NSA (vertical polarization, 1m height)

Table 7.2 Comparison of absorber materials

	Ferrite tiles	Pyramidal foam	Hybrid
Size	No significant loss of chamber volume	Substantial loss of chamber volume	Some loss of chamber volume
Weight	Heavy; requires ceiling reinforcement	Reinforcement not needed	Heavy; requires ceiling reinforcement
Fixing	Critical – no gaps, must be secure	Not particularly critical	Critical – no gaps, must be secure
Durability	Rugged, no fire hazard, possibility of chipping	Tips can be damaged, possible fire hazard; can be protected	Some potential for damage and fire
Performance	Good mid-frequency, poor at band edges	Good at high frequency, poor at low frequency	Can be optimized across whole frequency range

difficulties with ambient signals and the weather are less severe than in Europe. However, developments in absorber materials have made it quite practical and cost-effective to construct a small fully-anechoic room (FAR), that is, with absorber on the floor as well, which can meet the volumetric ±4dB NSA criterion. This environment is as near to free space as can be achieved. Its most crucial advantage is that, because there is no ground plane, there is no need for an antenna height scan. This eliminates a major source of uncertainty in the test (see section 7.5) and generally allows for a faster and more accurate measurement.

There is now a standard which defines the test method in a FAR, and the detailed criteria that must be met by the room itself. It eventually appeared as a combination of an amendment to CISPR 16-1-4 [181] (which describes the validation of the FAR) and another to CISPR 16-2-3 [182] (which describes the test method). Since it will have to co-exist with the standard CISPR test method for some time to come, much of the concern surrounding its development has been to ensure as far as possible that it produces results that are comparable to the OATS method, which means that the necessary adjustment to the limit levels (because of the elimination of the reflected signal) is carefully validated, and that the termination of the off-site cables is dealt with in an appropriate way. Neither of the above documents sets emissions limits.

7.3.1.4 Chambers above 1GHz

The foregoing sections referred to radiated measurements up to 1GHz, but there is also a need to define facilities for measurements above this frequency.

The same screened chamber as below 1GHz can be used, but another site validation has to be performed, in this case by measurements of a parameter called site voltage standing-wave ratio (S_{VSWR}), again described in CISPR 16-1-4. The validation method evaluates a given test volume for the specific combination of site, receive antenna, test distance, and absorbing material placed on the ground plane. Influences of the receive antenna mast located as used for the tests, and objects in the test volume such as a turntable, are evaluated by and included in the S_{VSWR} procedure. The purpose of the procedure is to check for the influence of reflections that may occur with any arbitrary EUT. A similar basic setup is used as for NSA below 1GHz (Figure 7.19), but the method is different.

The S_{VSWR} is the ratio of maximum received signal to minimum received signal, caused by interference between direct (intended) and reflected signals, or

$$S_{VSWR}(dB)=E_{max}(dB) - E_{min}(dB)=V_{max}(dB) - V_{min}(dB) \tag{7.7}$$

where E_{max} and E_{min} are the maximum and minimum received field strengths, and V_{max} and V_{min} are the corresponding measured voltages at the receiver or spectrum analyser (with consistent measuring antennas).

The value of S_{VSWR}(dB) is computed separately from the maximum and minimum signal obtained at each frequency and polarization for a set of six measurements. The receive antenna is the same type (potentially the same actual unit) as used for EUT emissions measurements. The transmit antenna has a dipole-like radiation pattern with specified directional characteristics which ensure illumination of all reflecting surfaces during the validation, and to simulate the possible low-directivity antenna gains exhibited by many actual EUTs. Both antennas must be linearly polarized.

The chamber is validated for a cylindrical volume, whose diameter is the largest required to accommodate an EUT including cables. Or to put it the other way, a test lab will decide the maximum volume they or their customers want and then attempt a validation of this volume. The S_{VSWR} is evaluated by placing the receive antenna at its intended position, and varying the transmit source location across a set of defined positions. These are shown diagrammatically in Figure 7.21. Front, centre (for diameters > 1.5m), left and right positions at the mid-height are each measured at a set of six radial locations spaced a few cm apart. An extra front measurement is needed at the top for volumes where the top is chosen to be more than 50cm above the middle. (An alternative method is the reciprocal arrangement where the transmit antenna is fixed and the receive antenna is moved around the test volume.)

For each set of six positions and for both horizontal and vertical polarizations the S_{VSWR} is calculated from the dB difference between min and max values, corrected for the slight variations in distance. For a compliant chamber each of the required positions must have an S_{VSWR} less than 6dB. As the method is purely ratiometric, there is no need to compare the result with a theoretical value.

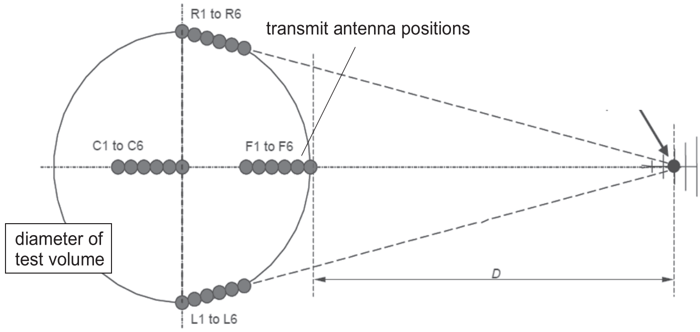


Figure 7.21 S_{VSWR} measurement positions

7.3.1.5 Pre-compliance and diagnostic tests

Full compliance with the EMC Directive can be achieved by testing and certifying to harmonized European standards; other sectors, such as military, aerospace and automotive have their own standards, which again require testing. However the equipment and test facilities needed to do this are quite sophisticated and often outside the reach of many companies. The alternative is to take the product to be tested to a test house which is set up to do the proper tests, but this itself is expensive, and to make the best use of the time some preliminary if limited testing beforehand is advisable.

This consideration has given rise to the concept of "pre-compliance" testing. "Pre-compliance" refers to tests done on the production unit (or something very close to it) with a test set-up and/or test equipment that may not fully reflect the standard requirements. The purpose (see also section 17.3.1.1) is to:

- avoid or anticipate unpleasant surprises at the final compliance test;
- adequately define the worst-case EUT configuration for the final compliance test, hence saving time;
- substitute for the final compliance test if the results show sufficient margin, and if this is acceptable in the context of company policy and/or customer demands.

Diagnostics

Although you will not be able to make accurate radiated measurements in the typical cluttered development lab environment, it is possible to establish a minimum set-up in one corner of the lab at which you can perform emissions diagnostics and carry out comparative tests. For example, if you have done a compliance test at a test house and have discovered one particular frequency at 10dB above the required limit, back in the lab you can apply remedial measures and check each one to see if it gives you a 15dB improvement (5dB margin) without being concerned for the absolute accuracy. While this method is not absolutely foolproof, it is often the best that companies with limited resources and facilities can do.

The following checklist suggests a minimum set-up for doing this kind of in-house radiated diagnostic work:

- unrestricted floor area of at least 5m x 3m to allow a 3m test range with 1m beyond the antenna and EUT;

- no other electronic equipment which could generate extraneous emissions (especially computers) in the vicinity – the EUT's support equipment should be well removed from the test area;
- no mobile reflecting objects in the vicinity, or those which are mobile should have their positions carefully marked for repeatability;
- an insulating table or workbench at one end of the test range for the EUT;
- equipment consisting of a spectrum analyser, optional preamplifier, antenna set and insulating tripod;
- antenna polarization generally horizontal, and the EUT cables stretched out horizontally and taped to the table facing it, since this reduces errors due to reflections and ground proximity.

Once this set-up is established it should not be altered between measurements on a given EUT. With the antenna is at a fixed height, there should be no ground plane and the floor should not be metallic, since floor reflections should be attenuated as far as possible. This will give you a reasonable chance of repeatable measurements even if their absolute accuracy cannot be determined.

7.3.2 Conducted emissions

By contrast with radiated emissions, conducted measurements need the minimum of extra facilities. The only vital requirement is for a ground plane of at least 2m by 2m, extending at least 0.5m beyond the boundary of the EUT. The mains LISN (section 7.2.2.1) must be effectively bonded to this ground plane with a very short strap. If your local mains supply is very noisy, you may need an extra filter in the supply before it feeds the LISN, or else use a dedicated supply source. It is convenient but not essential to make the measurements in a screened room, since this will minimize the amplitude of extraneous ambient signals, and either one wall or the floor of the room can then be used as the ground plane. Non-floor-standing equipment should be placed on an insulating table 40cm away from the ground plane.

Testing cable interference power with the absorbing clamp, as per EN55014-1, requires that the clamp should be moved along the cable by at least a half wavelength, which is 5m at 30MHz. This therefore needs a 5m "racetrack" along which the cable is stretched; the clamp is rolled the length of the cable at each measurement frequency while the highest reading is recorded. There is no guidance in the standards as to whether the measurement should or should not be done inside a screened room. There are likely to be substantial differences one to the other, since the cable under test will couple strongly to the room and will suffer from room-induced resonances in the same manner as a radiated test, though to a lesser extent. For repeatability, a quasi-free space environment would be better, but will then suffer from ambient signals.

7.4 Test methods

The major part of all the basic standards referred to in Chapter 4 consists of recipes for carrying out the tests. Because the values obtained from measurements at RF are so dependent on layout and method, these have to be specified in some detail to generate a standard result. This section summarizes the issues involved in full compliance testing, but to actually perform the tests you are recommended to consult the relevant standard carefully.

7.4.1 Test set-up

7.4.1.1 Layout

Conducted emissions

For conducted emissions, the principal requirement is placement of the EUT with respect to the ground plane and the LISN, and the disposition of the mains cable and earth connection(s). Placement affects the stray coupling capacitance between EUT and the ground reference, which is part of the common mode coupling circuit, and so must be strictly controlled; in most cases the standards demand a distance of 0.4m. Cable connections should have a controlled common mode inductance, which means a specified length and minimum possible coupling to the ground plane. Figure 7.22 shows the most usual layout for conducted emissions testing.

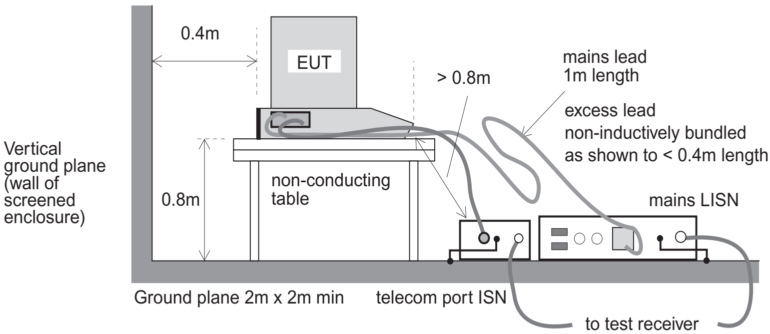


Figure 7.22 Layout for conducted emission tests

Radiated emissions

Radiated emissions to EN 55022 require the EUT to be positioned so that its boundary is the specified distance from the measuring antenna. "Boundary" is defined as "an imaginary straight line periphery describing a simple geometric configuration" which encompasses the EUT. A tabletop EUT should be 0.8m, and a floor-standing EUT should be insulated from and up to 15cm above the ground plane. The EUT will need to be rotated through 360° to find the direction of maximum emission, and this is usually achieved by standing it on a turntable. If it is too big for a turntable, then the antenna must be moved around the periphery while the EUT is fixed. Figure 7.23 shows the general layout for radiated tests.

7.4.1.2 Configuration

Once the date for an EMC test approaches, the question most frequently asked of test houses is "what configuration of system should I test?" The configuration of the EUT itself is thoroughly covered in CISPR 22:/EN 55022, and its replacement CISPR 32/EN 55032 (whose annexes B, C and D have 38 pages on the subject): these specify both the layout and composition of the EUT in great detail, especially if the EUT is a personal computer or peripheral. Factors which will affect the emissions profile from the EUT, and which if not specified in the chosen standard should at least be noted in the test plan (see Chapter 10) and report, are:

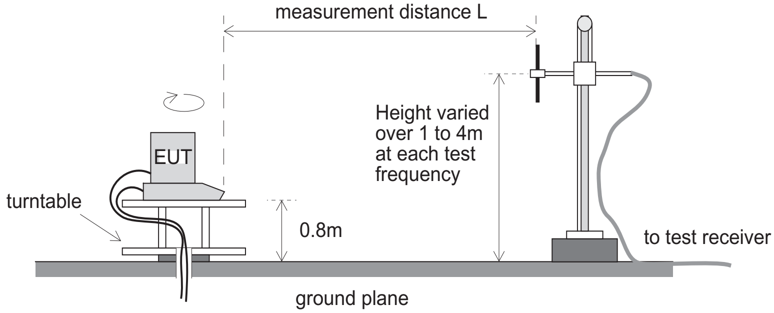


Figure 7.23 Layout for radiated emission tests

- number and selection of ports connected to ancillary equipment: you must decide on a "typical configuration". Where several different ports are provided each one should be connected to ancillary equipment. Where there are multiple ports for connection of identical equipment, only one need be connected provided that you can show that any additional connections would not take the system out of compliance;
- disposition of the separate components of the EUT, if it is a system; you should experiment to find the layout that gives maximum emissions within the confines of the supporting table top, or within typical usage if it is floor standing
- layout, length, disposition and termination practice of all connecting cables; excess cable lengths should be bundled (not looped) near the centre of the cable with the bundle 30 to 40cm long. Lengths and types of connectors should be representative of normal installation practice;
- population of plug-in modules, where appropriate; as with ancillary equipment, one module of each type should be included to make up a minimum representative system. Where you are marketing a system (such as a data acquisition unit housed in a card frame) that can take many different modules but not all at once, you may have to define several minimum representative systems and test all of them;
- software and hardware operating mode; all parts of the system should be exercised, e.g. equipment powered on and awaiting data transfer, and sending/receiving data in typical fashion. You should also define displayed video on VDUs and patterns being printed on a printer;
- use of simulators for ancillary equipment is permissible provided that its effects on emissions can be isolated or identified. Any simulator must properly represent the actual RF electrical characteristics of the real interface;
- EUT grounding method should be as specified in your installation instructions. If the EUT is intended to be operated ungrounded, it must be tested as such. If it is grounded via the safety earth (green and yellow) wire

in the mains lead, this should be connected to the measurement ground plane at the mains plug (for conducted measurements, this will be automatic through the LISN).

The catch-all requirement in all standards is that the layout, configuration and operating mode *shall be varied so as to maximize the emissions*. This means some exploratory testing once the significant emission frequencies have been found, varying all of the above parameters – and any others which might be relevant – to find the maximum point. For a complex EUT or one made up of several interconnected sub-systems this operation is time-consuming. Even so, you must be prepared to justify the use of whatever final configuration you choose in the test report.

Information technology equipment

The requirements for testing information technology equipment and peripherals are specified in some depth. The minimum test configuration for any PC or peripheral must include the PC, a keyboard, an external monitor, an external peripheral for a serial port and an external peripheral for a parallel port. If it is equipped with more than the minimum interface requirements, peripherals must be added to all the interface ports unless these are of the same type; multiple identical ports should not all need to be connected unless preliminary tests show that this would make a significant difference. The support equipment for the EUT should be typical of actual usage.

7.4.2 Test procedure

The procedure which is followed for an actual compliance test, once you have found the configuration which maximizes emissions, is straightforward if somewhat lengthy. Conducted emissions require a continuous sweep from 150kHz to 30MHz at a fixed bandwidth of 9kHz, once with a quasi-peak detector and once with an average detector – the more expensive test receivers can do both together. If the average limits are met with the quasi-peak detector there is no need to perform the average sweep. Radiated emissions require only a quasi-peak sweep from 30MHz to 1GHz with 120kHz bandwidth, with the receiving antenna in both horizontal and vertical polarization. CISPR 32/EN 55032 requires that the measurement results of at least the six highest emissions closer to the limit than 10dB are reported.

7.4.2.1 Maximizing emissions

But most importantly, for each significant radiated emission frequency, the EUT must be rotated to find the maximum emission direction *and* the receiving antenna must be scanned in height from 1 to 4m to find the maximum level, removing nulls due to ground reflections. If there are many emission frequencies near the limit this can take a very long time. With a test receiver, automatic turntable and antenna mast under computer control, software can be written to perform the whole operation. This removes one source of operator error and reduces the test time, but not substantially.

A further difficulty arises if the operating cycle of the EUT is intermittent: say its maximum emissions only occur for a few seconds and it then waits for a period before it can operate again. Since the quasi-peak or average measurement is inherently slow, with a dwell time at each frequency of hundreds of milliseconds, interrupting the sweep or the azimuth or height scan to synchronize with the EUT's operating cycle is necessary and this stretches the test time further. If it is possible to speed up the operating cycle to make it continuous, as for instance by running special test software, this is well worthwhile in terms of the potential reduction in test time.

7.4.2.2 Fast pre-scan

A partial way around the difficulties of excessive test time is to make use of the characteristics of the peak detector (see section 7.1.3.2 and 7.1.3.4). Because it responds instantaneously to signals within its bandwidth the dwell time on each frequency can be short, just a few milliseconds at most, and so using it will enormously speed up the sweep rate for a whole frequency scan. Its disadvantage is that it will overestimate the levels of pulsed or modulated signals (see Figure 7.3). This is a positive asset if it is used on a qualifying pre-scan in conjunction with computer data logging. The pre-scan with a peak detector will only take a few seconds, and all frequencies at which the level exceeds some pre-set value lower than the limit can be recorded in a data file. These frequencies can then be measured individually, with a quasi-peak and/or average detector, and subjecting each one to a height and azimuth scan. Provided there are not too many of these spot frequencies the overall test time will be significantly reduced, as there is no need to use the slow detectors across the whole frequency range.

You must be careful, though, if the EUT emissions include pulsed narrowband signals with a relatively low repetition rate – some digital data emissions have this characteristic – that the dwell time is not set so fast that the peak detector will miss some emissions as it scans over them. The dwell time should be set no less than the period of the EUT's longest known repetition frequency. It is also necessary to do more than one pre-scan, with the EUT in different orientations, to ensure that no potentially offending signal is lost, for instance through being aligned with a null in the radiation pattern.

A further advantage of the pre-scan method is that the pre-scan can be (and usually is) done inside a screened room, thereby eliminating ambients and the difficulties they introduce. The trade-off is that to allow for the amplitude inaccuracies if the room isn't semi-anechoic, a greater margin below the limit is needed.

7.4.2.3 Using an FFT receiver

The availability of time-domain measuring receivers using an FFT algorithm to convert the measurement into the frequency domain was mentioned in section 7.1.1.2. There are particular advantages to taking this approach. The problems with frequency domain scans, as outlined above, are that:

- The scan step size ΔF must be less than half the bandwidth to capture all possible emission frequencies adequately;
- each step must dwell for a time T_{dwell} at least as long as the slowest EUT modulation period to capture all transient signals;
- the whole span must be repeated for different geometries;
- the method assumes that emissions will be present for the whole span duration $(F_{span}/\Delta F) \times T_{dwell}$;
- at any frequency a transient emission will only be captured if it occurs at the same moment as the scan is on that frequency.

So, if the dwell time T_{dwell} is less than the period t_{EUT} of a repetitive emission, the probability of intercepting such an emission is T_{dwell}/t_{EUT} which is not 100%. Too short a dwell time creates the risk of missing relevant emissions during the pre-scan, and so never measuring them. (This is one reason why the same test at different test labs may give different results.) Historically, pulsed emissions were broadband and so the risk was low; but pulsed or transient narrowband emissions are now more common.

With the FFT method, the measurement time for a complete span can be dramatically improved, and at the same time, probability of intercept for transient narrowband signals can also be improved: transient signals will be seen and can be analysed as long as they are present within the segment at any time during the capture period.

Likely use of FFT in compliance tests

For the pre-scan there are significant advantages. The method allows better coverage of maximization procedures – turntable and height scan – and better probability of intercept. For non-QP measurements there is no real problem of accuracy and so for non-CISPR tests, particularly certain automotive and military specifications which call for narrow bandwidths over a large span, an FFT receiver would be the instrument of choice.

For spot frequency QP measurements once a comprehensive pre-scan has identified required frequencies, the FFT has less relevance since measurement time and probability of intercept are not important, and accuracy of the QP response is.

7.4.3 Tests above 1GHz

For a long time, CISPR emissions tests did not include measurements above 1GHz except for specialized purposes such as microwave ovens and satellite receivers. The US FCC had required measurements above 960MHz for some time, for products with clock frequencies in excess of 108MHz. This has now fed through into the CISPR regime and the test is more common. Section 4.8.1 describes the procedure to choose the top frequency as it appears in the various requirements.

7.4.3.1 Methods

Certain considerations affect the test methods by comparison with those used below 1GHz. The measurement system is less sensitive, but this is compensated by a closer preferred measurement distance (3m) and a higher limit level. The quasi-peak detector is not used; only peak and average detectors are used, with a measurement bandwidth of 1MHz. Spectrum analyser measurements can use a reduced video bandwidth to implement the average detection, although this will substantially increase the sweep time, so a peak scan and spot frequency average measurements would be usual. Because the antenna is more directional, reflections from the ground plane or from the walls are less troublesome and a height scan to deal with the ground reflection is not required, although absorbers on all chamber surfaces will nevertheless be needed. But the same principle applies to the EUT: at these frequencies, the EUT's own emissions are more directional and so more care is needed in finding the maximum in EUT azimuth, and 15° increments for the pre-scan turntable rotation steps are recommended.

Generally, the set-up conditions of the EUT are the same as those for tests below 1GHz; the tests can be performed on the same arrangement. The EUT should be wholly located within the volume that has been validated by the S_{VSWR} test (section 7.3.1.4). CISPR 16-2-3, which describes the method, defines a dimension *w* formed by the minimum 3dB beamwidth of the receiving antenna at the measurement distance *d* actually used (Figure 7.24):

$$w = 2 \cdot d \cdot \tan(0.5 \cdot \theta_{3db}) \tag{7.8}$$

It requires a minimum value of *w* over the frequency range 1 to 18GHz, which in turn implies careful selection of antenna type and measurement distance; and if the EUT's height is larger than *w* then it has to be scanned in height in order to cover the whole height of the EUT. A width scan is not needed as the EUT will be rotated on its turntable to find the maximum emission in azimuth.

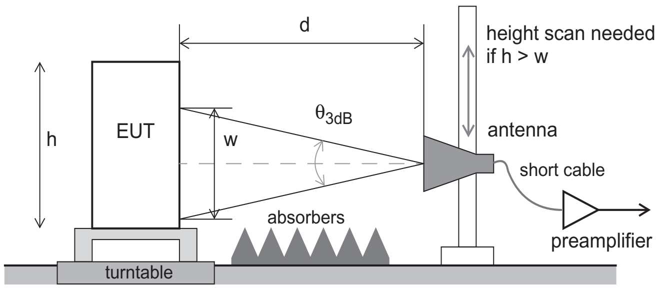


Figure 7.24 Arrangement of test above 1GHz

7.4.4 Military emissions tests

The foregoing has concentrated on emissions tests to commercial CISPR standards. Military and aerospace methods as set out in DEF STAN 59-411 and MIL STD 461G (section 5.2) are significantly different, to the extent that making a one-to-one comparison of the results, as is necessary if military applications are to use commercial-off-the-shelf (COTS) products, is very difficult. This section summarizes the most important differences. The instrumentation requirements have been covered in section 7.1.3 and Table 7.1.

7.4.4.1 Transducers

For conducted emissions, DEF STAN 59-411 tests use a LISN on the power lines, but it is the 50Ω/5μH version with a frequency range from 1kHz to 400MHz over which the impedance is defined (this is considerably more stringent than the CISPR LISN). It is permanently connected to the power supplies and used in all tests, not only those which measure power supply emissions. For dc supplies an additional 30,000 μF capacitor is connected between positive and negative on the power supply side of the two LISNs to improve the low frequency performance. The DCE01 test uses a current probe to measure current to ground on each supply line into the LISN, and it covers a much wider frequency range than commercial tests: down to 500Hz (20Hz for aircraft), and up to 100MHz (150MHz for aircraft). The signal line conducted emissions test DCE02 is a common mode current measurement with the same limits as for the power lines, and it applies both to external cables and intra-system cables longer than 0.5m.

For the radiated tests, all antennas are situated at a separation distance of 1m from the closest surface of the EUT to the antenna calibration reference point. This is probably the single most important difference from the commercial tests under CISPR. To cover the extended frequency range required by the radiated emissions measurement, the antennas used for E-field tests are:

14kHz–1.6MHz (land systems), 30MHz (air and sea systems): active or passive 41" vertical monopole (rod) antenna with counterpoise or ground plane

1.6–88MHz (land systems): antenna as used in installed systems

25–300MHz: biconical

200MHz–1GHz: log periodic or double ridged waveguide horn
1–18GHz: waveguide or double ridged waveguide horns

The requirements of MIL-STD-461G are similar except that there is no installed system antenna test, and for the range 200MHz–1GHz only a horn is allowed.

7.4.4.2 Test site

Radiated emission tests are all conducted in a screened room: there is no "open area" test site as such. The EUT is laid out on a ground plane bench which is bonded to the rear wall of the screened room, and the exact distances from the antenna to the bench and to the EUT are specified. The screened room itself has to comply with Annex C of part 3 of the DEF STAN, which includes the requirement for partial lining with anechoic material, and that the maximum dimensions of the room give a lowest chamber resonance (see equation (15.3) on page 439) not below 30MHz. It should be demonstrated that the room's normalized site insertion loss (NSIL) is representative of free-space theoretical values: the maximum permitted tolerances are ±10dB over the frequency range 30 to 250MHz and ±6dB from 250MHz to 1GHz. Measurements are to be made with both vertical and horizontal polarizations. The concept is similar to the CISPR ±4dB requirement but for a single position of the antenna (no height scan), and of course the tolerances are much wider.

MIL-STD-461G has no such requirement on the performance of the room; instead only the performance of the RF absorber material is specified, being a minimum absorption of 6dB from 80 to 250MHz and 10dB above 250MHz. The absorber "shall be placed above, behind, and on both sides of the EUT, and behind the receiving antenna".

7.4.4.3 Methods

A major difference between MIL-STD radiated tests, and the CISPR-based tests described earlier, is that there is no requirement for a height scan or to rotate the EUT for maximum emissions. This makes the test much quicker for a given span, although the spans are larger and require several antenna swaps. Because the antenna is always at 1m distance and is therefore closely coupled to the EUT there is no purpose in a height scan. DEF STAN 59-411 "encourages" a pre-scan to identify which face or faces of the EUT appear to emit the highest level. MIL-STD-461G doesn't even suggest this; it only requires that "EUTs shall be oriented such that surfaces which produce maximum radiated emissions face the measurement antennas", the implication being that test personnel will know which surfaces these are, presumably from experience.

Chapter 5 has discussed the comparison of military and commercial test results in the context of commercial-off-the-shelf (COTS) products; section 7.2.1.2 briefly describes the low frequency magnetic field emissions measurement.

7.4.5 Automotive emissions tests

In the automotive sector, neither CE Marking nor military/aerospace requirements apply. For emissions, the main standards are CISPR 25 and CISPR 12; vehicle manufacturers' own specifications reference these methods, as do the EU's e-marking market entry requirements. CISPR 25 applies to both whole-vehicle emissions and emissions from individual electrical/electronic sub-assemblies, for the protection of on-board receivers. CISPR 12 by contrast applies to whole vehicle emissions for the protection of receivers off board.

From the electronic product designer's perspective, the important tests are those mandated by CISPR 25 on components and modules. These are very similar to the MIL-STD-461G methods for power line conducted emissions and radiated emissions. The conducted emissions method is adapted for DC supplies and so its use of the 50Ω/5μH LISN depends on whether the EUT supply is locally or remotely grounded; if the latter, a LISN network is needed in both lines, otherwise only the (usually positive) line needs the LISN. The layout uses the same ground plane bench approach as in the military tests. CISPR 25 specifies a voltage measurement at the LISN terminal(s), and/or a common mode current probe measurement for control/signal lines around the complete harness at two distances, 50 and 750mm from the EUT.

Radiated tests

Radiated measurements from 150kHz to 2.5GHz can be made in an absorber-lined shielded enclosure (ALSE), or a TEM Cell, or a stripline. Vehicle manufacturers using CISPR 25 usually specify the ALSE method, which is well-known and understood by test houses. It is virtually identical to the MIL-STD-461G radiated test, using almost the same antennas and test layout, and with chamber absorber material specified as better than 6dB over the range 70MHz to 2.5GHz.

Limits

CISPR 25 is not of itself a compliance standard and so it provides a selection of limit levels which vehicle manufacturers can choose to include in their specification. Peak, quasi-peak and average limits are specified, with the standard CISPR bandwidths as per Table 7.1.

7.4.6 Integrated circuit emissions tests

One further type of standardized RF emissions test applies to integrated circuits. ICs themselves of course are not directly subject to a compliance regime; but as we see later on in this book, there are several areas where they may contribute to emissions from modules or products in which they are embedded. The clock frequencies of digital ICs appear as ΔI currents through the power pins, and as ground bounce dV/dt noise on all other pins, as well as being associated with the actual data level switching on signal circuits. To prevent the ΔI power currents from coupling out of the product, high quality decoupling and power plane design is needed. To prevent the ground bounce noise from coupling out, filtering or buffering of the interfaces is needed. Both of these place extra requirements on the circuit design, but both of them can also be controlled by the internal design of the IC. Bond wire inductance plays a large part in creating ground bounce, and detailed silicon cell design determines the amplitude and duration of the ΔI currents.

Hence there is a case for measuring the inherent emissions created by the IC during its normal functioning, so that different implementations of the same IC, or different ICs providing the same function, can be compared. A set of standards are available which specify how to test a "naked" IC for its emissions. These are the IEC 61967 series. They are listed in Table 7.3.

The most popular of these is the conducted 1/150Ω method of part 4 of the series. Essentially it defines a standardized impedance across which an RF voltage can be measured, matched to a 50Ω receiver, for each pin of the IC which is to be qualified. The generalized test circuit is shown in Figure 7.25. The 1Ω current probe allows the current in the 0V supply (after suitable decoupling) to be measured; the 150Ω voltage

Table 7.3 IEC 61967: Integrated circuits – Measurement of electromagnetic emissions, 150kHz to 1GHz

Number	Title	Content
IEC 61967-1	General conditions and definitions	Specifies generic test conditions, equipment, setup, and procedure, including a generalized description of the test board
IEC 61967-2	Measurement of radiated emissions – TEM cell and wideband TEM cell method	Conditions, equipment, setup, and procedure specific to the TEM cell method
IEC 61967-4	Measurement of conducted emissions – 1/150Ω direct coupling method	Equipment and setup specific to the 1/150Ω method, particularly the PCB layout and matching networks
IEC 61967-5	Measurement of conducted emissions – Workbench Faraday Cage method	Description of the Workbench concept (related to IEC 61000-4-6), detailed setup and practical implementation
IEC 61967-6	Measurement of conducted emissions – Magnetic probe method	Measurement principle and procedure, description of the magnetic probe, modifications to the standard test board

probe can be applied to any I/O pin to measure the voltage on this pin. The specified frequency range for the test is 150kHz to 1GHz.

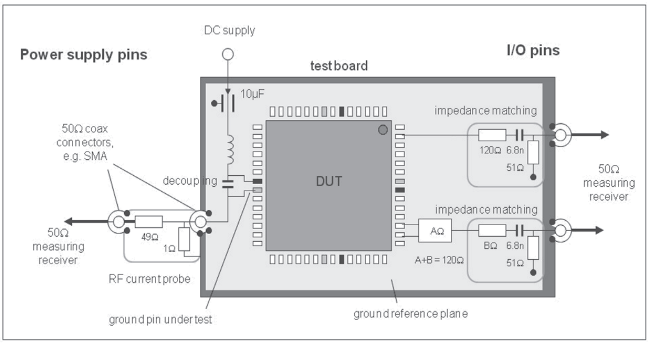


Figure 7.25 General test circuit of IEC 61967-4

Part 1 of the series defines the basic requirements for a 10cm square test board. This is expected to be a four-layer construction with outer ground planes, with the IC under test mounted on one side, and supply decoupling and necessary support components on the other. In the case of radiated rather than conducted measurements in a TEM cell, this allows the radiated field from the IC package alone to be isolated. A specific-to-type test board has to be made up for each variety and package of IC. Choice of pins to be tested, and the detailed networks that should be suitable for coupling to each pin on the test board, are a complex subject and treated in some detail in IEC/TR 61967-4-1:2005. This document also discusses the functional operation of the device while it is being measured.

A highly desirable outcome of IC-level testing would be to relate the measurements made at this level to the performance of an application circuit module using the same

IC, when tested for EMC against the test methods described in the rest of this chapter. While some generalizations can be made, an accurate relationship that holds for any application circuit will prove elusive.

This is because, unless the IC test PCB exactly mirrors the application, there will be differences in parasitic coupling networks as between the two situations. In the IC test, voltages are measured in a controlled manner at individual pins of the IC, or a radiated field is measured from the combination of IC and test board, so that levels are affected by the geometry of the traces on the test board. In the application module level test which the product manufacturer must meet, the disturbances which reach the outside world from the IC pins are passed through parasitic coupling networks which include intentional filtering, circuit components not related to the individual IC, and capacitances and inductances which are due to the individual trace layout of the application board. In general, the differences due to all these elements cannot be anticipated or predicted.

However, the simpler the circuit around the IC and the closer the application schematic and layout is to the test, the more likely it is that the IC test results can be used directly to determine the outcome of a module test. Otherwise, their main utility is to enable a comparison to be made between different implementations of the same IC function. For now, you are unlikely to find much data against these standards in IC manufacturers' data sheets, and it can't be said that the methods are widely applied.

7.5 Measurement uncertainty

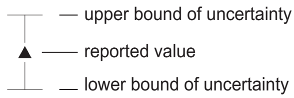
EMC measurements are inherently less accurate than most other types of measurement. Whereas, say, temperature or voltage measurement can be refined to an accuracy expressed in parts per million, field strength measurements in particular can be in error by 10dB or more, partly due to uncertainties in the measuring instrumentation and method and partly due to uncertainties introduced by the EUT set-up. It is always wise to allow a margin of about this magnitude between your measurements and the specification limits, not only to cover measurement uncertainty but also tolerances arising in production.

7.5.1 Applying measurement uncertainty

UKAS, the body which accredits UK EMC test houses, issues guidelines on determining measurement uncertainty in LAB 34 [209] and it requires test houses to calculate and if necessary to report their own uncertainties, but for EMC tests it does not define acceptable levels of uncertainty. Amongst other things this document suggests that, if there is no other specification criterion, guidance or code of practice, test houses express their results in one of four ways, as shown in Table 7.4.

Cases B and C in the table, whilst being metrologically sound, are clearly not helpful to manufacturers who want a simple statement of pass or fail. However, CISPR 16-4-2 ("Uncertainty in EMC measurements") [183] prescribes that for emissions tests the measurement uncertainty should be taken into account in determining compliance. But it goes on to give a total uncertainty figure U_{cispr} for each of the principal emissions tests (Table 7.5), based only on the instrumentation and test method errors and not taking into account any contribution from the EUT. If the test house's declared uncertainty is less than or equal to this value, then direct comparison with the limit is acceptable (cases A and D with an effective measurement uncertainty of zero). If the uncertainty is greater, then the test result must be increased by the excess before

Table 7.4 Statements of compliance with specification



Case A	Case B	Case C	Case D upper limit
The product complies	The measured result is below the specification limit by a margin less than the measurement uncertainty; it is not therefore possible to determine compliance at a level of confidence of 95%. However, the measured result indicates a higher probability that the product tested complies with the specification limit.	The measured result is above the specification limit by a margin less than the measurement uncertainty; it is not therefore possible to determine compliance at a level of confidence of 95%. However, the measured result indicates a higher probability that the product tested does not comply with the specification limit.	**The product does not comply**

comparison with the limit – effectively penalizing manufacturers who use test houses with large uncertainties.

Table 7.5 CISPR uncertainties according to CISPR 16-4-2

Measurement	$\mathbf{U_{cispr}}$
Conducted disturbance, mains port, 9–150kHz	4.0dB
Conducted disturbance, mains port, 150kHz–30MHz	3.6dB
Disturbance power, 30–300MHz	4.5dB
Radiated disturbance, 30–300MHz	5.1dB

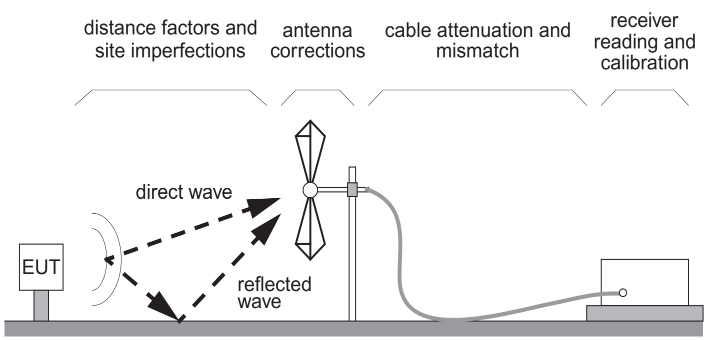


Figure 7.26 Sources of error in radiated emissions tests

7.5.2 Sources of uncertainty

This section discusses how measurement uncertainties arise (Figure 7.26).

7.5.2.1 Instrument and cable errors

Modern self-calibrating test equipment can hold the uncertainty of measurement at the instrument input to within ±1dB. To fully account for the receiver errors, its pulse amplitude response, variation with pulse repetition rate, sinewave voltage accuracy, noise floor and reading resolution should all be considered. Input attenuator, frequency response, filter bandwidth and reference level parameters all drift with temperature and time, and can account for a cumulative error of up to 5dB at the input even of high quality instrumentation. To overcome this a calibrating function is provided. When this is invoked, absolute errors, switching errors and linearity are measured using an in-built calibration generator and a calibration factor is computed which then corrects the measured and displayed levels. It is left up to the operator when to select calibration, and this is often done before each measurement sweep. Do not invoke it until the instrument has warmed up – typically 30 minutes to an hour – or calibration will be performed on a "moving target". A good habit is to switch the instruments on first thing in the morning (or leave them on overnight) and calibrate them just before use.

The attenuation introduced by the cable to the input of the measuring instrument can be characterized over frequency and for good quality cable is constant and low, although long cables subject to large temperature swings can cause some variations. Uncertainty from this source should be accounted for but is normally not a major contributor. The connector can introduce unexpected frequency-dependent losses; the conventional BNC connector is particularly poor in this respect, and you should perform all measurements whose accuracy is critical with cables terminated in N-type connectors, properly tightened (and not cross-threaded) against the mating socket.

Mismatch uncertainty

When the cable impedance, nominally 50Ω, is coupled to an impedance that is other than a resistive 50Ω at either end it is said to be mismatched. A mismatched termination will result in reflected signals and the creation of standing waves on the cable. Both the measuring instrument input and the antenna will suffer from a degree of mismatch which varies with frequency and is specified as a Voltage Standing Wave Ratio (VSWR). Appendix D (section D.2.4) discusses VSWR further. If either the source or the load end of the cable is perfectly matched then no errors are introduced, but otherwise a *mismatch error* is created. Part of this is accounted for when the measuring instrument or antenna is calibrated. But calibration cannot eliminate the error introduced by the phase difference along the cable between source and load, and this leaves an uncertainty component whose limits are given by:

$$\text{Uncertainty} = 20 \log_{10} (1 \pm \Gamma_L \cdot \Gamma_S) \tag{7.9}$$

where Γ_L and Γ_S are the source and load reflection coefficients

As an example, an input VSWR of 1.5:1 and an antenna VSWR of 4:1 gives a mismatch uncertainty of ±1dB. The biconical in particular can have a VSWR exceeding 15:1 at the extreme low frequency end of its range. When the best accuracy is needed, minimize the mismatch error by including an attenuator pad of 6 or 10dB in series with one or both ends of the cable, at the expense of measurement sensitivity. (This is standard practice when an NSA measurement is performed, see section 7.3.1.2.)

7.5.2.2 Conducted test factors

Mains conducted emission tests use a LISN/AMN as described in section 7.2.2.1. Uncertainties attributed to this method include the quality of grounding of the LISN to the ground plane, the variations in distances around the EUT, and inaccuracies in the LISN parameters. Although a LISN theoretically has an attenuation of nearly 0dB across most of the frequency range, in practice this can't be assumed particularly at the frequency extremes and you should include a voltage division factor derived from the network's calibration certificate. In some designs, the attenuation at extremes of the frequency range can reach several dB. Mismatch errors, and errors in the impedance specification, should also be considered.

Other conducted tests use a telecom line ISN instead of a LISN, or use a current probe to measure common mode current. An ISN will have the same contributions as the LISN with the addition of possible errors in the LCL (see section 7.2.2.5). A current probe measurement will have extra errors due to stray coupling of the probe with the cable under test, and termination of the cable under test, as well as calibration of the probe factor.

7.5.2.3 Antenna calibration

One method of calibrating an antenna is against a reference standard antenna, normally a tuned dipole on an open area test site [20]. This introduces its own uncertainty, due to the imperfections both of the test site and of the standard antenna – ±0.5dB is now achievable – into the values of the antenna factors that are offered as calibration data. An alternative method of calibration known as the Standard Site Method [133] uses three antennas and eliminates errors due to the standard antenna, but still depends on a high quality site.

Further, the physical conditions of each measurement, particularly the proximity of conductors such as the antenna cable, can affect the antenna calibration. These factors are worst at the low frequency end of the biconical's range, and are exaggerated by antennas that exhibit poor balance [21]. When the antenna is in vertical polarization and close to the ground plane, any antenna imbalance interacts with the cable and distorts its response. Also, proximity to the ground plane in horizontal polarization can affect the antenna's source impedance and hence its antenna factor. Varying the antenna height above the ground plane can introduce a height-related uncertainty in antenna calibration of up to 2dB [99].

These problems are less for the log periodic at UHF because nearby objects are normally out of the antenna's near field and do not affect its performance, and the directivity of the log periodic reduces the amplitude of off-axis signals. On the other hand the smaller wavelengths mean that minor physical damage, such as a bent element, has a proportionally greater effect. Also the phase centre (the location of the active part of the antenna) changes with frequency, introducing a distance error, and since at the extreme of the height scan the EUT is not on the boresight of the antenna its directivity introduces another error. Both of these effects are greatest at 3m distance. An overall uncertainty of ±4dB to allow for antenna-related variations is not unreasonable, although this can be improved with care.

The difficulties involved in defining an acceptable and universal calibration method for antennas that will be used for emissions testing led to the formation of a CISPR/A working group to draft such a method. It has standardized on a free-space antenna factor determined by a fixed-height 3-antenna method on a validated calibration test site [78]. The method is fully described in CISPR 16-1-5.

7.5.2.4 Reflections and site imperfections

The antenna measures not only the direct signal from the EUT but also any signals that are reflected from conducting objects such as the ground plane and the antenna cable. The field vectors from each of these contributions add at the antenna. This can result in an enhancement approaching +6dB or a null which could exceed −20dB. It is for this reason that the height scan referred to in section 7.4.2 is carried out; reflections from the ground plane cannot be avoided but nulls can be eliminated by varying the relative distances of the direct and reflected paths. Other objects further away than the defined CISPR ellipse will also add their reflection contribution, which will normally be small (typically less than 1dB) because of their distance and presumed low reflectivity.

This contribution may become significant if the objects are mobile, for instance people and cars, or if the reflectivity varies, for example trees or building surfaces after a fall of rain. They are also more significant with vertical polarization, since the majority of reflecting objects are predominantly vertically polarized.

Antenna cable

With a poorly balanced antenna, the antenna cable is a primary source of error [98]. By its nature it is a reflector of variable and relatively uncontrolled geometry close to the antenna. There is also a problem caused by secondary reception of common mode currents flowing on the sheath of the cable. Both of these factors are worse with vertical polarization, since the cable invariably hangs down behind the antenna in the vertical plane. They can both be minimized by choking the outside of the cable with ferrite sleeve suppressors spaced along it, or by using ferrite loaded RF cable (section 14.1.8.4). If this is not done, measurement errors of up to 5dB can be experienced due to cable movement with vertical polarization. However, modern antennas with good balance, which is related to balun design, will minimize this problem.

7.5.2.5 The measurement uncertainty budget

Some or all of the above factors are combined together into a budget for the total measurement uncertainty which can be attributed to a particular method. The detail of how to develop an uncertainty budget is beyond the scope of this book, but you can refer to LAB 34 [209] or CISPR 16-4-2 [183] for this. Essentially, each contribution is assigned a value and a probability distribution. These are derived either from existing evidence (such as a calibration certificate) or from estimation based on experience, experiment or published information. Contributions can be classified into two types: Type A contributions are random effects that give errors that vary in an unpredictable way while the measurement is being made or repeated under the same conditions. Type B contributions arise from systematic effects that remain constant while the measurement is made but can change if the measurement conditions, method or equipment is altered.

The "standard uncertainty" for each contribution is obtained by dividing the contribution's value by a factor appropriate to its probability distribution. Then the "combined standard uncertainty" is given by adding the standard uncertainties on a root-sum-of-squares basis; and the "expanded uncertainty" of the method, defining an interval about the measured value that will encompass the true value with a specified degree of confidence, and which is reported by the laboratory along with its results, is calculated by multiplying the combined standard uncertainty by a "coverage factor" k. In most cases, k = 2 gives a 95% level of confidence.

A simplified example budget for a straightforward conducted emissions test is given in Table 7.6. This is derived from LAB 34; the contributions are typical values, but each test lab should derive and justify its own values to arrive at its own overall uncertainty for the test. Each measurement method (conducted emissions, radiated emissions, disturbance power) needs to have its own budget created, and it is reasonable to sub-divide budgets into, for example, frequency sub-ranges when the contributions vary significantly over the whole range, such as with different antennas.

Table 7.6 Example uncertainty budget for conducted measurement 150kHz to 30MHz

Contribution	Value	Prob. dist.	Divisor	ui(y)	ui(y)^2
Receiver sinewave accuracy	**1.00**	Rectangular	1.732	0.577	0.333
Receiver pulse amplitude response	**1.50**	Rectangular	1.732	0.866	0.750
Receiver pulse repetition response	**1.50**	Rectangular	1.732	0.866	0.750
Receiver indication	**0.05**	Rectangular	1.732	0.029	0.001
Frequency step error	**0.00**	Rectangular	1.732	0.000	0.000
Noise floor proximity	**0.00**	Rectangular	1.732	0.000	0.000
LISN attenuation factor calibration	**0.20**	Normal k=2	2.000	0.100	0.010
Cable loss calibration	**0.40**	Normal k=2	2.000	0.200	0.040
LISN impedance	**2.70**	Triangular	2.449	1.102	1.215
Mismatch	-0.891	U-shaped	1.414	-0.630	0.397
Receiver VRC	**0.15**				
LISN + cable VRC	**0.65**				
Measurement system repeatability	**0.50**	Normal k=1	1.000	0.500	0.250
Combined standard uncertainty		Normal		1.936	3.746
Expanded uncertainty		Normal, k = 2.0		**3.87**	

Entered	**0.15**
Calculated	0.5
Result	**3.87**

It is important to realize that this is, strictly speaking, a measurement *instrumentation and method* uncertainty budget. It doesn't take into account any uncertainty contributions attributable to the EUT itself or to its set-up, because the lab cannot know what these contributions are, yet they are likely to be at least as important in determining the outcome of the test as the visible and calculable contributions.

7.5.2.6 Human and environmental factors

The test engineer

It should be clear from section 7.4 that there are many ways to arrange even the simplest EUT to make a set of emissions measurements. Equally, there are many ways in which the measurement equipment can be operated and its results interpreted, even to perform measurements to a well-defined standard – and not all standards are well defined. In addition, the quantity being measured is either an RF voltage or an electromagnetic field strength, both of which are unstable and consist of complex waveforms varying erratically in amplitude and time. Although software can be written to automate some aspects of the measurement process, still there is a major burden on the experience and capabilities of the person actually doing the tests.

Some work has been reported which assesses the uncertainty associated with the actual engineer performing radiated emission measurements [128]. This work was done many years ago, but its conclusions are still valid. Each of four engineers was asked to evaluate the emissions from a desktop computer consisting of a processor, VDU and keyboard. This remained constant although its disposition was left up to the engineer. The resultant spread of measurements at various frequencies and for both horizontal and vertical polarization was between 2 and 15dB – which does not generate confidence in their validity! Two areas were recognized as causing this spread, namely differences in EUT and cable configurations, and different exercising methods.

The tests were repeated using the same EUT, test site and test equipment but with the EUT arrangement now specified and with a fixed antenna height. The spread was reduced to between 2 and 9dB, still an unacceptably large range. Further sources of variance were that maximum emissions were found at different EUT orientations, and the exercising routines still had minor differences. The selected measurement time (section 7.1.3.4) can also have an effect on the reading, as can ancillary settings on the test receiver and the orientation of the measurement antenna.

Ambients

The major uncertainty introduced into EMC emissions measurements by the external environment, apart from those discussed above, is due to ambient signals. These are signals from other transmitters or unintentional emitters such as industrial machinery, which mask the signals emitted by the EUT. On an OATS they cannot be avoided, except by initially choosing a site which is far from such sources. In a densely populated country such as the UK, and indeed much of Europe, this is wishful thinking. A "green-field" site away from industrial areas, apart from access problems, almost invariably falls foul of planning constraints, which do not permit the development of such sites – even if they can be found – for industrial purposes.

Another Catch-22 situation arises with regard to broadcast signals. It is important to be able to measure EUT emissions within the broadcast bands since these are the very services that the emission standards are meant to protect. But the *raison d'être* of the broadcasting authorities is to ensure adequate field strengths for radio reception throughout the country. The BBC publish their requirements for the minimum field strength in each band that is deemed to provide coverage [1] and these are summarized in Table 7.7. In each case, these are (naturally) significantly higher than the limit levels which an EUT is required to meet. In other words, assuming country-wide broadcast coverage is a fact, *nowhere* will it be possible to measure EUT emissions on an OATS at all frequencies throughout the broadcast bands because these emissions will be masked by the broadcast signals themselves.

The only sure way around the problem of ambients is to perform the tests inside a screened chamber, which is straightforward for conducted measurements but for radiated measurements is subject to severe inaccuracies introduced by reflections from

Table 7.7 Minimum broadcast field strengths in the UK

Service	Frequency range	Minimum acceptable field strength
Long wave	148.5–283.5kHz	5mV/m
Medium wave	526.5–1606.5kHz	2mV/m
VHF/FM band II	87.5–108MHz	54dBμV/m
TV band IV	471.25–581.25MHz	64dBμV/m
TV band V	615.25–853.25MHz	70dBμV/m

Source: [1]

the wall of the chamber as discussed earlier. An anechoic chamber will reduce these inaccuracies and requirements for anechoic chambers are now in the standards, as mentioned in section 7.3.1.3, but a fully compliant anechoic chamber will be prohibitively expensive for many companies. (Major blue-chip electronics companies have indeed invested millions in setting up such facilities in house.) The method of pre-scan in a non-anechoic chamber discussed in section 7.4.2 goes some way towards dealing with the problem, but doesn't solve the basic difficulty that a signal that is underneath an ambient on an OATS cannot be accurately measured.

Emissions standards such as EN 55022 recognize the problem of ambient signals and in general require that the test site ambients should not exceed the limits. When they do, the standard allows testing at a closer distance such that the limit level is increased by the ratio of the specified distance to the actual distance. This is usually only practical in areas of low signal strength where the ambients are only a few dB above the limits. Some relief can be gained by orienting the site so that the local transmitters are at right angles to the test range, taking advantage of the antennas' directional response at least with horizontal polarization.

When you are doing diagnostic tests the problem of continuous ambients is less severe because even if they mask some of the emissions, you will know where they are and can tag them on the spectrum display. Some analysis software performs this task automatically. Even so, the presence of a "forest" of signals on a spectrum plot confuses the issue and can be unnerving to the uninitiated. Transient ambients, such as from portable transmitters or occasional broadband sources, are more troublesome because it is harder to separate them unambiguously from the EUT emissions. Sometimes you will need to perform more than one measurement sweep in order to eliminate all the ambients from the analysis.

Ambient discrimination by bandwidth and detector

Annex A to CISPR 16-2-3 [182] attempts to address the problem of ambients from another angle. This distinguishes between broadband and narrowband EUT emissions in the presence of broadband or narrowband ambient noise (Figure 7.27). If both the ambient noise and the EUT emissions are narrowband, a suitably narrow measurement bandwidth is recommended, with use of the peak detector. The measurement bandwidth should not be so low as to suppress the modulation spectra of the EUT emission. If the EUT noise is broadband, the measurement cannot be made directly underneath a narrowband ambient but can be taken either side, and the expected actual level interpolated.

When the ambient disturbance is broadband, bandwidth discrimination is not possible, but a narrowband EUT emission may be extracted by using the average detector with a narrower measuring bandwidth that maximizes the EUT disturbance-to-ambient ratio. The average detector should reduce the broadband level without affecting the desired EUT narrowband signal, as long as the EUT signal is not severely amplitude or pulse modulated; if it is, some error will result.

Broadband EUT disturbances in the presence of broadband ambients cannot be directly measured, although if their levels are similar (say, within 10dB) it is possible to estimate the EUT emission through superposition, using the peak detector.

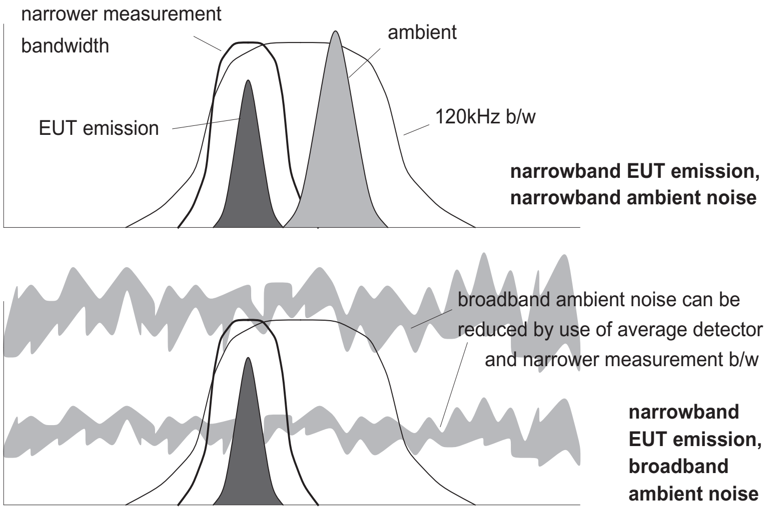


Figure 7.27 Ambient discrimination on the basis of bandwidth