Calibration and use of artificial mains networks and absorbing clamps

Proper use of transducers for CISPR-based emissions measurements

List of figures

1. Introduction

This booklet has been written to advise test engineers and others on the best practice techniques for the use and calibration of transducers for RF conducted emissions and disturbance power measurements. These measurements are inherent in many European EMC standards that are based on the CISPR emissions methods, and form an important part of testing to meet the compliance requirements of the European EMC Directive. There are two particular aspects of these tests which are of great relevance to equipment manufacturers who must make a declaration of compliance based on the test results:

- accuracy of measurement: allowing too great a tolerance on the measurement result has the effect of artificially tightening the emissions limits, which translates into a greater cost for the manufacturer to ensure that his product emits below the limit level minus the measurement uncertainty. Uncertainties of measurement should be minimised as far as possible.
- repeatability of measurement: a manufacturer should expect that, if his compliance statement is ever challenged, he can have a product re-tested at a different test facility to the same standard as the original compliance test, and achieve the same measurement result. Otherwise, allowing for uncertainties due to lack of repeatability has the same cost impact as discussed above.

These factors are directly affected by a number of parameters that relate to the test method and the test equipment. Among them are the calibration and method of use of the transducers. Of these transducers, the most important are the artificial mains network (AMN) or line impedance stabilising network (LISN) for the conducted emissions test on the mains lead up to 30MHz, and the absorbing clamp for the disturbance power test on the mains and other leads above 30MHz. This document therefore sets out best practice in the use and calibration of these items, with the intent of minimising uncertainties which can be attributed to these particular aspects.

The project of which this document is the result has drawn on a number of sources of information:

- A literature review to investigate the existing state of the art in use and calibration of these items;
- A questionnaire sent to a number of UKAS accredited EMC test laboratories, asking for their experience in using and calibrating the items;
- A programme of experimental work using a variety of clamps and AMN/LISNs to determine and compare the factors which may contribute to their uncertainties.

It should be noted that, to limit the work programme to an acceptable degree, only frequency domain investigations were carried out. Measurements of noise which is predominantly broadband and pulsed in nature may well be affected by the time domain parameters of the transducers. These would be a fruitful subject for future investigation.

This programme of work was carried out by the partners in the project, Schaffner Chase EMC and the National Physical Laboratory, both of whom are accredited by UKAS to perform these types of calibration.

2. Summary of results and best practice recommendations

These recommendations result from our investigations as described in the main part of this guide, as well as other sources that are referenced where relevant. They are presented roughly in order of priority. The comments are intended to amplify the instructions contained in the various CISPR standards; test procedures and design aspects that are already commonplace or typical are not discussed.

2.1. AMNs/LISNs

2.1.1. Results

The anticipated contributions to measurement uncertainty for calibration of and testing with the standard CISPR 16-1 AMN/LISN have been systematically investigated. The uncertainties referred to below are expanded uncertainties for $k = 2$. The investigation has shown that

- calibration of AMN/LISNs by different organisations can be reproduced to within 2% for impedance and 0.1dB for insertion loss, provided that the correct method is used and certain straightforward precautions are taken
- the five commercial units investigated are generally within the CISPR 16-1 specification, with a few excursions outside the ±20% impedance limit at the frequency extremes
- over the frequency range 25kHz to 15MHz it is possible to achieve test results with an expanded uncertainty of ±2dB, assuming typical system contributions, with all five AMN/LISNs; the AMN/LISN itself is not a major contributor to this figure
- the uncertainty degrades slightly below 25kHz, principally because of worsening isolation from the mains supply impedance variations
- the uncertainty degrades substantially above 15MHz to more than ±3dB, due to several factors associated with the AMN/LISN's design, construction and use; if a vertical rather than horizontal ground reference plane is used, with most designs of commercial AMN/LISN this figure may be doubled
- even greater variations are possible above 15MHz if tight control is not exercised over several aspects of the test setup and layout; the amplitude of the variations depends on the coupling modes and source impedance of the equipment under test, and cannot easily be factored into the uncertainty quoted above

The investigation has made it possible to recommend improvements to best practice in testing and calibration, and certain changes to the design of commercial AMN/LISNs.

2.1.2. Use

- positioning on top of a horizontal ground reference plane (rather than against a vertical ground reference plane) is preferred (3.2.2)
- use the shortest, most direct wide strap from the earth bonding post to the ground reference plane (3.2.2)
- do not raise the unit on its feet (if provided) (3.2.2)
- never switch in the earth inductor (if provided), either accidentally or deliberately; if possible, modify the unit so that it cannot be accidentally selected (3.2.5)
- ensure that the mains (and other) cables never drop to the ground reference plane but are spaced from it by >10cm or as per the standard requirement (3.2.3)
- prefer standard length mains cables wherever possible (3.2.3)

2.1.3. Calibration

- a standard design of test adaptor (as recommended in the appropriate section) should be adopted for the calibration (3.3.1)
- both the impedance and insertion loss measurements should pay careful attention to the earthing arrangements to ensure repeatability and reproducibility (3.3.2, 3.3.3)
- the correct way to make the insertion loss calibration is to feed the AMN/LISN and measuring system in parallel through a Tee adaptor, providing effectively a zero source impedance (3.3.3)
- although impedance and insertion loss calibration results need only be reported at spot frequencies, the measurements should be swept in frequency to detect any resonances (3.3.3)
- impedance measurements in the range 9kHz up to 25kHz should be made with the mains input port terminated with open circuit, short circuit and 50Ω; above this frequency an open circuit termination is sufficient (3.3.4)
- non-mandatory tests can usefully be performed by a calibration laboratory to ensure proper and safe performance of the unit, including isolation between the mains input port and the EUT port, isolation between lines, and DC or AC 50 Hz resistance (3.3.4)

2.1.4. Design of unit

(see section 3.4 for further elaboration)

- the enclosure construction should emphasize a low impedance bond to the ground reference plane
- there should be minimum spacing between the reference earth connection(s) and the bottom of the unit; with no extendable feet
- the EUT connector should be mounted near the top of the front panel, upside down (for BS1363 13A types) to encourage the mains lead to exit away from the ground reference plane and to give a short connection from the earth pin to the reference earth connection(s)
- a reference earth connection close to the EUT port L and N pins should be provided for calibration
- no earth lead inductor should be included
- provision of locally switched 50Ω loads is preferable to external loads
- the CISPR 50μH inductor L1 should be resistively damped if it is a single solenoidal winding, and should not be coaxial with L2
- the selection of component values for CISPR C2, L2 and R2 is important to ensure that the CISPR impedance specification is met at 9kHz

2.2. Absorbing clamps

2.2.1. Results

The expected uncertainty contributions for calibration of and testing with the CISPR 16-1 absorbing clamp have been investigated. The results are:

- repeatability of calibration by different organisations of absorbing clamp insertion loss is generally possible to within ±0.5dB, given control over the method used, and an adequate test site and setup
- the CISPR 16-1 specification allows wide variations in construction, evident in the three units investigated; nevertheless it is possible to achieve test results within ±1dB with the most commonly used clamps on the same EUT up to 300MHz, and within ±4dB up to 1GHz
- uncertainties in calibration and testing below 100MHz are dominated by reflections from the far end of the cable or wire under test, and by the proximity of large conducting objects; as long as testing is not

performed within a screened room, an expanded uncertainty for testing of ±2.5dB is achievable with proper control of the test set-up

- uncertainties in calibration and testing above 300MHz are dominated by variability in wire position within the clamp, departures of the clamp impedance from specified values and a worsening of the clamp's output reflection coefficient; with attention to these sources of error, an expanded uncertainty for testing of around ±2.5dB up to 700MHz is possible, degrading to around ±4dB above this frequency

The investigation has made it possible to clarify the important parameters in the test and calibration setups and methods, and to recommend some improvements to best practice in testing and calibration.

2.2.2. Use

- apply a secondary absorber at the end of the cable (6 or more large ferrite clip-on sleeve absorbers are acceptable in lieu of a second clamp) (4.3.2)
- the cable under test should be kept central within the clamp (4.3.1)
- other objects including personnel should be kept at least 1m away from the setup when the measurement is made (4.3.4)
- for measurements close to the limit, the clamp output should be taken immediately through a 6dB pad before connecting to the cable to the measuring instrument; this pad can be left out for initial scans (4.3.4)
- the output cable should extend away from the set-up at right angles, above or to the side rather than straight down, and should carry ferrite absorbers (4.3.4)
- the test area should not incorporate a ground plane on the floor (4.3.3)

2.2.3. Calibration

- apply a secondary absorber at the end of the calibration wire (10 or more large ferrite clip-on sleeve absorbers are acceptable in lieu of a second clamp) (4.2.3)
- the calibration wire should be kept central within the clamp via centralising guide(s), and tensioned to keep it taut (4.2.2)
- the calibration should be performed in an open area devoid of large metal structures, with no ground reference plane on the floor, and with no objects including personnel closer than 1.25m to the wire when a calibration measurement is made (4.2.4)
- the calibration wire should have at least $2mm^2$ cross section, with $4mm^2$ cross section preferred if the standard is changed to allow this (4.2.1)
- the clamp output should be taken immediately through a 6dB pad; the output cable should extend away from the set-up at right angles, above or to the side rather than straight down, and should carry ferrite absorbers; this output cable assembly is to be regarded as part of the calibrated equipment (4.2.5, 4.2.6)

2.2.4. Design of unit

- a wire centralising guide should be provided with each clamp as a standard calibration accessory
- although our investigation does not give conclusive evidence, it appears that the current transformer should be as close as possible to the end of the clamp's body, and a non-metallic housing should give markedly lower VRC variation and sensitivity to wire position and operator hand capacitance
- the BNC connection to the output cable could be brought out on the side of the clamp to encourage the measurement cable to exit perpendicular to the cable under test

3. The artificial mains network

For the specific purpose of making conducted emissions voltage measurements on the mains input of apparatus, CISPR 16-1 [3] defines a transducer known as an Artificial Mains Network (AMN). The US term Line Impedance Stabilisation Network (LISN) is in more general use and usually means the same thing, although strictly speaking it can be applied to a stabilising network intended for any type of line. The AMN/LISN has three main purposes:

- to define the RF impedance seen by the EUT's mains port. Otherwise, tests done on the same EUT with different mains supplies would not be repeatable.
- to couple the interference signal from the EUT mains terminals to the measuring instrument in a defined fashion, and to prevent the mains voltage from being directly applied to the measuring instrument.
- to reduce extraneous ambient noise that might be present on the incoming mains circuit.

Several variants of AMN/LISN are specified in CISPR 16-1, but one in particular (the "50Ω/50µH + 5Ω" version) has become established as the norm and is widely available from commercial suppliers. Other impedance stabilising networks are specified for military, aerospace or automotive tests or are defined in draft specifications for signal or control ports. These are not discussed in this document.

For the investigations which form the basis of this section, five manufacturers' AMN/LISNs were used and compared:

- MN2050C, Chase EMC, UK
- L2-16, PMM, Italy
- LISN 1600, Thurlby Thandar Instruments, UK, supplied by Laplace Instruments
- ESH3-Z5, Rohde & Schwarz, Germany
- 4825/2, EMCO, USA

A view of these five units is shown in Figure 1.

Figure 1 - The five commercial units investigated

A purpose-designed surrogate EUT was used for all comparisons of these five units. The salient features of this EUT are that it provides a fixed and stable comb output voltage consisting of harmonics of 150kHz or 10kHz up to and beyond 30MHz; the dominant coupling mode can be selected as differential or common mode directly coupled, or common mode via a capacitive plate on one side; the direct coupling source impedance can be selected as high (around 100Ω differential, 1nF common mode) or low (around 1Ω differential, 10nF common mode); the interference source is self-powered, but the unit can accept applied mains voltage or can draw a load current of up to 20A without affecting its interference characteristics.

3.1. Conducted emissions tests

3.1.1. The conducted emissions equivalent circuit

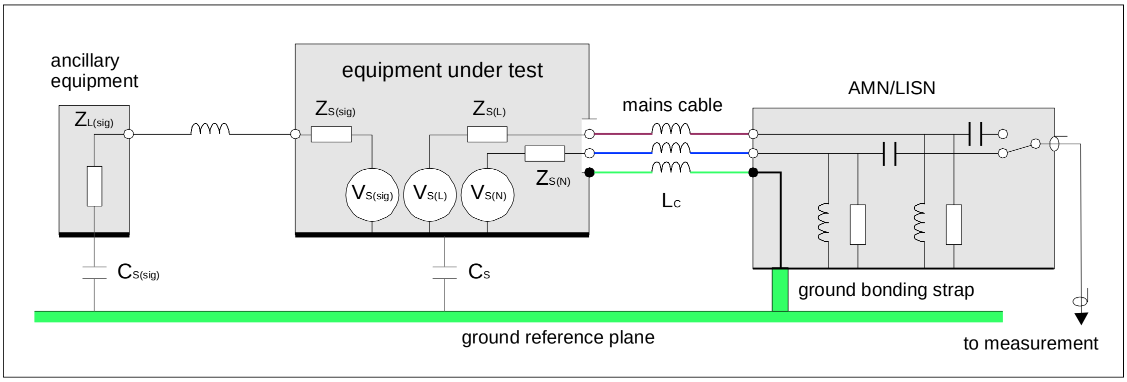


Figure 2 – The equivalent circuit for conducted emissions

Any typical EUT will contain multiple noise sources. These can be represented by those which are coupled directly to live and neutral mains connections, and those which appear in series with other connections. Referring to Figure 2, the mains-coupled noise signals are $V_{S(L)}$ and $V_{S(N)}$, applied to the live and neutral lines respectively through $Z_{S(L)}$ and $Z_{S(N)}$, and referenced to the EUT's chassis or enclosure. The mains lead connects these signals to the AMN/LISN where they are measured across the 50Ω/50µH impedance with respect to the ground connection. If the EUT enclosure is metallic and is grounded via a safety earth lead, this refers the enclosure back to the ground reference plane at the LISN. If the enclosure is non-metallic and there is no safety earth, the coupling is dominated by stray capacitance C_S between the EUT and the ground plane. This stray capacitance may also form a resonance with the inductance of the earth lead L_C if it is present.

For diagnostic purposes it is often easier to divide the sources into differential (symmetric) mode and common (asymmetric) mode. In this case the common-mode voltage is given by $½·(V_{S(L)} + V_{S(N)})$ appearing between both live – chassis and neutral – chassis, and the differential mode is given by $½·(V_{S(L)} - V_{S(N)})$ appearing between live – neutral. Neither of these voltages are measured directly by the AMN/LISN, although it can be modified to do so [10]. As well as resonances occurring between the mains cable and stray capacitances, there is also coupling between the conductors of the mains cable which may become significant at the higher frequencies.

As well as the noise directly coupled to the power leads, noise voltages at $V_{S(sig)}$ may drive current through any signal lines connected to the EUT. Although the signal line emissions are not measured directly, such current can flow through the impedances which are common to the power line measurement circuit (C_S and/or the safety earth) and therefore contribute to emissions measured on the power lines. This is why the connection and layout of any ancillary equipment (represented by $C_{S(sig)}$, $L_{C(sig)}$ and $Z_{L(sig)}$) can have an impact on the conducted emissions measured on the mains port.

3.1.2. Construction and theory of operation of the AMN/LISN

The CISPR 16-1 defined frequency response is shown in Figure 3. This is the impedance to RF ground – that is, typically the reference ground point on the front panel, but see 3.3.2 and 3.4 with regard to calibration – separately of each of the supply lines: live and neutral in the case of single phase supplies, or each phase and neutral for three-phase supplies. The curve is specified up to 30MHz as conducted measurements are required up to this frequency. In practice the curve will depart significantly from a flat 50Ω if the unit is used above 30MHz, due to resonances in the impedance-defining components. This does not necessarily make it unusable, especially for diagnostic work, although any limiter or filter in series with the output may further limit the HF response.

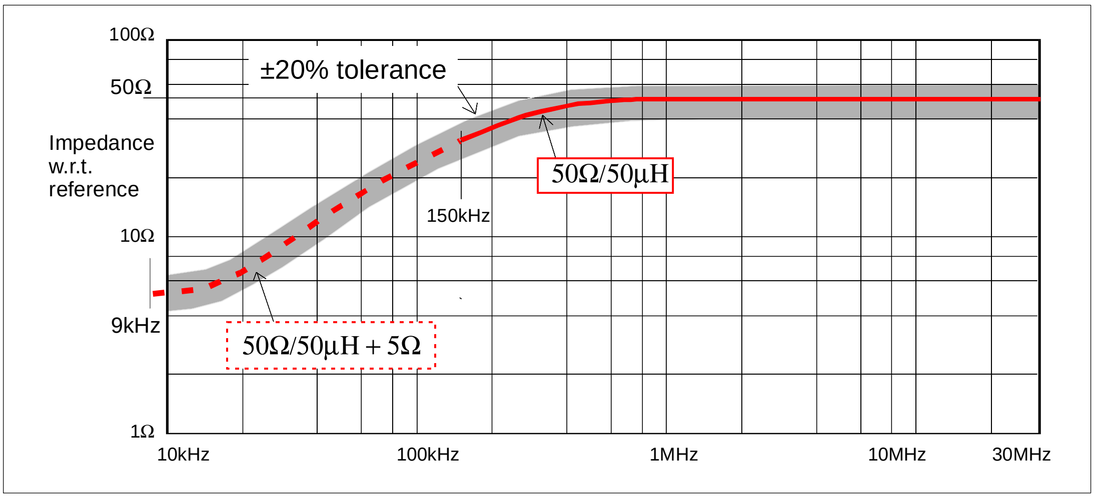


Figure 3 – AMN/LISN frequency response

CISPR 16-1 only actually specifies the impedance curve, but suggests how this may be achieved using the circuit and component values shown in Figure 4. Because of the component values used the standard has become known as the “50Ω/50µH + 5Ω” AMN/LISN. Two variants are defined; one of these, the “cut-down” version, has fewer components and its impedance stabilisation is only good above 150kHz. The components to the mains side of the 50µH inductor are replaced by a single 1µF capacitor, and the coupling capacitor to the receiver is 0.1µF rather than 0.25µF. This is perfectly adequate for measurements to the generic emissions standards or many other common product standards which do not define tests below 150kHz.

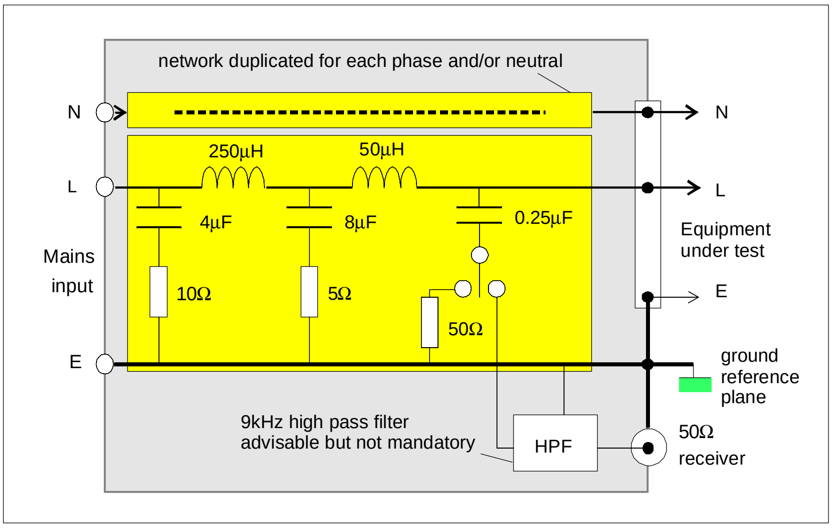


Figure 4 – AMN/LISN circuit

The main impedance determining factors are the test receiver/spectrum analyser impedance, the 50µH inductor and the 5Ω resistor. A common addition to the basic circuit is a high-pass filter (HPF in Figure 4) with a cut-off at 9kHz following the 0.25µF coupling capacitor, to attenuate low frequency noise such as switching and 50Hz harmonics that would otherwise be passed to the receiver input with a consequent risk of overload. This is now a specific requirement according to clause 2.4.3.1.3 of CISPR 16-2 [4]. When a line is not being measured, it must be terminated in 50Ω to maintain the correct impedance for the rest of the system; this is normally achieved by default through line switching in most commercial units, though in one of the units investigated it was necessary to manually load the line that was not being measured. If this is not done, a substantial fixed error (dependent on the EUT's source impedance) is introduced.

The remaining components serve to decouple the mains supply, both to reduce feedthrough of mains-borne interference and to prevent variations in the RF impedance of the mains connection from affecting the impedance at the EUT port. Construction of the inductors is critical; they must be able to carry the required supply current without saturating, yet should be physically small to keep their self-resonant frequency above 30MHz. Air-cored inductors are preferred, especially for higher currents.

Inspection of the circuits of the five different commercial AMN/LISNs shows that the 8μF capacitor and 5Ω resistor are uniformly implemented. The construction of the chokes is different in each case, with some manufacturers opting for ferrite-cored chokes in some positions. The 4μF capacitor and 10Ω resistor are not always present with these values, and the coupling from each line through to the receiver terminal varies widely from the 0.25μF capacitor recommended. Some manufacturers provide an in-built switchable limiter; all include a high pass filter, but their implementations differ.

3.2. Use of the AMN/LISN

3.2.1. Safety

Two particular safety precautions are necessary when using an AMN/LISN on the mains supply. The first has to do with personnel safety and is due to the presence of approximately 12μF capacitance within the unit from the live to the earth terminal. With an applied voltage of 240V 50Hz this allows a current of about 0.9A to flow in the supply earth conductor. This level of current can easily be lethal if it flows in the body. Even with the smaller version which has 1.1μF from live to earth, the earth current is too high for safety.

If the AMN/LISN is not properly bonded to the supply earth and it becomes disconnected for any reason then its case (including, for example, any RF connectors attached to it) will immediately become live. THE AMN/LISN CASE MUST BE SOLIDLY BONDED TO THE SUPPLY EARTH AND TO THE GROUND PLANE. Best practice is to permanently install the unit at the test facility. Portable AMN/LISNs for on-site work demand especial care in installation.

A secondary result of this earth current is that AMN/LISNs cannot be used on mains circuits that are protected by earth leakage or residual current contact breakers. To allow this, and for best safety practice, use an isolating transformer in the mains feed to the LISN. This will not affect the performance of the network itself, but may of course limit the power that can be supplied to the EUT.

The second precaution concerns the safety of the measuring instrumentation.

The supply mains is a fruitful source of 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, supply 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 measuring instrument without attenuation.

For this reason it is essential to incorporate a transient limiter at the output of the AMN/LISN when a spectrum analyser is used (two of the five commercial units investigated included a switchable limiter in the output signal path). This adds an extra 10 dB loss to the signal, as well as contributing a small factor to the measurement uncertainty, but this can normally be tolerated and is a much cheaper option than expensive repair bills. Note that some limiters also incorporate a low-pass filter to restrict the frequency range transmitted.

A limiter is less necessary, though may still be advisable, when a measuring receiver is used since the receiver's front end is narrowband and already protected.

3.2.2. The ground reference plane and its connection to the AMN/LISN

The ground reference plane (GRP) is a crucial part of the conducted emissions test set-up. It provides the reference for the measurement and offers a defined coupling to the EUT. CISPR standards specify a minimum size for the GRP of 2m x 2m, or that it should be the wall or floor of a screened room. It should extend at least 0.5m beyond the boundaries of the EUT. This ensures adequate electric field coupling.

The GRP should be a conductive material such as aluminium, steel or copper. The thickness is unimportant in most applications since its prime function is to provide capacitive coupling to the EUT. Skin depth in aluminium at 150kHz is 0.2mm and therefore for tests above this frequency, extra thickness does not substantially affect the impedance of the plane. However if the EUT generates strong LF magnetic fields, such as might be caused by switchmode power magnetic components, these will induce eddy currents in the GRP which could in turn create voltage differentials across it, and hence measurement errors, if the impedance of the plane at these frequencies is too high. For these applications the use of copper or aluminium sheet with a thickness greater than 1mm is recommended.

The GRP should be electrically unbroken under the EUT and between it and the point of connection to the AMN/LISN. Where seams occur they should be welded or bonded with fasteners at short intervals. A thin floor-covering material is acceptable since it will not materially affect the capacitive coupling at distances of 40cm, but appropriate provision for electrical contact from the plane to the AMN/LISN is necessary.

A short, direct connection from the AMN/LISN to the ground reference plane is vital for repeatability above 10-15MHz. **Experiments show that this aspect is probably the most important in allowing a repeatable test**. At close distances, the case exhibits a capacitance to the GRP according to

$$C_{stray} = 0.0885 \cdot \text{area/distance} \quad \text{(pF)}$$

where *area* is the footprint of the LISN in cm^2, and *distance* is the separation of the AMN/LISN from the ground plane in cm. The ground connection exhibits an inductance according to

$$L_{strap} = 0.002 \cdot \text{length} \cdot (\ln[4 \cdot \text{length/dia}] - 0.75) \quad \text{(microhenries)}$$

where *length* is the strap length and *dia* its diameter, both in cm. If these variables are incorporated into the equivalent circuit shown in Figure 2 then the actual input impedance with respect to the ground plane will show a resonant peak somewhere in the 10–100MHz region, which in turn will upset the measurement in this region. (The impedance is plotted in Figure 5 for C_{stray} = 500pF and L_{strap} = 100nH.)

For a typical LISN-to-ground plane capacitance of 500pF the resonance will be adequately above 30MHz, the top of the measuring frequency range, if the ground strap inductance is less than about 40nH, which requires a length no more than 5cm. Clause 2.4.4.1 of CISPR 16-2 states that the impedance should preferably be less than 10Ω at 30MHz, and suggests a connection strap with length-to-width ratio of not more than 3:1.

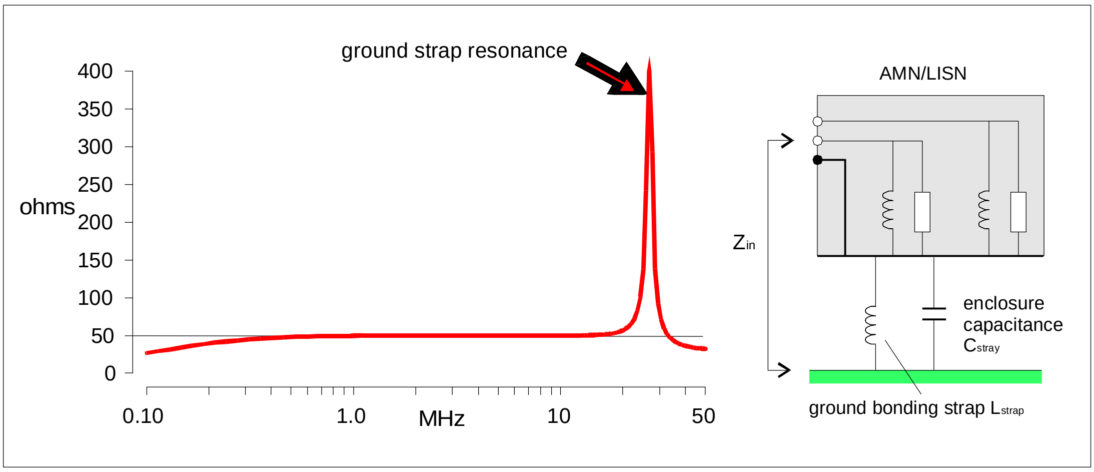


Figure 5 – AMN/LISN impedance (theoretical) showing ground strap resonance

Several experiments were done to attempt to quantify the effect of the ground strap. The issue is complicated by the difference in construction between commercial AMN/LISNs, and by the alternatives offered by different test standards, to bond either to a horizontal or a vertical reference plane. Four out of the five commercial units investigated had ground reference connections provided by a front panel binding post, between 33 and 60mm from the base of the unit; the fifth had a bare metal strip along its side. The latter has the ability to provide a very low inductance connection if it is used correctly, but the binding post requires an inductive strap of variable length depending on the unit. Some units included retractable front feet, which further increased the distance to the ground reference when extended. If a connection to a vertical (rather than horizontal) reference plane was required, a ground strap of up to 30cm depending on the unit would be necessary.

The following page shows a number of graphs which illustrate the following aspects:

- Figure 6 - with a 30cm x 10mm^2 cable to the vertical ground reference plane, the differences which exist when the AMN/LISN is moved away from the vertical plane by 10cm (changing C_{stray} in Figure 5);
- Figure 7, Figure 8 - the difference between a 30cm and 60cm cable to the vertical plane (changing L_{strap} in Figure 5);
- Figure 9 - with a 7cm x 3cm strap to the horizontal ground plane, the effect of lifting the AMN/LISN 5mm off the horizontal ground plane, as might occur on a covered floor, for example.

These graphs lead to the following conclusions:

- the effect of the ground connection and the shape, size and proximity to the reference plane of the AMN/LISN are largely negligible below 15MHz, but dramatic above this frequency;
- the greatest effect is found when the EUT coupling is primarily by stray capacitance (“plate” in the figures);
- the effect is least for differential mode and/or low impedance coupling from the EUT, but not negligible in either case;
- different AMN/LISNs show substantial variations from each other due to case size and construction when the ground connection is long, but the variation is almost negligible when the units are solidly bonded to the horizontal ground plane.

We can make two recommendations resulting from these investigations. One is that, in using present commercial designs of AMN/LISN, test houses ensure that the unit is solidly and permanently bonded to the horizontal ground reference plane using the shortest possible right-angled metal plate (Figure 10 shows a photograph of the optimum construction that was used in the experiments), and that the unit is placed as close as possible to the plane. The other is that future commercial designs of AMN/LISN should concentrate on providing the facility for a low inductance ground connection, preferably by using a mounting plate or bracket (see Figure 28), even if this means a less attractive outward appearance.

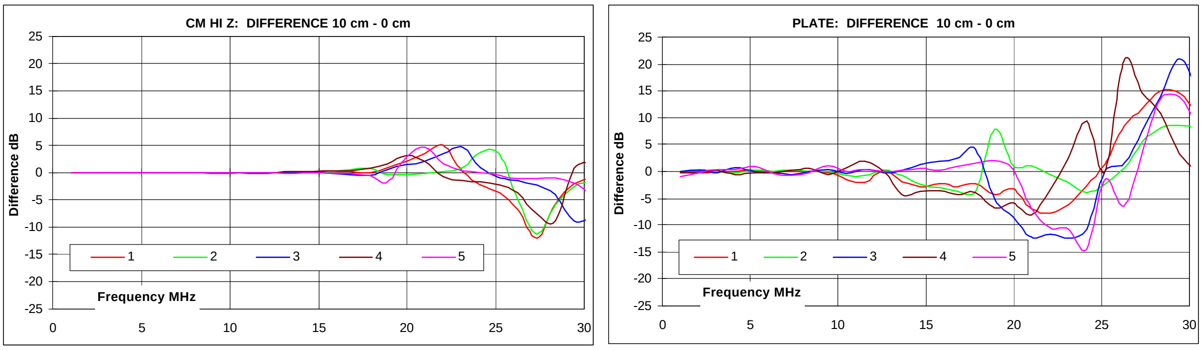


Figure 6 – Effects of AMN/LISN distance from vertical reference plane, 30cm ground strap

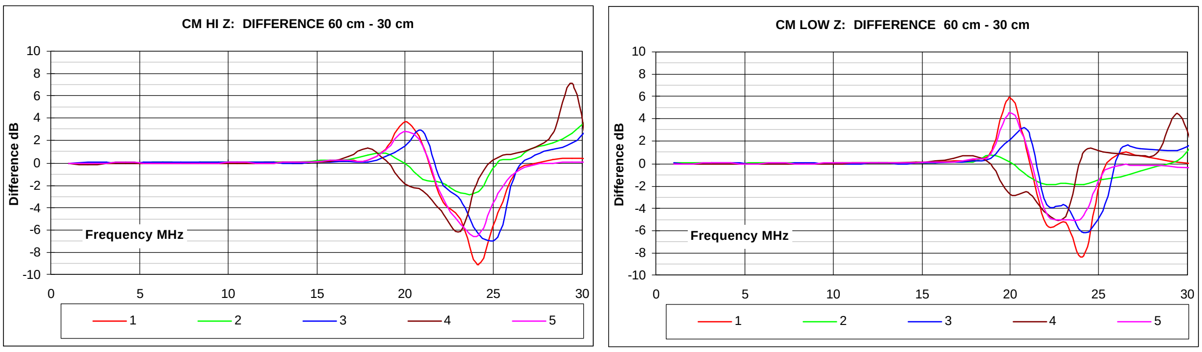


Figure 7 – Change of earth strap length, AMN/LISN 1cm from vertical plane, CM coupling

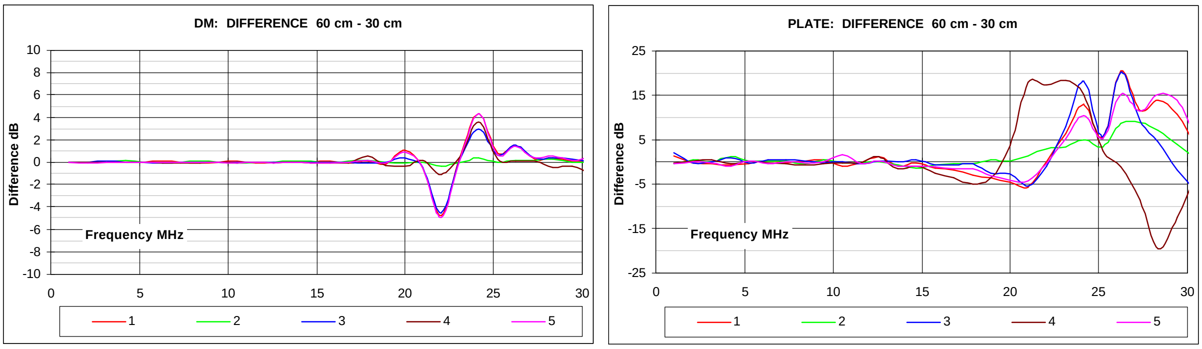


Figure 8 – Change of earth strap length, AMN/LISN 1cm from vertical plane, DM/plate coupling

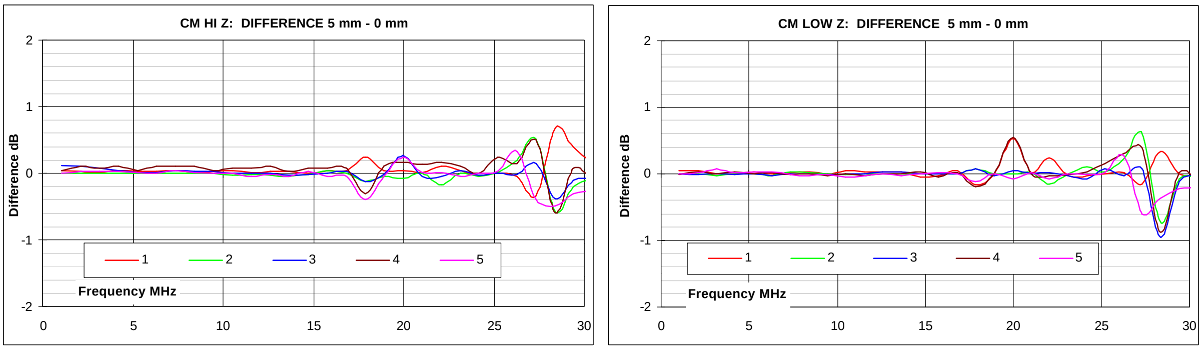


Figure 9 – Effect of AMN/LISN distance from horizontal ground plane, short earth strap

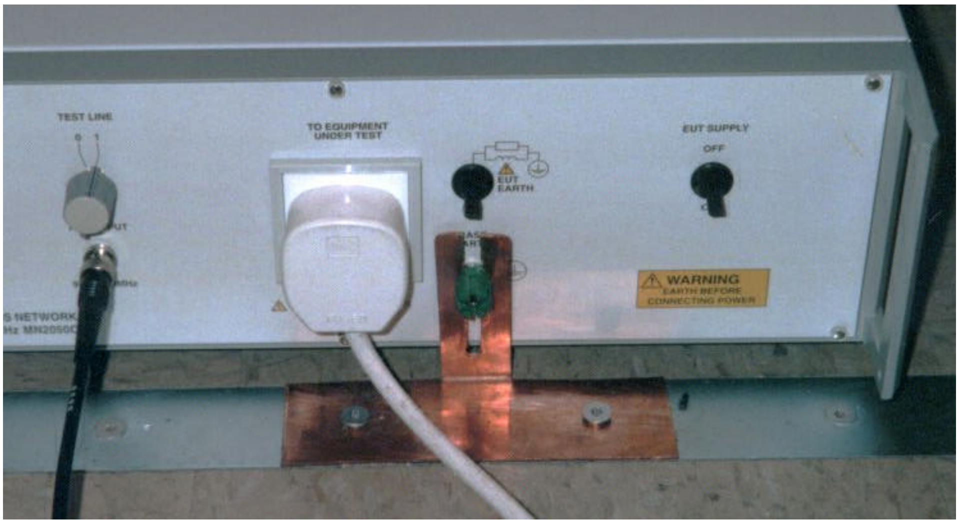


Figure 10 – View of AMN/LISN bonding to the horizontal ground reference plane

A related issue is that several of the commercially available AMN/LISNs, including three of the five that were investigated, used enclosures that had retractable feet, presumably for aesthetic purposes. When the unit is used on the horizontal ground plane and these are extended, the front panel of the unit is raised away from the plane by up to 5cm. The effect of this is quite significant and means that the ground reference plane connection is longer than it need be. Also, the AMN/LISN's distance from the ground reference plane is uncertain. The graphs in Figure 11 show the impact this has on the measurement. In the light of this, we must recommend that these feet are never used in actual testing, and that the construction of commercial units does not include them in future.

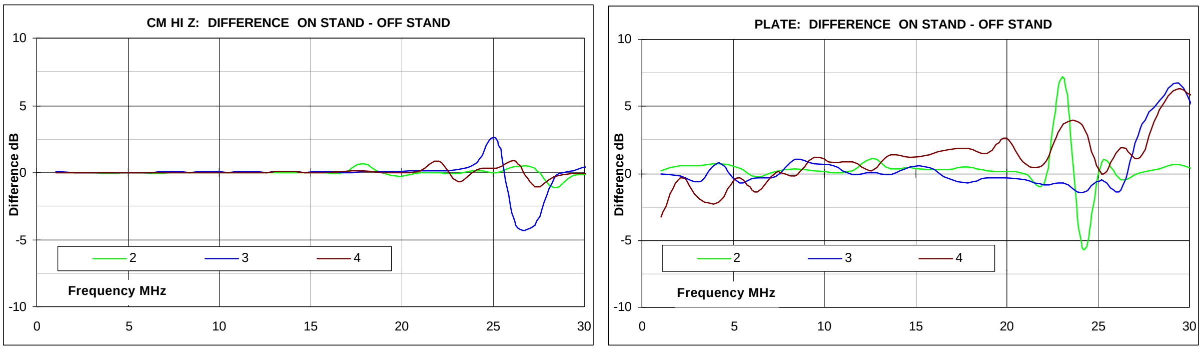


Figure 11 - The effect of raising the front feet

3.2.3. The test layout: lead arrangement and EUT distance from the ground plane

The test layout is most rigorously defined in CISPR 22 Amd 2 [6] (now re-published in the third edition of CISPR 22 [7]), with several alternative layouts offered for different EUT situations. Other product standards give layout instructions but are not as prescriptive as CISPR 22; CISPR 16-2 does give fairly prescriptive instructions (which differ in detail from other standards) but it has no status directly as a product standard and can only be implemented by reference. The preferred layout for table-top equipment in CISPR 22 Ed. 3 is shown in Figure 12. Note that although it allows AMN/LISNs to be bonded to the vertical plane, our experiments suggest that with many current commercial designs this is not to be preferred.

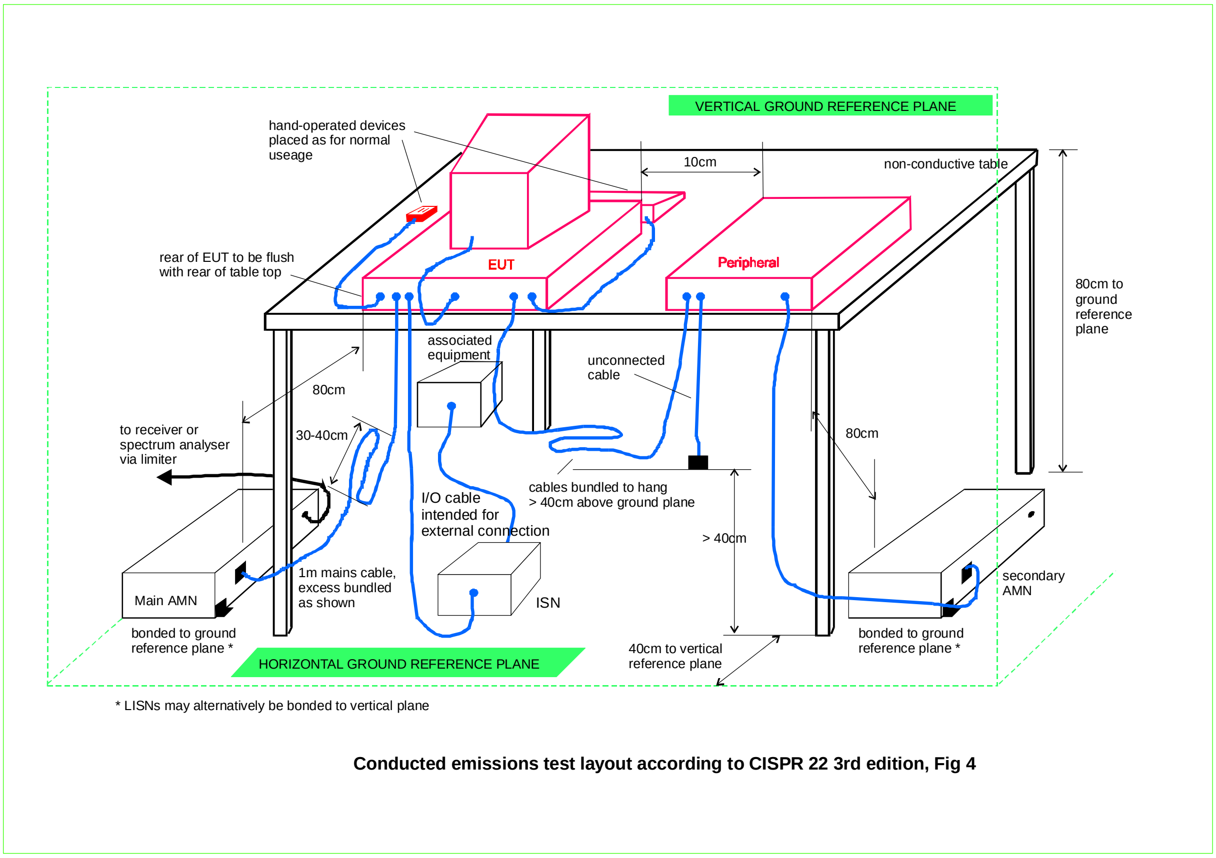


Figure 12 – Conducted emissions layout for table-top equipment (CISPR 22)

Investigations for this project centred on the AMN/LISN to EUT distance, and the length and layout of the mains lead between the two. [12] points out that the mains cable can present a substantial impedance variation from the required 50Ω/50µH at its far end; a 2.5m cable has a resonant impedance of 300Ω at around 15MHz, and even short cables can create impedance discontinuities exceeding the 20% tolerance. The standards dictate a 1m length cable with excess length bundled non-inductively. Therefore we investigated the difference between a 1m cable and a 2.5m bundled cable (Figure 13), with the AMN/LISN closely bonded to the horizontal ground reference plane. Also, the routing of the mains cable can have a significant effect: if it is run close to the ground reference plane the stray capacitance increases sufficiently to modify the cable's transfer characteristic. If the cable is more than 1m long but not long enough to bundle, the lead can sag and touch the floor. The graphs in Figure 14 show the difference between the lead touching the ground plane for 40cm of its length, versus being raised at least 10cm above the plane. Further graphs in Figure 15 show the differences for distances of 10cm and 60cm from the vertical plane.

The standards universally require the AMN/LISN-to-EUT distance to be maintained at 0.8m, but this is not always easy to ensure, particularly with EUTs of complex shape and with mains leads exiting in awkward places. We investigated the impact of varying this distance from 0.8m to 0.7m (Figure 16).

From these graphs, the following conclusions can be drawn:

- as with the issue of AMN/LISN connection to and distance from the ground reference plane, the effect of variations in the mains cable are generally negligible below 15-20MHz, but significant above this frequency;
- the mains cable length, even when longer leads are non-inductively bundled as per the standard, has a substantial effect on the result; up to 18dB variation between AMN/LISNs can be found (Figure 13), although this depends on the mode of coupling within the EUT, with low-impedance common mode coupling being the worst case;
- routing the mains cable near to the ground reference plane can affect the result by 5-10dB near the resonant frequencies of the whole assembly; up to 5dB difference in this effect can be found between different AMN/LISNs, with the method of bonding the unit to the ground reference plane also affecting the result (in Figure 15, the unit was connected via a 30cm strap);
- the effect of a 10cm variation in the EUT – to – AMN/LISN distance is moderate by comparison to the other effects, being confined to the region above 25MHz, whether a horizontal or vertical ground reference plane is used; this aspect should not affect measurement uncertainty seriously if the distance can be controlled to 1cm as is the case for most set-ups.

A further experiment was carried out to test the effect of resonances on the 1m mains lead by varying its distance above the horizontal ground plane between 4 and 6cm. Four out of the five AMN/LISNs exhibited a resonance resulting in differences of up to 4dB between 28 and 29MHz when the mains lead was moved by only 2cm. Clearly the separation of the mains lead from the ground plane is very important. This aspect is not helped by the design of most of the AMN/LISNs investigated, with respect to the placement of the 13A EUT socket on the front panel. These are all mounted with the earth pin at the top. Since the 3 pin plug has the mains lead outlet at the bottom this means that the mains lead is routed directly towards the horizontal ground plane. It would be better if the EUT socket on the AMN/LISN is mounted the other way up which would route the mains lead away from the ground plane and place the earth pin closer to the ground reference plane terminal, which should be as near to the base of the AMN/LISN as practical. Ideally the EUT socket should be near the top face of the AMN/LISN. This proposal is incorporated into the recommendations for AMN/LISN design given in 3.4.

A final factor which was investigated was the effect of length and position of the output cable, that is the RF cable that takes the output of the AMN/LISN to the measuring instrument. On some commercial units this lead may come into close proximity to the mains lead and there is some possibility of coupling. Experiments showed that this does occur but that the effects are not substantial. Nevertheless, the disposition of the output cable should be a factor when recording the test configuration and layout.

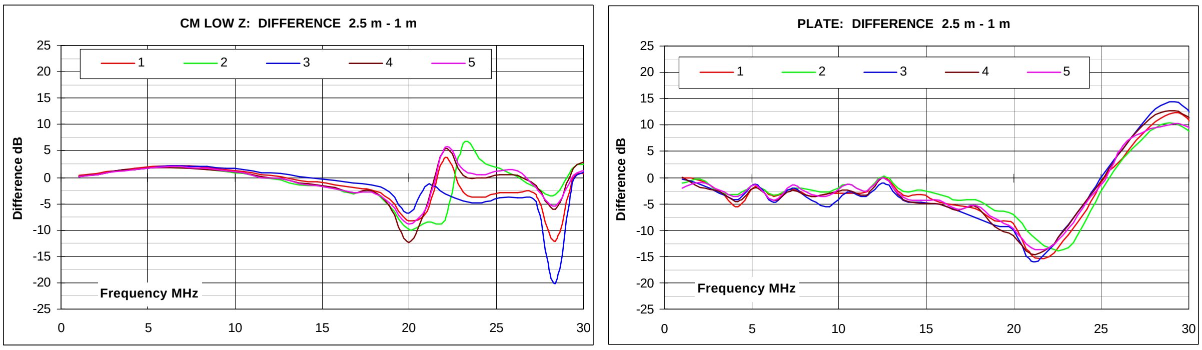


Figure 13 - Difference between lengths of mains cable

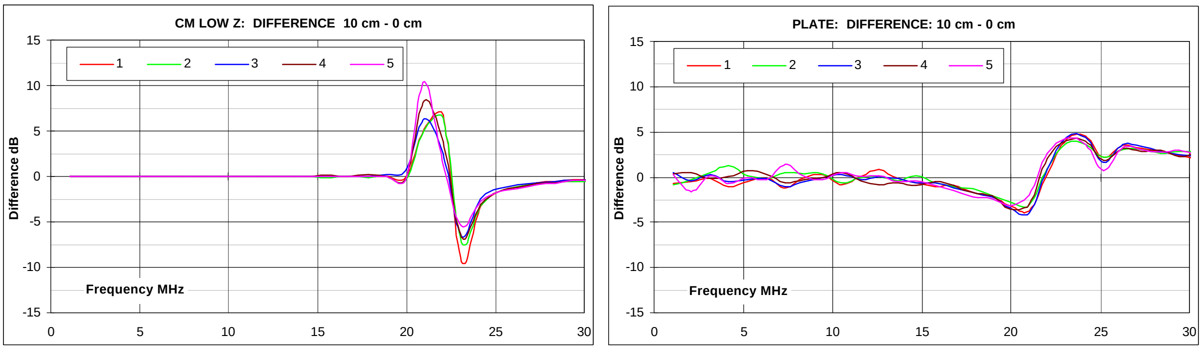


Figure 14 - Difference in routing of 2.5m bundled mains cable near horizontal plane

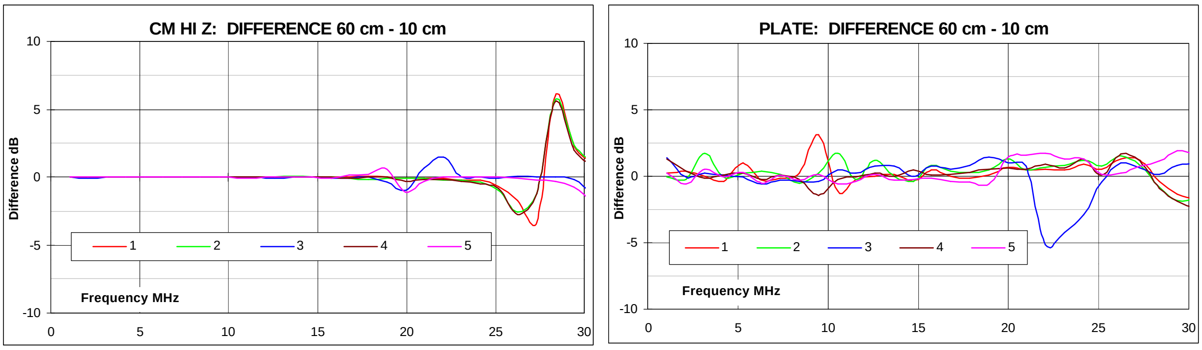


Figure 15 - Difference in routing of 1m mains cable near vertical plane

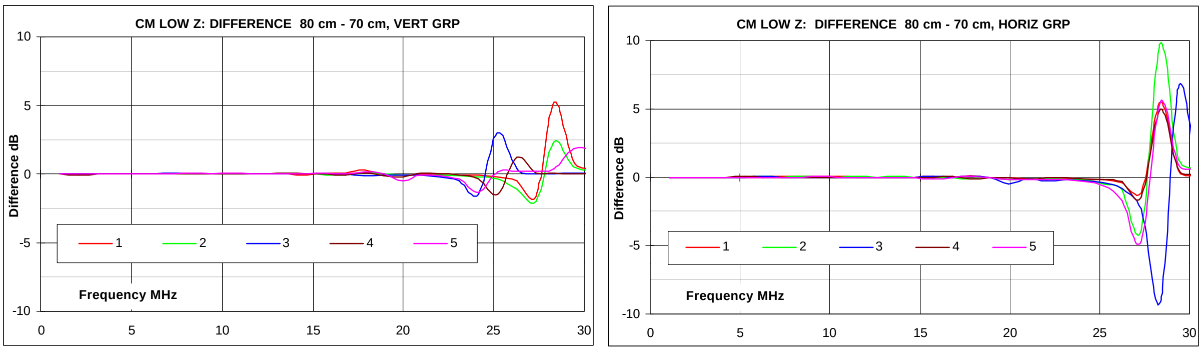


Figure 16 - Effect of AMN/LISN-to-EUT distance

3.2.4. Connection of auxiliary apparatus and use with unusual EUTs

As can be seen from the equivalent circuit (Figure 2), the connection of auxiliary apparatus to the EUT can have a significant effect on the measurement even if the actual emissions from this apparatus are negligible. This is because the disturbance developed by the EUT at the port to which the auxiliary apparatus is connected is referred back to the ground reference plane by this connection. Part of this noise then appears at the mains port and is measured, the level depending on the various impedances in the total circuit.

For this reason control and stabilisation of these impedances is as important as control of the primary circuit variables. There are two principal aspects (besides the construction of the auxiliary apparatus itself):

- the positioning and connection of the auxiliary apparatus with respect to the ground reference plane;
- the layout of the cables between the EUT and the auxiliary apparatus.

Any strictures in the test standard regarding these aspects must be respected. In default, the cable(s) should be a fixed length (typically 1m, bundled non-inductively if necessary) and routed in a fixed layout and at a minimum distance above the ground plane (typically 10cm). The auxiliary apparatus should be positioned above the ground plane as for the EUT, i.e. at 40cm distance if table top or 10cm if floor standing, and if it is connected to the mains supply, this should be via an auxiliary AMN/LISN, following all the precautions described elsewhere in this document for the main test connection.

There will be cases where a conducted mains emission test has to be performed on equipment for which the method given in the test standard is not explicit enough, or cannot be followed for some reason. Examples are:

- the equipment's current rating is too high for available AMN/LISNs;
- the test must be performed *in situ* and the mains supply cannot be interrupted;
- the test must be applied to a supply other than the standard mains, for instance a DC supply.

Several standards in fact give some guidance for these situations. For instance CISPR 11 describes methods for *in situ* testing, and ETS 300 386-1 describes conducted emissions measurements on telecomms DC power supplies. Where there is otherwise insufficient information, the test should be carried out with the following principles in mind:

- the reference for the voltage measurement is the ground reference plane. Some such reference must always be available; if necessary it can be created by sliding a suitable metal sheet underneath the EUT, or the metal structure of the EUT can be used, if it is large enough and is normally bonded to the installation earth. But simply connecting the earth terminal of the AMN/LISN to the earth terminal of the mains supply via a length of wire is never adequate to give a repeatable and reliable reference connection at high frequencies (see 3.2.2 above).
- the AMN/LISN used should be appropriate to the supply. CISPR 16-1 defines an alternative circuit for high currents (above 100A) and this should be used wherever necessary.
- where it is physically impossible to disconnect the supply a voltage probe as per CISPR 16-1 clause 12.2 can be used, but the measurements made with it will be entirely site-specific since they will depend on the impedance of the supply. It is also possible to use an AMN/LISN as a voltage probe, by connecting its EUT port in parallel across the supply to the EUT, without passing the supply current through it. The benefit of this is questionable, since (a) the length of the connection to the EUT port will affect the actual impedance seen at high frequencies, (b) it will not stabilise the impedance unless the supply impedance is very high (substantially above the 50Ω/50μH presented by the AMN/LISN), and (c) there may be safety implications in having the supply voltage, and/or the earth leakage current, present at the supply input to the AMN/LISN. In any case, a voltage probe is considerably more portable than an AMN/LISN.

3.2.5. Using the earth lead inductor

CISPR 16-1 clause 11.9 allows the AMN/LISN to be constructed with a switchable inductor between the earth connection of the EUT port and the ground reference connection. The purpose of this is that, when the inductor is in circuit, the RF impedance of the EUT's earth lead is raised and this may allow a higher voltage to be measured at the phase connections, with respect to the ground reference plane. None of the current CISPR-based standards require use of this inductor in the test, although some older national emissions test standards did.

CISPR 16-1 is equivocal regarding the value of this inductor. It may be either 1.6mH or it may be 50Ω in parallel with 50µH. Two of the AMN/LISNs investigated for this project were found to have the one value, two of them had the other, and one did not have an earth lead inductor at all. Naturally, when this inductor was switched into circuit and the EUT was emitting primarily in common mode, different AMN/LISNs gave substantially different results (see Figure 17). The effect of implementing this inductor is that there must be a small impedance in series with the EUT earth connection even when it is switched out, due to the finite length of wiring to the front panel switch, which compromises the unit's impedance curve at high frequencies, even if it remains within the specification limits. Figure 17 shows the differences between the four units with the switchable inductor, with the EUT emitting in common mode, high impedance. The two units with the 50Ω/50µH combination showed essentially the same result, a small increase of around 3dB over most of the frequency range. The units with the 1.6mH choke showed much greater increases of up to 40dB, and were also substantially different from each other; this difference might be explained by the fact that the unit with the greatest increase also had a second 1.6mH choke in the incoming mains earth line, whereas the other unit did not. Self-resonances in the choke construction are also noticeable.

The inductor is not now a requirement of any international standards. Since its inclusion compromises the HF impedance from EUT earth connection to ground reference plane (because of the need for a switch), best engineering practice would dictate that it is left out of modern designs of AMN/LISNs.

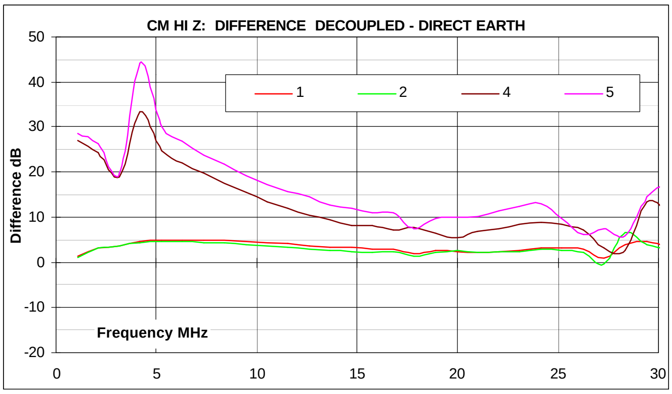


Figure 17 – Comparison of use of earth lead inductor

3.2.6. The impact of the EUT source impedance

It has been shown [13] that the source impedance of the EUT ($Z_{S(L)}$, $Z_{S(N)}$ in Figure 2) is an important factor in the overall conducted emissions measurement. This can be understood by inspection of the equivalent circuit: when Z_S is much higher than the AMN/LISN impedance, the EUT acts as a current source, and variations in load impedance due to AMN/LISN imperfections, bonding and layout, make a considerable difference to the measured voltage. On the other hand, if Z_S is much lower than the AMN/LISN impedance, the EUT acts as a voltage source. This means that variations in load impedance are less critical. Therefore, the factors discussed in this document regarding the correct way to carry out conducted emissions tests have a proportionately greater effect for high impedance EUTs. [13] shows that different types of apparatus have quite different source impedance characteristics, with dependencies on frequency and the mode of coupling. Nevertheless, appliances can be categorised into broad groups depending on their construction (earthed or non-earthed), their type and the suppression techniques that are employed. Low impedances (< 100Ω) are associated with permanently earthed apparatus with high suppression capacitance, while high impedances (> 100Ω) are associated with portable or hand-held apparatus with low or non-existent suppression capacitance.

3.2.7. Low frequency current rating

CISPR 16-1 states that the 50Ω/50µH + 5Ω circuit is useable up to 100A; for higher currents, up to 500A, the 50Ω/5µH alternative is recommended. If the AMN/LISN will be used near to its rated current, check whether the rating refers to continuous or occasional use. There are three implications:

- over-temperature of the internal components, principally the chokes, leading to equipment damage;
- saturation of the chokes at current peaks, leading to inadequate impedance stabilisation and inaccurate measurements;
- excessive voltage drop through the AMN/LISN, leading to an out-of-specification power supply voltage at the EUT.

Experiments were done to attempt to discover any effect on the measurement results when the maximum rated AMN/LISN mains current was passed through the unit, compared to no current. Differences for any particular unit were found to be a maximum of 1.2dB and these could have been due to other random effects in the test. Three out of the five units investigated used only air-cored chokes which should be immune to saturation effects. The fact that the other two also showed no serious effect is encouraging and confirms that the chokes are properly designed for their purpose.

CISPR 16-1 requires (clause 11.8) that the mains voltage drop across the AMN/LISN should not exceed 5% of the total applied. All those investigated were able to meet this specification. But note that some EUTs may draw a current which though its RMS value is within the AMN/LISN's rating, nevertheless has a high crest factor and takes a peak current several times its RMS value. Such a waveform might still cause a high voltage drop at the peaks with a consequent unacceptable reduction in the voltage supplied to the EUT and possible erroneous measurements.

The DC resistance was not measured as part of this project but is a useful indicator of any connection problems in the AMN/LISN circuit. The DC resistance between the mains input and the EUT port is specified by the manufacturer for some of the AMN/LISNs tested while others give the voltage drop, at 50 Hz, for a specified current. It is recommended that the DC resistance is checked when calibration is performed and also between calibrations by the user as a safeguard against incorrect operation caused by corrosion of connection points within the unit.

3.2.8. Low frequency voltage rating

Theoretically, it might be possible for the applied supply voltage to affect the impedance presented by the AMN/LISN. The only likely mechanism for this would be via the capacitance/voltage coefficient of the parallel capacitors used in the CISPR network. In practice, commercial units use capacitors of either polyester, polypropylene or paper dielectrics, which have a low capacitance/voltage coefficient and in any case, change of capacitance value will only cause a second order effect on the impedance. A test to show the effect of applying mains voltage to the AMN/LISN versus its absence showed no observable effect on the measurements.

3.2.9. Comparison of units

To show the agreement that could be reached between test houses using different models of AMN/LISN and the best possible measurement practice, this section discusses the actual results from all five units investigated, measuring the surrogate EUT over the low frequency range up to 1MHz and the high frequency range from 1 to 30MHz. These results are for when the AMN/LISN and EUT are in the recommended configurations, that is:

- The LISN bonded to a horizontal ground plane with a low impedance earth strap
- The mains lead supported at least 10 cm above the ground plane

The plots in Figure 18 and Figure 19 show the difference for each AMN/LISN compared to the *mean* result for all units. The uncertainty limits shown are based on the calculations given in 5.2.3 with the following changes:

- The uncertainty for the receiver is not included as this is common to all measurements.
- The uncertainty due to coupling between the mains lead and ground is reduced from 2 dB to 0.5 dB because the mains lead position was kept as far as possible the same for each AMN/LISN
- The earth strap was the same for each unit so this uncertainty is reduced from 0.5 dB to 0.2 dB
- The mismatch uncertainty between the AMN/LISN and receiver is calculated for a receiver input reflection coefficient of 0.02.
- As the remaining errors for each AMN/LISN are substantially independent the uncertainty used for comparison purposes is the root sum of squares of two equal uncertainties.

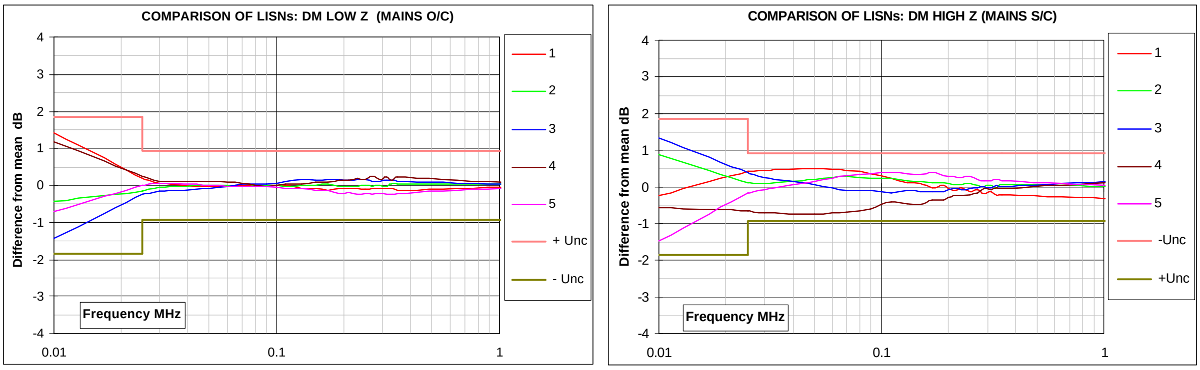


Figure 18 - 10 kHz to 1 MHz differential mode low Z, mains O/C and high Z, mains S/C

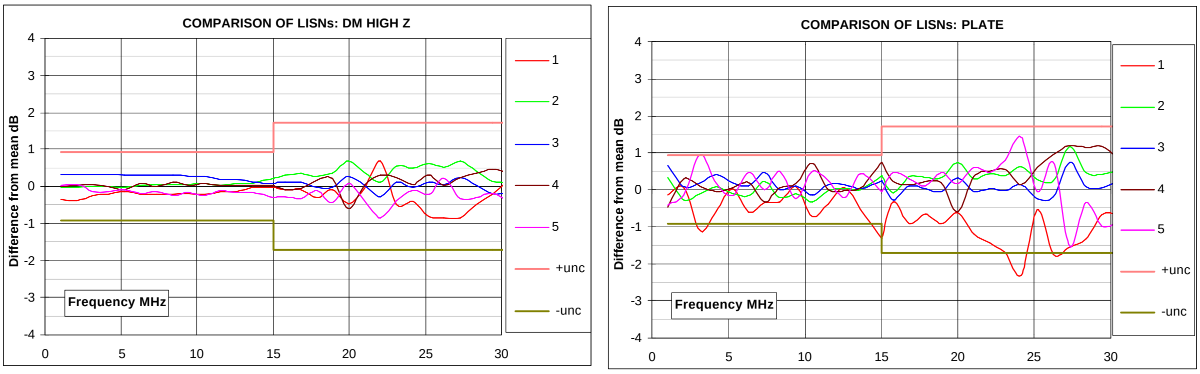


Figure 19 - 1 MHz to 30 MHz differential mode high Z, and plate

Comments on comparisons

Figure 18 clearly shows that the error between units rises steeply at frequencies below 25 kHz and is almost certainly due to the lower isolation at these frequencies (see 3.3.4) and the higher reactance of the EUT port, which makes the voltage developed at the EUT port more dependent on small variations in the impedance between units.

Figure 19 differential mode shows that despite the possibility of significant errors, particularly above 15 MHz, there is very good agreement between all the units tested with the errors well within the estimated uncertainty. In general the differences between AMN/LISNs was the lowest with the EUT operating in differential mode.

The second plot in Figure 19 shows the increase in the difference between AMN/LISNs when the EUT was coupled via its “plate” circuit, that is, the coupling is mediated entirely by stray capacitance and hence is much more susceptible to small layout variations, particularly those causing changes in parasitic inductance and capacitance. This represents the likely worst case and demonstrates the significance that must be attached to variations between EUTs that are largely unknown.

3.3. Calibration of the AMN/LISN

The calibrations required for an AMN/LISN to ensure compliance with CISPR 16-1 and ANSI C63.4 are as follows:

- impedance at the EUT port
- insertion loss between the EUT port and the receiver output port

Other calibrations and performance tests can usefully be carried out by a calibration laboratory to ensure proper and safe performance of the unit, these include:

- isolation between the mains input port and the EUT port

- isolation between lines
- DC or AC 50 Hz resistance

CISPR 16-1 does not explicitly specify a calibration method but ANSI C63.4 does. Measurements cover the frequency range 9 kHz to 30 MHz so that the measuring instrumentation will normally be within a 50Ω coaxial system. Since the calibration is made at the EUT port, an adaptor is needed to transform from a coaxial transmission line to a mains connection, for example a 3 pin 13A socket.

3.3.1. Construction and use of the test adaptor

The adaptor should be mechanically rigid with the distance between the pin of the mains plug and the coaxial connector as short as possible. It is recommended that 16 swg copper sheet is used as an earth plate onto which two BNC bulkhead connectors (N type connectors can equally be used) are mounted. The pins from a three pin mains plug are soldered to the centre connection on the BNC connector directly using the holes that normally take the wire clamping screw. The earth pin from the three pin plug is attached to the copper plate by means of the wire clamping screw or by soldering. The form of construction is shown in Figure 20, and Figure 21 shows two views of the actual adaptors used.

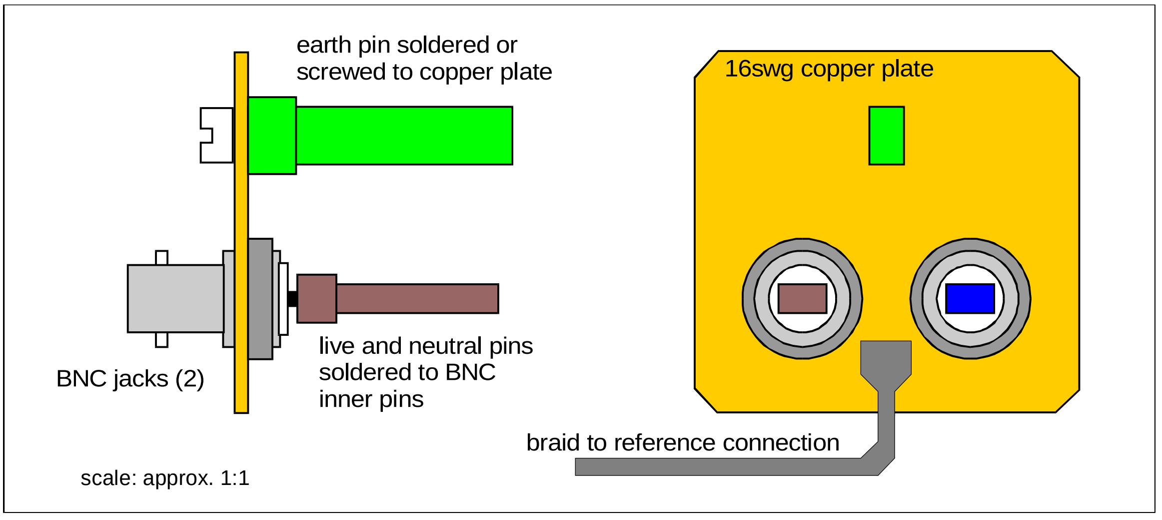


Figure 20 - The 3 pin to coaxial adaptor

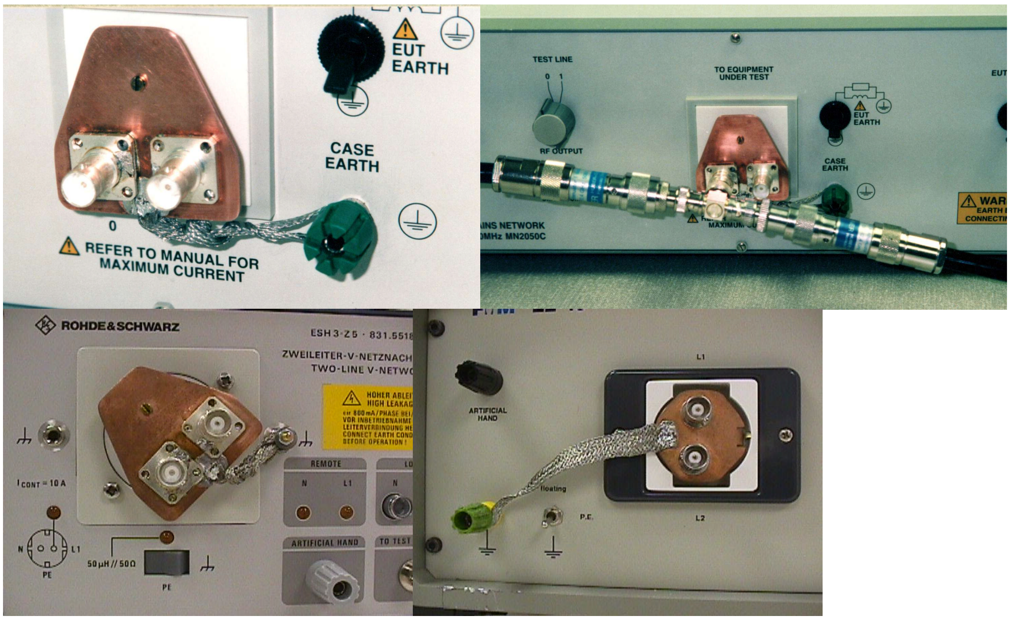


Figure 21 - View of adaptor and setup used for the calibration experiments

The adaptor is used for both the loss measurements and the impedance measurements and it is therefore necessary to assess its effect on these. Since the measuring systems are coaxial it is convenient to measure the adaptor in combination with a mating one so that the input and output are coaxial, a back-to-back pair. This arrangement is not ideal because some assumptions have to be made concerning the asymmetry of the two adaptors. For this project a trailing 3 pin socket was used for the female adaptor, with a similar construction to the male adaptor.

The results for the impedance and loss measurements for the back-to-back pair up to a frequency of 100 MHz (Figure 22) indicate, perhaps surprisingly, that the adaptor is not a significant contribution to the uncertainty. For this reason further work to try to resolve the asymmetry problem was not considered worthwhile.

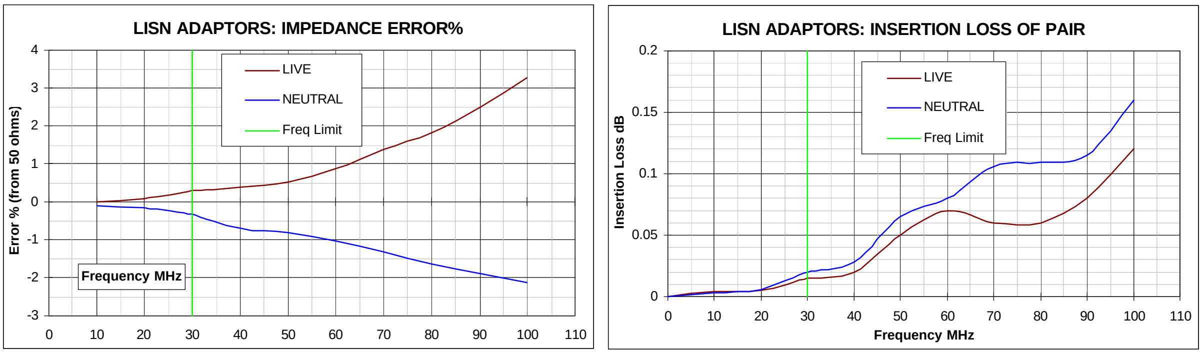


Figure 22 - Measured adaptor impedance error and insertion loss

3.3.2. Impedance

For this project an impedance analyser was used for the frequency range 9 kHz to 5 MHz and a network analyser between 5 MHz and 30 MHz [14]. There is a frequency overlap between the two instruments so that a comparison could be made. The measurement uses the coaxial to 3 pin adaptor to obtain the input impedance at the EUT port. The required impedance is between the live terminal and the RF ground reference and also between the neutral line and RF ground reference. The receiver output port is terminated in a precision 50Ω load (VRC < 0.01), this is referred to as the remote load. Where an AMN/LISN is provided with an internal (local) 50Ω termination the input impedance should be measured using this load as well; this is achieved by switching to the neutral line when measuring the live line and vice versa.

The RF ground reference is not the same as the EUT earth (as discussed in 3.2.2), and it is essential to ensure that the coax outer is connected to the AMN/LISN's reference terminal using a low impedance connection. One of the units investigated is fitted with two 4mm sockets, one each side of the EUT port, specifically for impedance measurement purposes. For this particular unit an adaptor was manufactured from copper sheet that connects directly to this earth terminal. For the other units it was necessary to use the normal earth binding posts provided on the front panel, unfortunately these are at difference distances from the EUT port on different AMN/LISNs so either separate adaptors need to be manufactured for each type or the earth strap has to be flexible. Experiments showed that the difference between the two earthing arrangements was less than 0.3% in the measured impedance.

When making the impedance measurements it is recommended that the earthing arrangements are checked to ensure repeatability and reproducibility. An indication that this has been achieved is that the measurements are stable when connecting leads are moved and hand contact has no effect. Also, the unit being calibrated should be located at least 1m away from the network analyser, and should not sit near or on top of it.

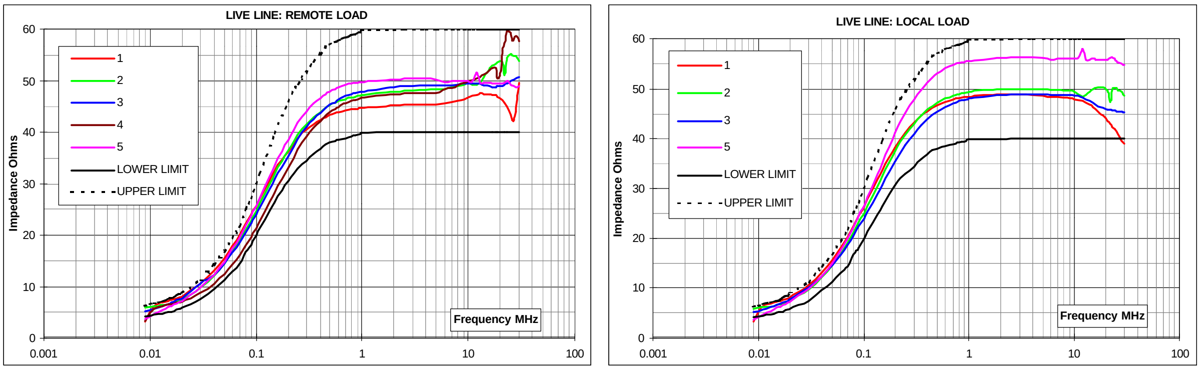


Figure 23 - Results of impedance measurements

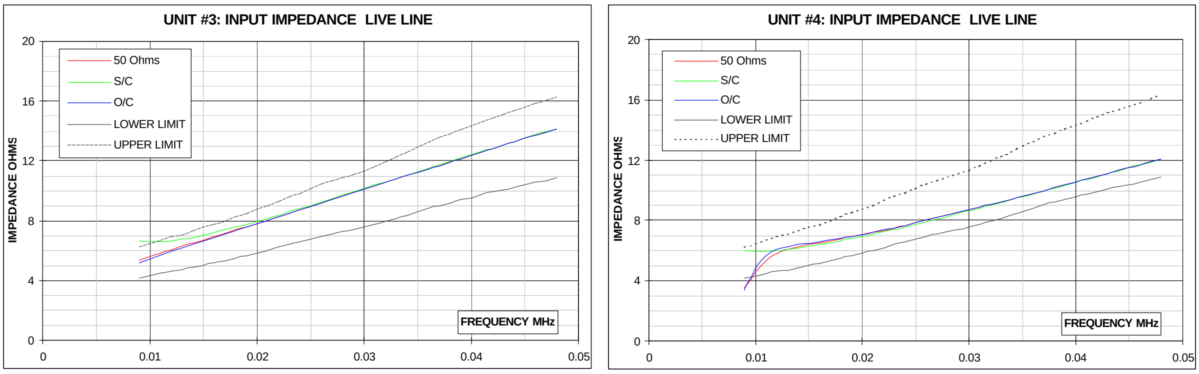


Figure 24 - LF impedance measurements versus mains termination

The results obtained for all the AMN/LISNs between 9 kHz and 30 MHz are shown in Figure 23 for the live line with the mains input open circuit; the results for the neutral lines were very similar for all units. Also plotted are the limit lines as given in CISPR 16-1: 1993. Figure 24 shows the frequency range 9 kHz to 50 kHz for two of the units with the mains input line-to-earth open circuit, short circuit and 50Ω.

Most of the measured values fall within the CISPR limits, with some exceptions, particularly at 9 kHz as can be seen in Figure 24. All units implement the values for CISPR C2, L2 and R2 differently and this is likely to explain the variations observed at the bottom end, with respect to changes in mains termination (see also 3.3.4). Simulating the CISPR circuit at these frequencies suggests that C2 and R2 could best be fixed at 2µF and 5Ω. Adding a 1.6mH inductor in series with the mains input earth pin, as is done by units #2 and #5 (not shown in the above figures) eliminates variations of impedance with mains termination, but it is difficult to recommend this as a universal practice since it means that the incoming mains supply earth must float at RF with respect to the ground reference plane.

The unusually high value in Figure 23 for unit #5 with a local load is traceable directly to this unit's use of a 56Ω resistor as the load, rather than the 51Ω or 50Ω values used by the other manufacturers. (Unit #4 does not provide an internal local load and so is omitted from the relevant graph.)

In the case of unit #4 with a remote load at 24 MHz the measured value is right on the edge of the CISPR specification. This unit is the only one of those investigated whose inductors (CISPR L1 and L2) are arranged coaxially rather than side-by-side; also, in common with unit #2, which shows similar but less extreme behaviour, its L1 uses a single solenoidal construction with no resistive damping. The other units all implement some form of damping on L1. Even if the measured value is within the CISPR specification, when the calibration measurement uncertainty is added to this value the limit could be exceeded. Under these circumstances the calibration laboratory could not declare with certainty that the AMN/LISN meets the impedance requirements given in CISPR 16-1, leaving the user in some doubt about the validity of using the unit for compliance testing. This is a difficult problem to resolve, but as shown earlier in this guide there are significantly larger contributions to measurement uncertainty, especially at high frequencies. These departures from the impedance specification should be of little significance for the test results, causing a maximum deviation of 1.6 dB from the correct measurement for EUTs with high source impedance, reducing for lower source impedances. The question remains, though, to what extent any departure is acceptable in declaring calibration results.

3.3.3. Insertion loss

The insertion loss will directly affect the measurements of conducted emissions made with the AMN/LISN and should therefore be known and compensated for if necessary. The loss is measured as a voltage ratio between the EUT port and the receiver port for all lines. It is normal practice to use a 50Ω system for the measurement, but as the input impedance of the AMN/LISN varies with frequency from 5Ω at 9 kHz to 50Ω at 30 MHz, driving the EUT port from a 50Ω source would give an input voltage that changes with frequency. The correct way* to make the measurement is to feed the AMN/LISN and measuring system in parallel through a Tee adaptor, providing effectively a zero source impedance. The receiver port is terminated with a 50Ω load and readings taken on the attenuation measuring system over the required frequency range. The measurement system is then transferred to the receiver port and the 50Ω load transferred to the Tee adaptor. The insertion loss of the AMN/LISN is the difference between these two measurements. The system layout for insertion loss measurements is given in Figure 25.

As with the impedance measurements good bonding of the outer of the coaxial input to the AMN/LISN reference earth is required. The insertion loss measurement should be made as a swept measurement so that any resonance can be detected. For the units tested there were resonance effects between 15 MHz and 30 MHz with some models significantly worse than others. The earthing arrangements made for the impedance measurements will also serve for the insertion loss measurements but checks should be made to ensure that the effects of any stray coupling are minimised. As with the impedance measurement an indication that good repeatability and reproducibility has been achieved is when the insertion loss measurements are stable when cables are moved and hand contact is made with different parts of the system.

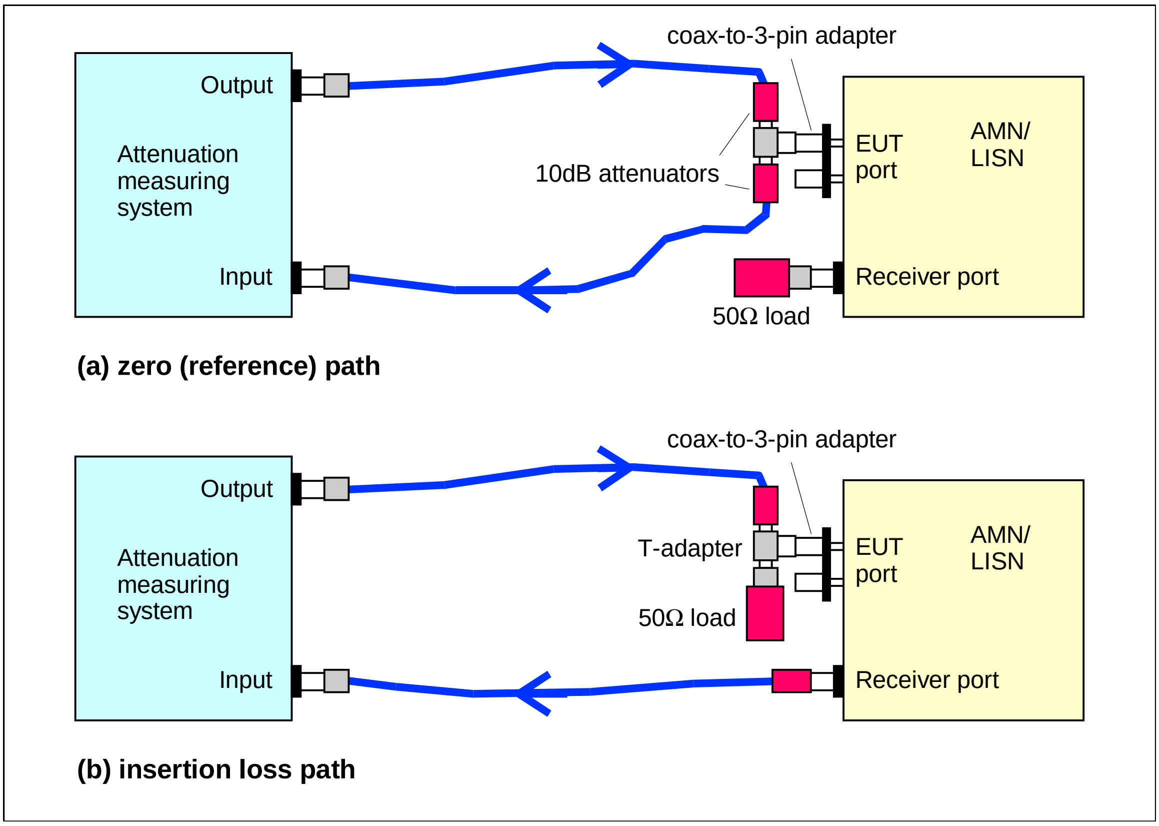


Figure 25 - Insertion loss measurement layout

* According to ANSI C63.4: 1992 [8] and a proposed revision to CISPR 16-1, CISPR/A/201/CDV [9].

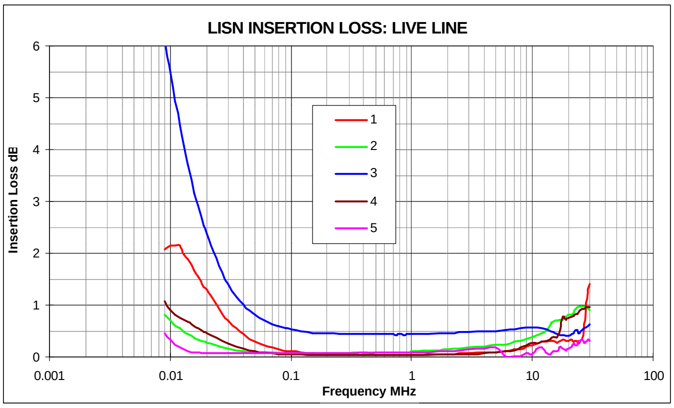


Figure 26 - Results of insertion loss measurements

The results of the insertion loss measurements for the live line are shown in Figure 26, the neutral line gave very similar results. This shows that all but one of the AMN/LISNs have negligible loss between 100 kHz and 5 MHz (< 0.2 dB) with the exception being approximately 0.5 dB over this range (the circuit of this unit shows a small series resistance in the signal path, absent from the other units). The insertion loss increases for all units below 100 kHz generally rising to a maximum at 9 kHz, the variation between units at this lowest frequency is 0.5 dB to 6 dB. This variation can be traced to the use of different values and circuits for C3, the coupling capacitor in the CISPR circuit. There is also an increase above 25 MHz for most of the units with the maximum being 1.4 dB at 30 MHz.

3.3.4. Isolation

The output impedance of the AMN/LISN as measured at the EUT port will depend to some extent on the impedance terminating the mains connection. For most of the impedance measurements the mains input was open circuit but the effect was investigated by making the measurements with the mains connection terminated with a short circuit and with 50Ω. It was found that for all units tested the mains impedance has a negligible effect above 30 kHz but below this frequency there is a significant variation on some models, and so we recommend that impedance measurements in this range are made with the mains input terminated with open circuit, short circuit and 50Ω. Note that ANSI C63.4 [8] requires AMN/LISN calibration with a mains RF filter in place if this will be used in the test environment; the proposed revision to CISPR 16-1 [9] requires the sensitivity of insertion loss to the mains terminating impedance to be checked across the whole frequency range, and if this exceeds 0.1 dB, then each line of the mains port must be terminated with 50Ω.

The isolation that the LISN provides between the mains input and the EUT port is not specified in CISPR 16-1 but was investigated for this project. The measurements of isolation were made in a 50Ω system and the results are given in Figure 27. This shows that the isolation is greater than 25 dB over most of the frequency range although one model gave results below 20 dB at 20 MHz. All units have reducing isolation below 100 kHz falling to between 13 dB and 19 dB at 9 kHz. When this measurement is made with a zero impedance source instead of 50Ω the figure for isolation is in the order of 8 dB at 9 kHz. The actual value applicable to a test situation will depend on the source impedance of the mains supply. The isolation between the mains input and receiver port was also measured and generally gave higher values than that to the EUT port.

The lower isolation at frequencies below 100 kHz could have some effect on the test results if the mains supply carries LF noise and is not sufficiently filtered. See also Figure 18 and associated discussion.

Isolation between lines also is not a specified requirement but was investigated for this project. The isolation between live and neutral was measured with the input applied to the live line of the EUT port from a zero impedance source and measuring the difference in insertion loss at the receiver port when the input was switched to the neutral line. With one exception the isolation between lines for all units was greater than 30 dB over the full frequency range, the one exception decreased to 25 dB at 30 MHz. The use of the calibration adaptor should not noticeably degrade line-to-line isolation.

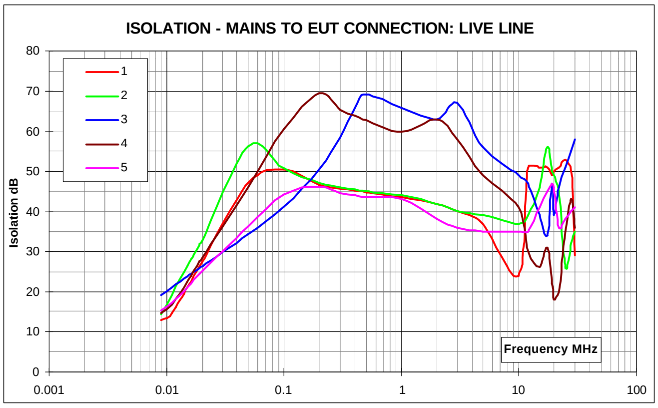


Figure 27 - Mains to EUT port isolation

3.4. Recommendations for general AMN/LISN design features

Resulting from the experiments described in this document, we can offer some guidelines regarding the actual construction of a standard AMN/LISN. These were summarised earlier but are amplified here, with a drawing (Figure 28) for clarification.

- the enclosure construction should emphasize a low impedance bond to the ground reference plane. The design should concentrate on providing the facility for low inductance ground connections to which the EUT earth connection is tightly coupled, preferably by using a mounting plate, even if this means a less attractive outward appearance. Connections both to a horizontal and a vertical plane should be envisaged.
- there should be minimum spacing between the reference earth connection(s) and the bottom of the unit; with no extendable feet. This allows the lowest possible impedance to be realised by the connecting strap, as above.
- the EUT connector should be mounted near the top of the front panel, upside down (for BS1363 13A types) to encourage the mains lead to exit away from the ground reference plane and to give a short connection from the earth pin to the reference earth connection(s). When the mains lead exits towards the ground plane, it is harder to maintain the necessary separation.
- a reference earth connection should be provided close to the EUT port's live and neutral pins that is specifically used for calibration purposes.
- no earth lead inductor should be included. It is not a requirement of current measurement standards, and its inclusion compromises the impedance between the EUT earth and the reference earth connection(s); the value is not properly defined in CISPR 16-1, and this results in different implementations between AMN/LISN manufacturers. Providing a switch to control the earth coupling allows an extra source of accidental error in the test procedure.
- provision of locally switched 50Ω loads is preferable to external loads, as long as the load value is correct. Requiring an external load to be fitted to the unused receiver port(s) allows an extra source of accidental error in the test procedure. Internal loads appear to give a better-behaved impedance curve at high frequencies.
- the CISPR 50µH inductor L1 should be resistively damped if it is a single solenoidal winding, and should not be coaxial with L2; this appears to minimise resonances in the high frequency impedance response.
- care should be taken over the selection of component values for CISPR C2, L2 and R2, in order to ensure that the impedance curve at 9kHz is maintained whatever the terminating impedance of the mains input port.

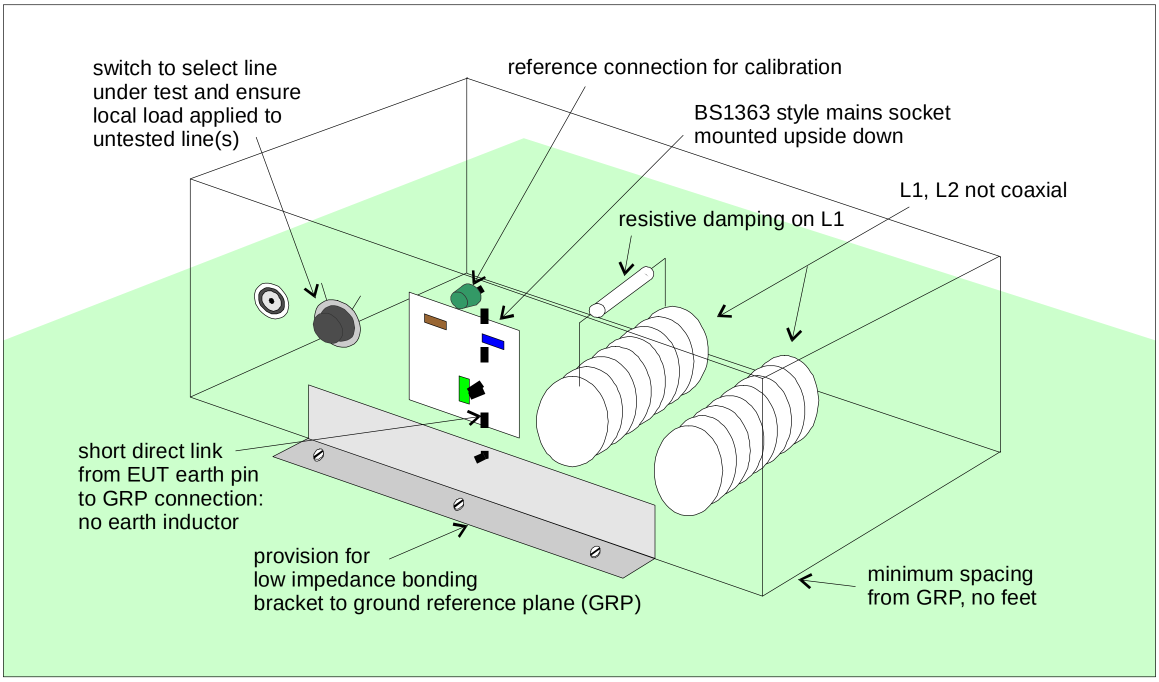


Figure 28 - Recommendations for AMN/LISN design

4. The absorbing clamp

For the investigations which form the basis of this section, three manufacturers' absorbing clamps were used:

- Luthi MDS-21, manufactured in Switzerland by Schwarzbeck
- Fischer F-201, manufactured in the USA by Fischer Custom Communications Inc
- Laplace RF-400, manufactured in the UK by Laplace Instruments Ltd

4.1. Disturbance power tests

The principal standards which require disturbance power tests are EN 55013 and EN 55014-1, derived from CISPR 13 [1] and CISPR 14-1 [2] respectively. Other standards require the use of the clamp for other purposes, notably for cable screening effectiveness tests, but these are not considered here.

4.1.1. The emissions equivalent circuit

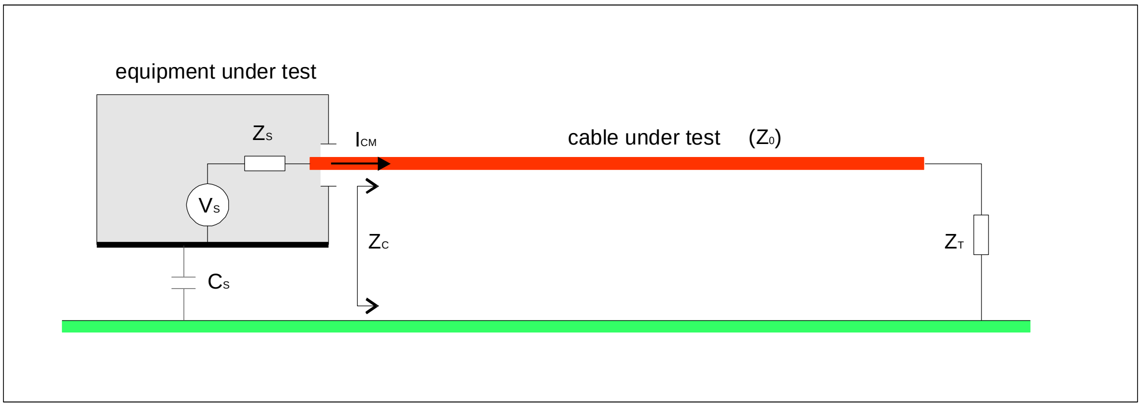


Figure 29 – Equivalent circuit for the disturbance power test

The essential assumption of the disturbance power measurement method is that the primary source of high frequency emissions is the signal that is coupled onto a connected cable from interference generated within the EUT. Then, an indication of the disturbing capability of the EUT is obtained by measuring the current that is fed in common-mode onto this cable, and which will be coupled away from the cable by radiation. The assumption is valid for many types of apparatus that have only one cable (typically the mains cable) and whose dimensions are small compared to a wavelength. When the equipment has several connected cables, or when its dimensions are greater than a quarter wavelength (that is, it is physically large, and/or the frequency of interest is high) the assumption is harder to justify and a radiated test is preferred. Nevertheless this measurement method has a good record as a means of assessing the interference potential of many types of equipment, and it is generally simpler to carry out than the radiated method.

The equivalent circuit for high frequency emissions in the standard absorbing clamp test set-up is shown in Figure 29. A length (normally >5m) of the cable under test is stretched out at a constant height above ground and thus forms a transmission line of characteristic impedance Z_0, a value which is determined by the geometry of the set-up. The far end of this cable is terminated in an impedance Z_T, which is generally unknown, being fixed by the high frequency impedance of the mains supply or the ancillary equipment which may be connected. (Placing a second absorber at this end stabilises Z_T, as discussed later.) The impedance presented to the EUT is Z_C, which is the transmission line impedance Z_0 modified by Z_T and any other mismatches that are present on the line.

The disturbing source in any EUT can be represented by a voltage source V_S in series with an impedance Z_S, referred to the enclosure (this simplification is valid whether or not the equipment has a Class II insulated or Class I earthed metal enclosure). Of course, both V_S and Z_S are frequency dependent. Z_S is coupled in common mode to the cable under test – that is, the resulting current I_{CM} flows equally and in the same sense in all conductors in the cable. The mechanism of coupling depends on the design detail and may be complicated, but need not concern this discussion. The EUT is isolated from the ground but coupled to it via stray capacitance C_S, which is a function of the equipment's geometry and its distance from the floor and other surrounding objects.

Matching considerations dictate that the maximum power transfer from the EUT to the cable will occur when

$$Re(Z_C) \quad = \quad Re(Z_S + 1/j\omega C_S)$$

Z_S and C_S are fixed by the EUT and the set-up, so power matching can be achieved by varying Z_C. This is the purpose of applying the clamp to the cable and moving it through a half wavelength, as discussed in the next section.

4.1.2. Construction and theory of operation of the clamp

The absorbing clamp as defined in clause 13 of CISPR 16-1 has three principal features:

- a loop of coaxial cable wound round two or three ferrite rings, which acts as a current transformer, inducing a signal into the loop from any RF current which flows through the cable under test to which the ferrite rings are coupled;
- an absorbing section made up of a further cascade of ferrite rings, located further down the cable under test away from the emitting source, whose purpose is to stabilise the RF common-mode impedance of the cable under test and reduce its dependence on the far-end termination;
- a further section of absorber over the sheath of the cable leading from the current transformer, which increases the common mode impedance of this cable and thereby reduces the impact of any variations in this impedance which may be coupled via stray capacitance through the transformer to the cable under test.

The ferrite material presents an impedance on the cable which is complex (that is, shows both resistive and inductive components) and varies with frequency. The CISPR 16-1 requirement is that the clamp as a whole should present an impedance between 100 and 250Ω, not more than 20% reactive, when measured in the standard calibration set-up with the signal generator and 10dB attenuator replaced by an impedance measuring instrument. Impedance curves for the three clamps tested are shown in Figure 30. In general the resistive part remains within the requirement, but the reactive part is mostly > 20% above 300MHz, even allowing for positional adjustment. (The wording in CISPR 16-1 does not make clear what the reactive requirement is a percentage of: we have interpreted it as being a percentage of the resistive value at each frequency.) EN 55014 does not use the clamp above 300MHz, but EN 55013 does.

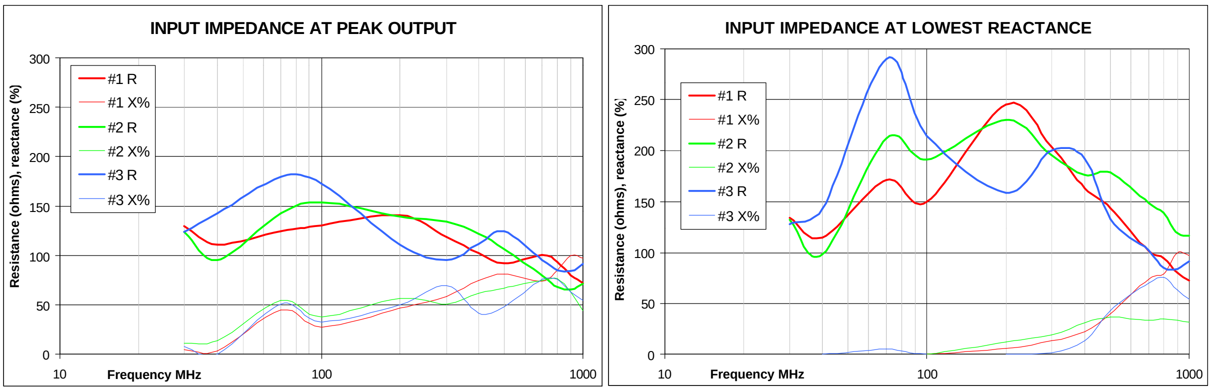


Figure 30 - Clamp impedance versus frequency

The ferrite rings are halved, and the clamp is so hinged that the cable under test can be laid through the whole assembly and the other halves brought down to enclose it completely. Good mating between the halves is essential and the ferrite housings are sprung to ensure this. Typically, the ferrites are mounted in the body of the clamp which is made of insulating material; there are no galvanic connections to be made either to the cable under test or to the transducer output cable. A typical construction is shown in Figure 31 and photographs of those used for the comparative measurements are shown in Figure 32. CISPR 16-1 shows two alternative construction possibilities, but in practice all those commercially available use variants of the form shown in Fig 39 of the standard.

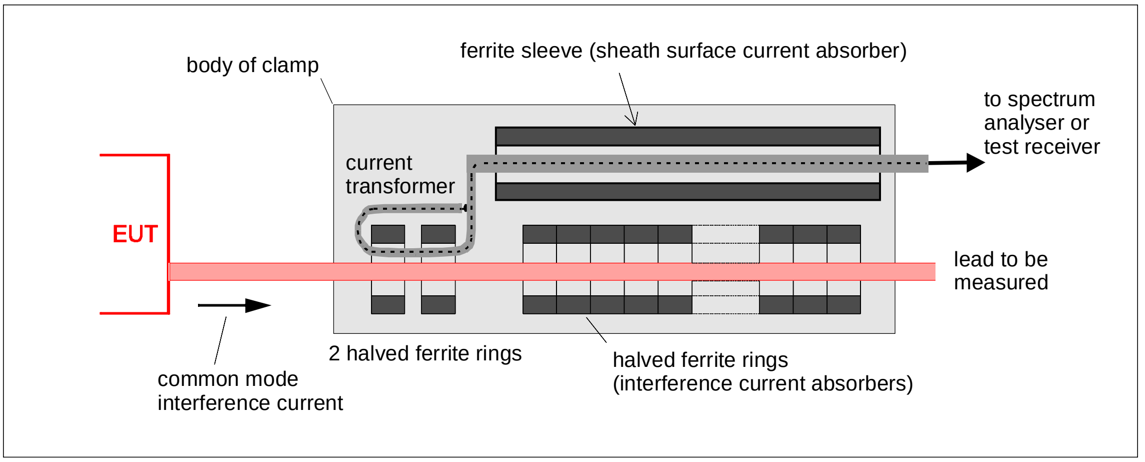


Figure 31 - Clamp construction

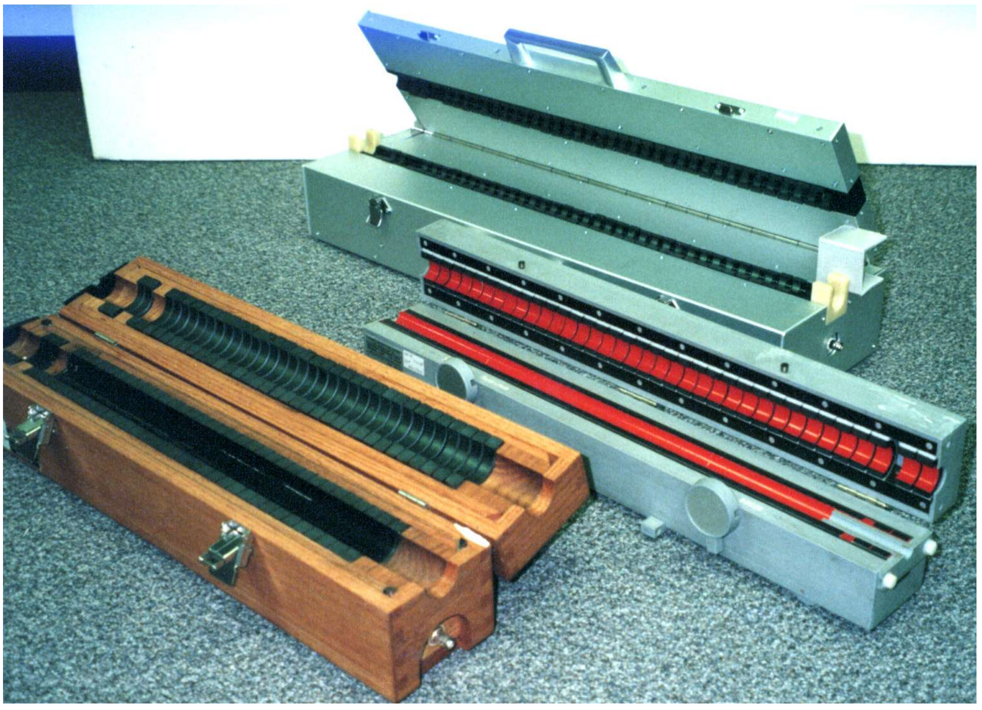


Figure 32 - The three commercial clamps investigated

In use, the clamp is placed round the cable under test with the current probe facing the emitting source. The far end of the cable is connected to the mains supply or to ancillary equipment, or left open in calibration; a second absorber may be placed over the lead. The clamp output is connected to the measuring receiver or spectrum analyser.

To determine the maximum power that the disturbing source can deliver to a lead of indeterminate length, the clamp is moved along the cable under test to find a maximum at any given frequency [15]. The output level varies periodically with distance, the distance between peaks being around half the wavelength of the measured frequency. The horizontal cable is acting against the ground as a transmission line, on which current standing waves are induced, and the clamp is measuring these standing waves (Figure 33). For a standing wave to form, there must be a mismatch along the transmission line. Such a mismatch will be caused by either of two sources:

- the termination (or lack of it) at the end of the line, or
- the absorbing clamp itself.

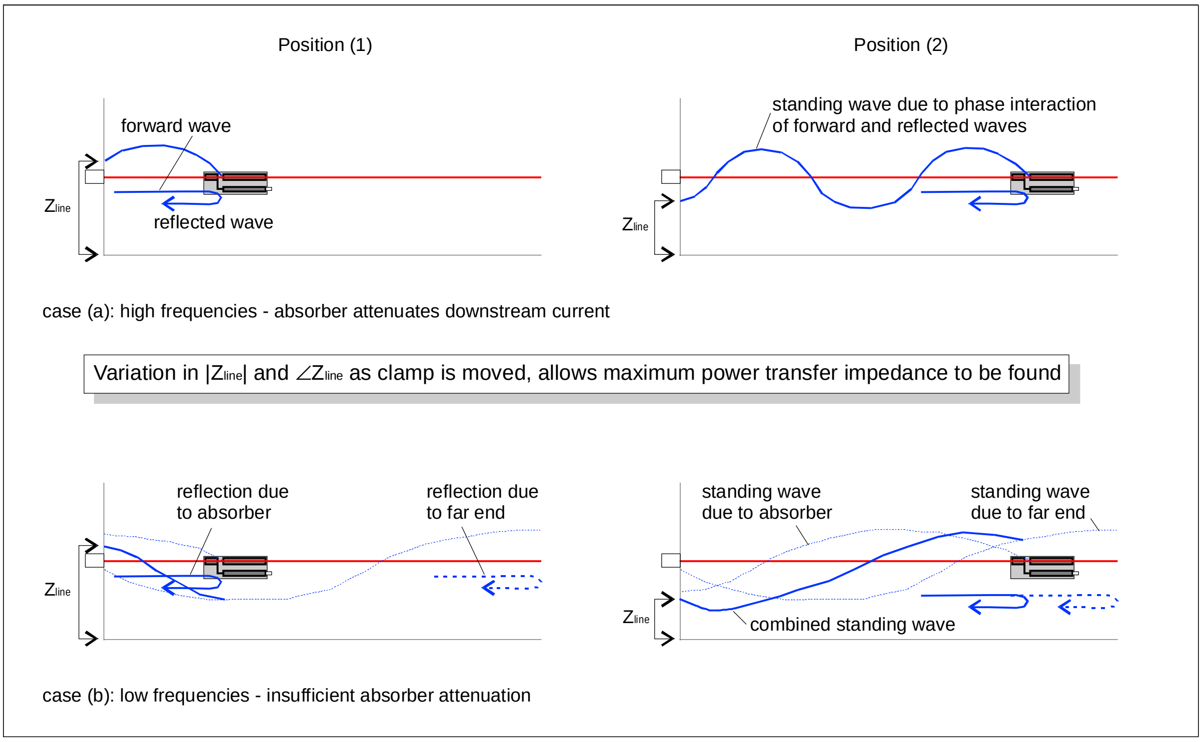


Figure 33 – Standing waves

If the absorbing section of the clamp is fully effective, the end of line termination should be invisible to the line between the clamp and the disturbing source, and should not therefore contribute to the standing wave measured by the current transformer. Nevertheless, the absorber itself will be mis-matched with respect to the transmission line impedance and will therefore cause a reflection, which in turn creates a standing wave. The current transformer is fixed in relation to the absorber and therefore remains at the same point on the standing wave, yet still senses a periodic variation in output; this is because as the clamp is moved, the amplitude of the signal fed to the cable varies, because the impedance presented to the disturbing source is varied. Therefore, moving the clamp will present an envelope of load impedances to the source which will allow, within limits, the maximum power transfer to be achieved.

At frequencies where the absorbing section is less effective (typically, below 50-100MHz) the far-end termination mis-match becomes visible to the measurement. The probe output still varies as the clamp is moved, and the maximum position can still be found; thus this condition is indistinguishable from correct operation at the higher frequencies. But the pattern on the cable is now partly due to the absorber mis-match as described above, and partly to the stationary standing wave caused by the far-end reflection. The maxima are thus not entirely due to the optimisation of power transfer. This is why typical insertion loss curves show patterns of peaks and nulls at the lower frequencies as well as the higher. It is also why placing a secondary absorber at the far end of the cable under test (or the calibration wire) will give different and more repeatable results at the lower frequencies.

4.2. Calibration of the clamp

The calibration method is specified in CISPR 16-1 Annex H and Fig. 40. This section reviews sources of error that may be found in this method. Figure 34 shows the basic set-up. As well as the experiments carried out especially for this report, reference has also been made to a CISPR/A document [16] proposing improvements in the absorbing clamp calibration method. At the time of writing, CISPR are organising a round-robin comparison programme for clamp calibration, and the comments made here are aligned as far as possible with the methods proposed in that programme.

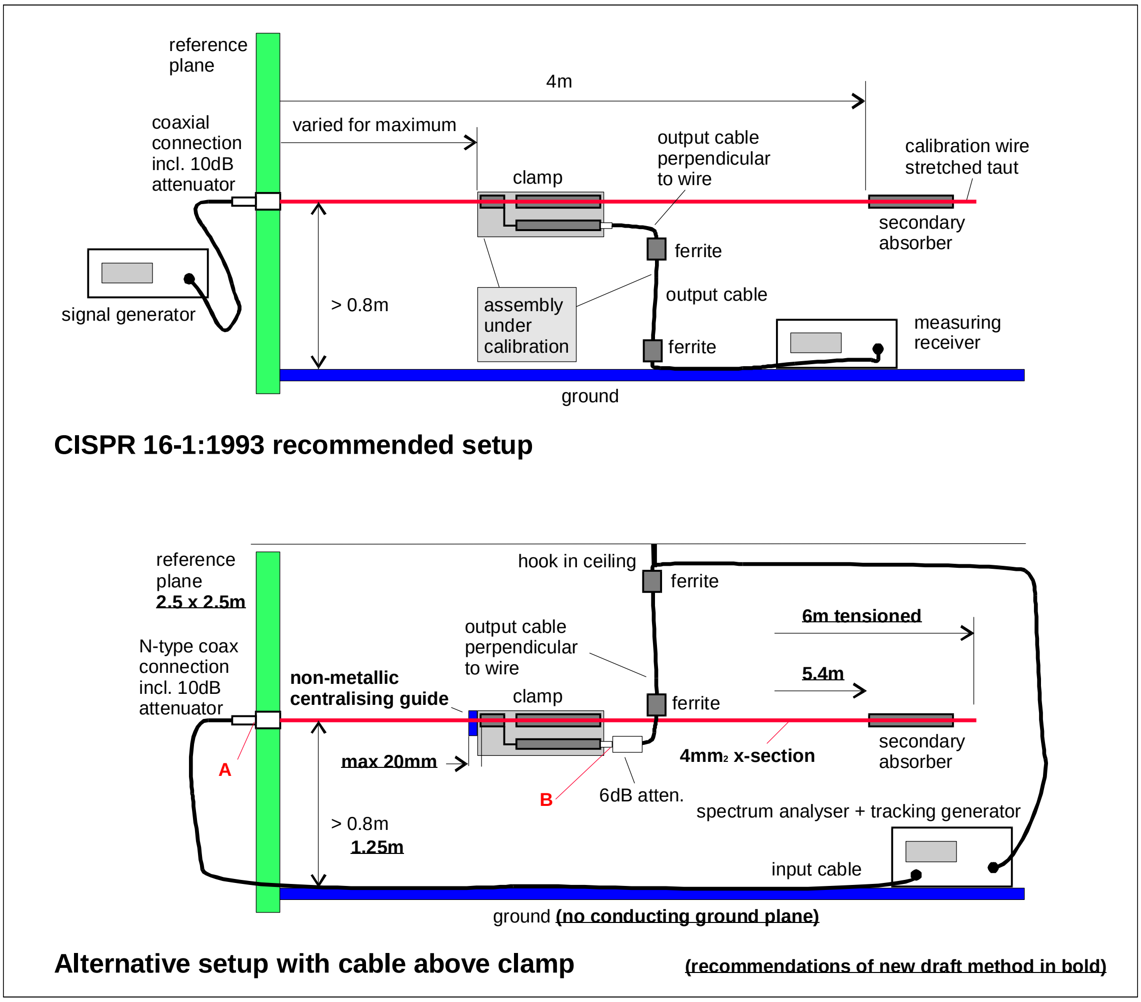


Figure 34 – Side view of calibration set-up

The calibration procedure is to compare the clamp's insertion loss with the reference loss through the 10dB and 6dB attenuators, i.e. points A and B (in red, above) are joined and the system loss is calibrated at spot frequencies in the range 30 - 1000MHz. The clamp set-up is then reconnected and at each frequency, the minimum insertion loss d_e is determined while the clamp is moved through about 3m (from next to the reference plane). During calibration personnel should be further than 1.25m from the cable. The calibration factor is then derived from the following formula:

$$K\ [\mathrm{dB(pW/\mu V)}] = d_e[\mathrm{dB}] - 17\ [\mathrm{dB(pW/\mu V)}]$$

The factor 17dB converts between microvolts and picowatts in a 50Ω system. Strictly speaking, the calibration factor applies to the clamp *only when it is connected via a 6dB attenuator and the output cable used in this set-up*. If no attenuator, or a different cable is used, the calibration factor is likely to diverge.

4.2.1. The effect of wire diameter

CISPR 16-1 requires that the wire which provides the calibrating signal should be between 1mm^2 and 2mm^2 in cross section. Measurements have shown that the difference in calibrated insertion loss between 1mm^2 and 2.5mm^2 is around 1dB, constant with frequency, for all three types of clamp. Figure 35 shows this for clamp #1. The larger wire diameter gives the lower insertion loss.

Since most cables under test are larger, and to remain within CISPR 16-1's requirement, it is recommended that at least the 2mm^2 cross section is used wherever possible by calibration facilities. The proposal for an amendment to CISPR 16-1 [16] calls for a 4mm^2 cross section wire.

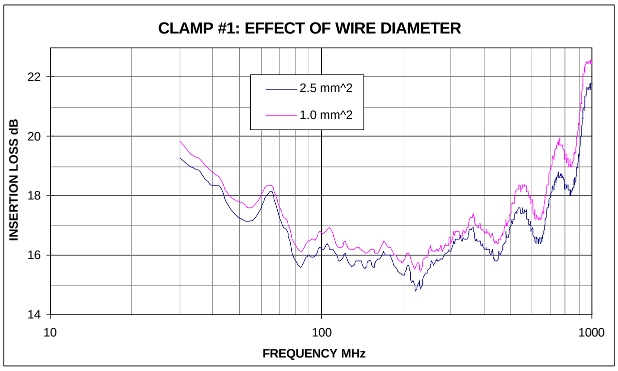


Figure 35 - Effect of wire diameter

4.2.2. The effect of wire position

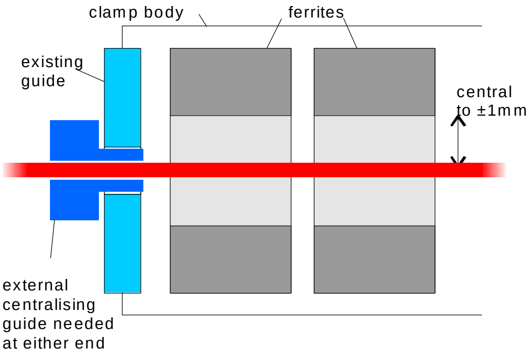


Figure 36 – Centralising the wire within the clamp

The cable under test should be maintained central within the clamp. However, when calibrating the clamp with a much thinner wire there can be significant variation in the position of the wire relative to the centre of the ferrites in the clamp. Offsetting the wire up to 10mm (where the construction of the clamp allowed this) showed that the difference could be up to 5dB with one model of clamp, the effect being greatest at the higher frequency end.

During calibration, the effect can be minimised by using additional guides within the clamp at either end that will hold the wire central to within ±1mm (see Figure 36). The wire should be maintained taut along its length.

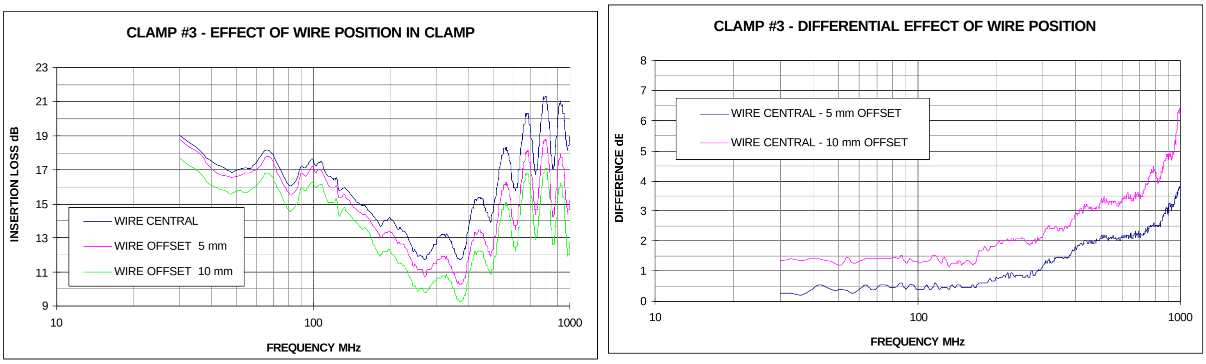


Figure 37 – Wire position measurements

4.2.3. Use of a second clamp or subsidiary ferrites

CISPR 16-1 recommends that a second absorber should be placed around the far end of the wire (item F in CISPR 16-1 fig.40). It should be fixed at “about 4m” from the reference plane, although this conflicts with the requirement to move the clamp through a half wavelength. There have also been some draft recommendations that two clamps should be used.

Insertion loss measurements were made with no clamp, one clamp and two clamps at the far end and the results show that the difference made by adding one clamp can be as high as 3dB at frequencies below 100MHz, although the effects above 100MHz are negligible. Clamp #3 shows the least effect. However, adding another clamp to make two in series produces very little further change and cannot be recommended. Error in placement of the load of 10cm about the 4m value gives a difference in the insertion loss of approximately 0.25dB.

The user or calibrator of an absorbing clamp may not have a second clamp available to act as a load, and the cost of purchasing one may not be easy to justify. Widely available clip-on ferrite sleeves can be used equally successfully and easily, and are very much cheaper. Comparisons were made between the use of a string of 12 ferrites and an absorbing clamp as the far end load and these show that the difference for all models of clamp is no more than 0.5dB. Further, a series of measurements were made with increasing numbers of clip-on sleeves. These show that once there are six clip-on ferrites on the wire the effect of adding further units is negligible.

The units used in these tests were Fair-Rite part no. 2643-164151, which have an ID of 13mm, an outside dimension of 26 x 26mm and a length of 28mm. Their quoted impedance is 125Ω at 25MHz and 250Ω at 100MHz. Provided that similar or equivalent parts are used, it is recommended that at least six of these items be applied at 4m distance from the reference plane.

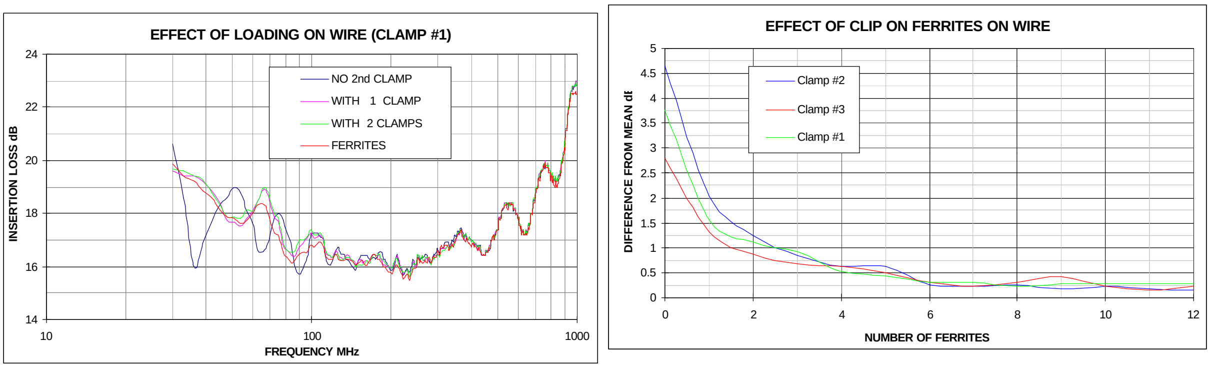


Figure 38 – Effect of loading with ferrites and clamps

4.2.4. The reference plane and nearby objects

CISPR 16-1 suggests a reference plane dimension of 2.5m x 2.5m, but has nothing to say about the area in which the calibration is carried out. Changing the size of the plane from 2m x 2m to 4m x 2m, in an open area, made no more than 0.3dB difference, even at low frequencies. This dimension appears not to be critical.

The laboratory area may have a greater effect. Comparisons were made between insertion loss measurements inside and outside; inside the laboratory there are some large metal objects including a screened room wall, although all such objects are more than 1.5m away from the calibration wire. Outside, the measurements were done over a concrete base at least 2m away from any other object. Differences up to 2dB below 100MHz, and 1dB above it and decreasing with frequency, were found.

Measurements were made to quantify the effect of a metal sheet near the wire by measuring the insertion loss with a 2m x 1m aluminium sheet at increasing distances from the wire. The sheet was parallel to the wire with the 2m side vertical and 1m from the reference plane. The results for all three clamps are similar and indicate that once this relatively large metal object is more than 1m from the wire the effect on insertion loss is negligible. This result can be expected also to apply to cables and instruments.

4.2.5. The output cable

There is the potential for the cable from the clamp to the measuring receiver to couple with the calibration wire and cause erroneous results. Fig. 40 of CISPR 16-1 shows this cable bearing ferrite sleeves at either end and dropping to the floor directly as it exits from the clamp. The length of this cable, and the impedance of the ferrite sleeves, will both affect the transmission line impedance of the wire. This effect will become more marked the more closely coupled the output cable is to the wire, although it is lessened by occurring on the downstream end of the clamp. Minimum coupling will occur when the cable is immediately brought away from the wire at right angles to it, and this geometry should always be maintained in calibration (see Figure 34).

Since the output cable and its ferrites can have an effect on the result, the clamp and its cable assembly should always be treated as a unit and calibrated and used together.

4.2.6. Uncertainty due to output voltage reflection coefficient

The output voltage reflection coefficient (VRC) was measured for all the clamps, with the clamp coupled to the calibration wire. The reflection coefficient can vary between 0.3 and 0.8 with significant ripple appearing above 200MHz. This variation appears to account for the ripple in the insertion loss characteristics at high frequencies. If untreated, the VRC will be a significant contributor to the overall measurement uncertainty, but its effect can be substantially reduced by adding a 6dB attenuator pad at the output connector, at the expense of sensitivity. This should be treated as part of the whole calibrated assembly, as discussed above.

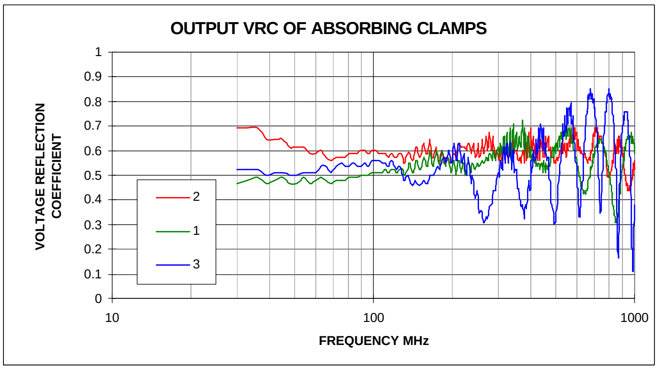


Figure 39 – Measured output voltage reflection coefficient

4.2.7. The length of the wire

CISPR 16-1 does not specify a particular length for the calibration wire but it must be long enough to include the second absorber positioned at 4m, so that the wire will need to be 4.5m or longer. Measurements outside the laboratory on one of the clamps with the wire extended in stages from 5.5m to 9.5m gave a variation of less than 0.3dB. Without the second absorber this can be expected to increase significantly.

4.3. Use of the clamp

Many of the issues discussed under this heading are similar to those which appear under *calibration* of the clamp. For the investigations described here, a comb generator was used as a surrogate EUT which provided a measurable output at 10 MHz intervals between 30 MHz and 1 GHz. The centre conductor of the comb generator's coaxial output was connected directly to two wires of a three core mains lead with the screen connected to the third wire; this would give part differential, part common mode excitation as might be expected in a real EUT. The output of the absorbing clamp was connected, via a 6 dB attenuator to a spectrum analyser which was used to measure the level of each 10 MHz harmonic over the 30 MHz to 1 GHz range.

The mains lead was 6 m long with the far end open circuit. 10 clip on ferrites were placed 4.5 m from the EUT, and the output cable had 3 clip on ferrites close to the clamp output and a further 6 spaced along its length (5m). The output cable was brought away from the clamp perpendicular to the mains lead and was suspended at least 0.4 m above the floor. The clamps were moved along the wire by means of a pulley arrangement to avoid personnel contact.

4.3.1. Cable under test: positioning within the clamp

This series of measurements were made in the laboratory with the EUT and mains lead at 0.8 m height. Measurements were made firstly with the mains lead left to take its own position in the clamp and then with the mains lead tensioned and supported within the clamp so that it was at the centre of the ferrite rings.

Figure 40 shows the results. For clamps #1 and #2 the differences are less than 0.3 dB over most of the frequency range with peaks up to 1 dB at the highest frequencies. Clamp #3 shows increasing difference with frequency rising to 5 dB at 1 GHz. These results largely confirm those found in calibration (see 4.2.2).

Both the first two clamps incorporate guides at the current transformer end that keep the mains lead more or less central irrespective of tension, and do not allow the lead to droop towards the ferrite cores of the current transformer. Additionally, clamp #2 has a metal screen against the current transformer as per CISPR 16-1 Fig. 39, which may account for its good performance at the highest frequencies. The third clamp has no equivalent guide and the position of the lead is more dependent on the tension on the lead. In practice it is unlikely that the lead would be tensioned sufficiently to keep it in the centre, and therefore it would drop to the bottom of the channel and rest on the cores. It is also the case that the third clamp has a metal enclosure, which could exacerbate stray capacitive coupling to the cable.

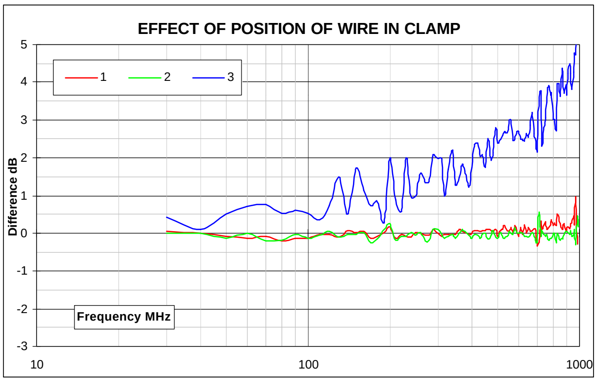


Figure 40 - Effect of cable position

4.3.2. Use of a second clamp or subsidiary ferrites

Measurements were made with and without ferrite loading on the mains lead. For clamps #1 and #3 the maximum difference occurs at 40 MHz and is between 2 dB and 2.5 dB. For clamp #2 the maximum difference is at 30 MHz and is between 1 dB and 1.5 dB.

A comparison was made with 10 clip on ferrites and then these replaced by an absorbing clamp at the same position on the mains lead. Measurements were also made with the 10 clip on ferrites placed at intervals of 0.25m between 4 m and 5m. The differences are mostly below ±0.5 dB.

We can recommend from this that an absorbing load of some description must be placed on the mains lead, but it appears that the use of clip on ferrites is equivalent to using a clamp, within the normal uncertainties of the measurement. EN55014:1997 para 6.2.4 suggests that the fixed ferrite absorber should be placed about 6 m from the EUT. (It also suggests that the purpose of this is to reduce extraneous noise from the mains supply, but our experiments show that this is only a secondary effect.) The positioning of the ferrites does not seem to be very critical but they should be at least 5 m from the EUT so that the travel of the clamp is not restricted.

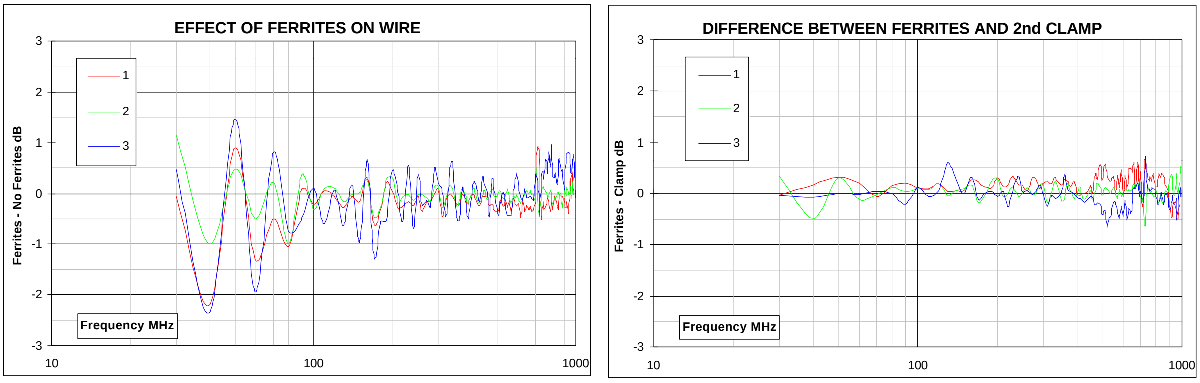


Figure 41 - Effect of absorbing load at far end of mains lead

4.3.3. The effect of the test lab

CISPR documents do not specify whether the clamp should be used in an open area or within a screened room. Use in a screened room will eliminate ambient signals from the measurement, but introduces errors due to the coupling of the cable under test with room resonances, as is the case for a radiated field measurement. Experiments were made to show the difference between a measurement made inside a semi-anechoic screened room of dimensions 7.3m L x 4.2m W x 3.6m H, versus measurements made in a typical lab environment with a concrete floor and no screening. The walls and ceiling of the room have 24 inch truncated pyramid RAM but there is no absorber on the floor.

The graphs in Figure 42 show the difference between measurements in the lab and in the screened room with the cable at 0.8 m height and at 0.4 m height.

For 0.8m height, all clamps are very similar with maximum difference of 5 dB at 40 MHz and 3 dB at 70 MHz. For 0.4m height, the maximum differences are significantly smaller at 1.5 dB for 40 MHz and 2.5 dB for 70 MHz. This may be because the test assembly couples more strongly with the screened room resonances (which calculation shows to exist at the above frequencies) at the greater height.

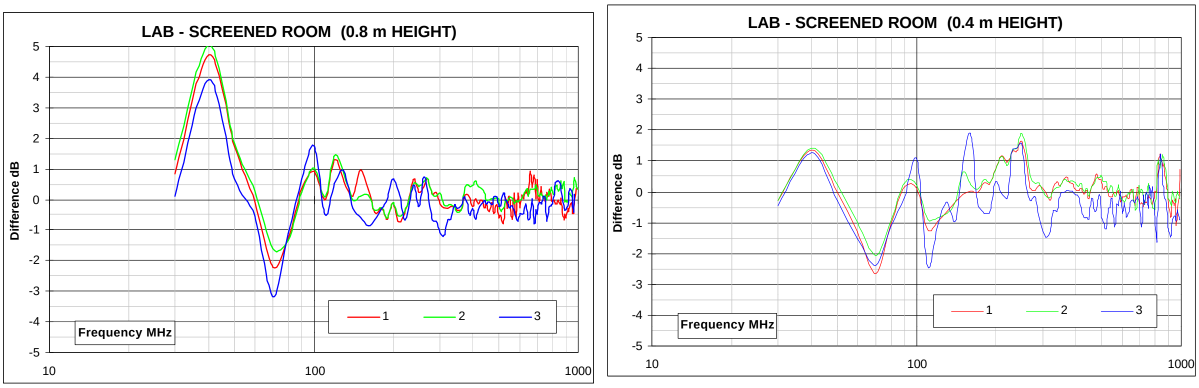


Figure 42 - Differences between open lab area and screened room

The results for this particular laboratory and screened room are probably typical but smaller screened rooms may well show greater differences. In general when measurements have to be made in a screened room, because of ambient signals, then the uncertainty needs to be increased by at least 5 dB at frequencies up to 100 MHz and 1 dB above this frequency. If a result obtained in a screened room is within ± 5 dB of the limit at frequencies up to 100 MHz then this measurement should be repeated outside the screened room, if ambient signals levels are acceptable.

4.3.4. The test layout

Various issues arise with respect to the test layout. Those addressed here are:

- the height of the cable under test above the ground

- the routing of the output cable away from the clamp
- the proximity of metal objects
- the proximity of the operator

EN55013: 1990 specifies a height of 0.8 m for the EUT. EN55014-1:1997 does not specify a height but says "The appliance to be tested is placed on a non-metallic table at least 0.4 m from other metal objects". It is not clear whether this should be interpreted as meaning that the whole cable run should be at 0.4m above the floor. The data shown above are re-arranged in Figure 43 to show the difference between 0.4m and 0.8m height, in an open test lab and in a screened room. There are clearly differences when the height above the floor is changed and not surprisingly this is more marked in the screened room. For the lab environment, all clamps show similar differences with the maximum occurring between 70 MHz and 110 MHz of 1.5dB to 2.5 dB. In the screened room, again all clamps show similar differences with the maximum of 4 dB occurring at 40 MHz. Obviously, the height above the floor should be explicitly stated in test results.

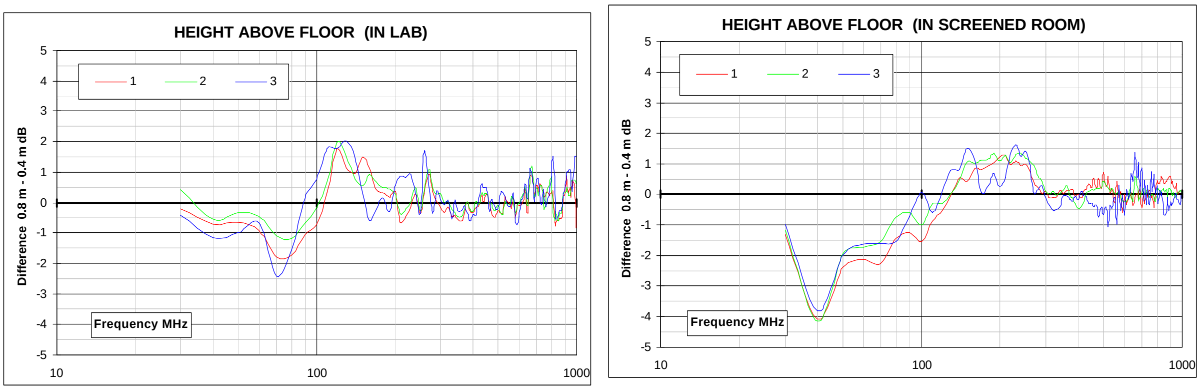


Figure 43 - Difference when height above floor is changed

The output cable appears as a conducting structure coupled with the transmission line impedance of the cable under test. The routing of this cable away from the clamp might be expected to affect the results. Measurements were made in the lab and in the screened room with the output cable suspended at least 0.4 m above the floor and with it lying on the floor. In each case the cable was perpendicular to the mains lead as soon as it cleared the 6dB attenuator.

The results show that in the laboratory the difference between suspending the cable and having it on the floor is insignificant. In the screened room the maximum difference is approximately 0.8 dB. For measurements in a laboratory it appears that if it is more convenient to allow the output cable to rest on the floor then this is acceptable. In a screened room, it is preferable that arrangements should be made to suspend the cable above the floor by at least 0.4 m.

As quoted above, EN 55014-1 requires metal objects to be more than 0.4m from the EUT but says nothing further about the set-up. EN 55013 extends this distance to 0.8m and includes personnel. In order to check these effects, measurements were made with all three clamps, first using the pulley and then pushing the clamps by hand; and then with clamp #2 only to determine the effect of metal objects near the mains lead. A 1 m x 2 m metal sheet was placed parallel to the wire with the long dimension vertical and approximately 1 m from the EUT. The plate was progressively moved closer to the mains lead in steps of 0.2 m from 1.2 m to 0.2 m. Figure 44 shows the result of this experiment. The resonance introduced by this plate at around 65MHz is clearly apparent. The maximum difference rises to 2.7 dB at 0.2 m distance. The second plot shows the variation of difference with respect to distance from the mains lead and indicates that maximum difference at 1.2 m is less than 0.4 dB.

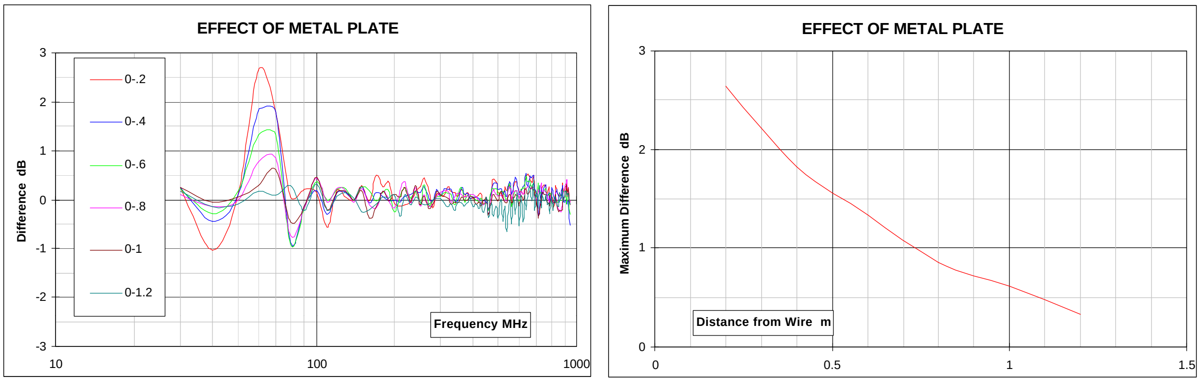


Figure 44 - Effect of proximity of large metal sheet

The size of the metal object has a distinct bearing on the effect and therefore the safe distance from the wire. The distances specified in the standards should be regarded as the limit for *relatively small* objects, probably no larger than 0.4 m^3. Larger objects should be further away and very large objects such as the wall of a screened room at least 3 m away for the effects to be less than 0.5 dB.

Comparing movement of the clamp by hand and by a rope and pulley arrangement, the difference for clamps #1 and #2 were less than 0.5 dB while for clamp #3 it was 1.2 dB at 30 MHz. When hand pushing the clamps attempts were made to keep the body as far away from the front of the clamp and the mains lead as possible. EN 55013: 1990 says that "No metallic object, including a possible other unit of the equipment under test, or any person, shall be closer to the lead or unit than 0.8 m". This is difficult to achieve unless there is an arrangement that moves the clamp without personnel touching it.

We can recommend that using a pulley arrangement is preferable but if hand pushing is used the following precautions are taken: where a signal is within 3 dB of the limit the clamp should be positioned on the peak by hand but the final measurement is made when the person is well away from the clamp and lead. The presence of a person will probably not alter the position of the maximum but it may affect the level. If hand contact is necessary, it should be made at the end of the clamp away from the current probe.

4.3.5. Differences between clamps, and use of the manufacturer’s calibration figures

Test houses will normally expect to use the manufacturers' calibration figures in default of those provided by an accredited calibration laboratory. The figures provided in the documentation accompanying those clamps that were investigated for this project, varied substantially in their quality. Clamp #3 supplied no more than "typical" values and a plot. Clamp #1 was fully calibrated by the supplier with a certificate and quoted accuracy of ±1.5dB, while #2 came with a correction factor curve that was not explicitly traceable to the serial number of the unit. None of the three units' documentation quoted a calibration method.

Figure 45 shows the manufacturer's figures versus the actual insertion loss for each of the units, measured in an open environment following the best practice calibration techniques presented in this guide. It can be seen that there is a quite severe difference in some instances, approaching 6dB in the worst case, though all units can show a divergence of 2dB at some frequencies.

In Figure 46 measurements made with the three clamps are compared in optimum conditions, that is:

- the EUT was measured in a laboratory environment
- the EUT and its mains cable were 0.8 m above a non conducting floor
- 10 clip on ferrites of the type described in 4.2.3 were placed on the mains lead 5.5m from the EUT
- a 6 dB attenuator was connected to the output of the clamp
- the output cable was supported at least 0.6 m above the floor and perpendicular to the mains cable

The plots show the differences between each clamp with respect to each other. The uncertainty limits shown are based on the calculations given in 5.3.2 with the following changes:

- the uncertainty due to the receiver is not included

- the mismatch uncertainty is calculated using a receiver input reflection coefficient of 0.05 (at the input to the 6 dB attenuator)
- the remaining errors are substantially independent for each clamp and because the plots show the difference between each clamp, rather than the difference from the mean, the uncertainty has been multiplied by 2.

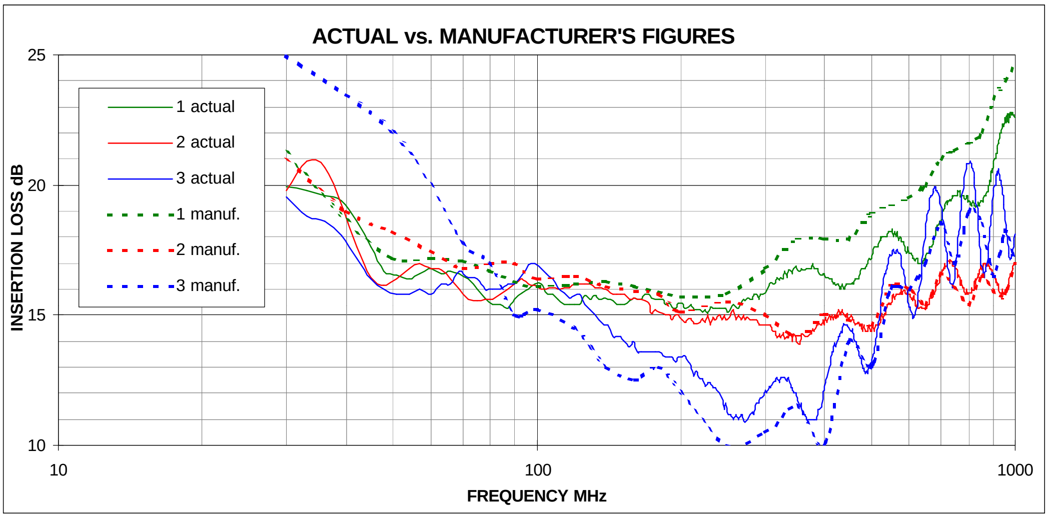


Figure 45 - Comparison of quoted versus measured insertion loss

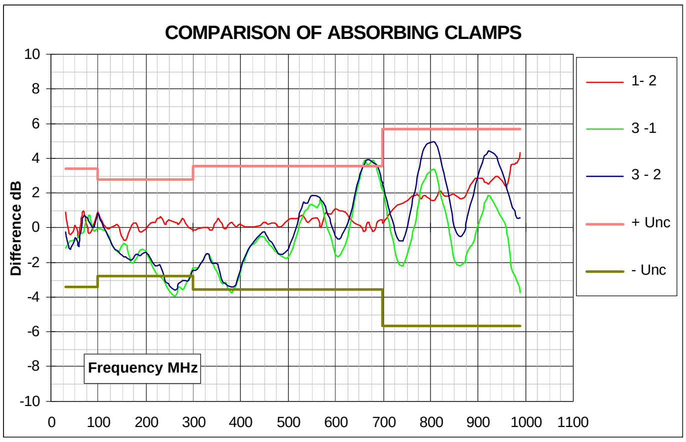


Figure 46 - Comparison of the three clamps under best possible conditions

Comments

Absorbing clamps #1 and #2 agree well over most of the frequency range but start to differ above 700 MHz, possibly due to the position of the mains lead in the clamps or to the clamp impedance, however, the differences remain within the estimated uncertainty.

Absorbing clamp #3 gave results that were significantly different from the other two. The difference shows a ripple that is characteristic of the correction factor and output reflection coefficient for this clamp. No specific explanation was found for this difference and, as can be seen, the estimated uncertainty does not include a contribution to allow for it. It can be speculated that since this is the only clamp with a metal case there is a substantially different coupling with the wire, in the calibration setup, and with the mains lead in the test setup, that is the cause of the variation for this unit.

4.3.6. Directivity

Directivity is the difference between the forward insertion loss - that is, with the clamp used in its usual direction - and the reverse insertion loss, with the current transformer facing away from the source. Since the current transformer is largely bi-directional, the directivity is determined by the attenuation offered by the ferrite absorber material, which of course is dependent on frequency.

Checks were made in the calibration set-up of the directivity of each of the clamps investigated. Figure 47 shows the results. For all clamps the directivity falls to near zero at the lowest frequency; clamp #3 has a greater directivity at 30MHz (3dB) but is lower than the other two at the higher frequencies. This is likely to explain the effect noted in 4.2.3, that loading the far end of the line has a slightly less effect on this unit than on the other two.

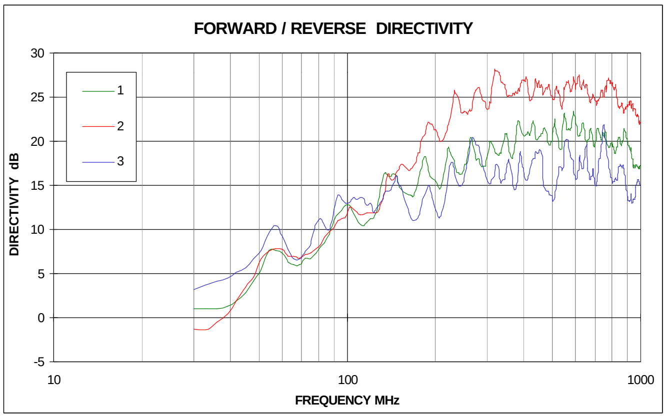


Figure 47 - Directivity of the three clamps

4.3.7. Comparison with OATS results, and use for pre-compliance check

There has been considerable interest in using the absorbing clamp as a partial or complete replacement for radiated emissions tests, though to date no proposal to do this has succeeded in CISPR. Direct correlation between clamp measurements and radiated emissions on an open area test site (OATS) is not possible; reference [17] shows a graph of the extreme values of such a relationship versus frequency for small EUTs, which exhibits a 15 dB range. Nevertheless, as also pointed out in [17], the clamp can be used to provide a peak-detected pre-scan of significant emission frequencies on particular cables, which are then selectively and fully measured on an OATS. This method can offer a reduced total measurement time compared to a full scan on an OATS.

A further advantage of the clamp is its suitability for diagnostic work on EUTs before they are subjected to a full compliance test. Emissions present on different cables can be compared to discover the worst EUT port on which remedial effort can be concentrated. For this kind of work, absolute accuracy is not required and the clamp position need not be varied, but other precautions outlined in this document are advisable for repeatability, particularly the use of a second absorber on the far end of the cable under test, and control of the test layout.

5. Sample uncertainty budgets

5.1. Introduction

This section gives some guidance on the estimation of uncertainty involved in both calibrating and using AMN/LISNs and Absorbing Clamps. The uncertainty budgets are intended only as guidance. Actual contributions to uncertainty are very dependent on the particular equipment used and the layout of systems, particularly in the case of testing where the EUT can be a significant contributor. Test houses are expected to calculate and present their own uncertainty budgets, omitting any consideration of the EUT contribution, although in those cases where the nature of the EUT is known and consistent (such as in manufacturers' own test facilities) this could usefully be included.

The method of calculating the total uncertainty is consistent with widely used practice as outlined in the ISO document "*Guide to the Expression of Uncertainty in Measurement*" [19] and the United Kingdom Accreditation Service (UKAS) document M3003, "*The Expression of Uncertainty and Confidence in Measurement*" [18].

The Expanded Uncertainty, U, for a confidence level of approximately 95% is obtained from:

$$U = 2\sqrt{\sum_{i=1}^{N} c_i^2 u^2(x_i)}$$

Where

$u(x_i)$ are standard uncertainties for the individual contributions, expressed in dB

c_i are the sensitivity coefficients associated with each standard uncertainty.

In all the measurements made during this investigation the effect of contributions to uncertainty have been assessed for their influence on the overall result of the measurement and therefore all sensitivity coefficients have been taken as unity.

The standard uncertainties $u(x_i)$ are obtained from:

- assessed limit values with assumed rectangular probability distribution where the semi range limit is divided by the square root of three,
- uncertainties already expressed as expanded uncertainties where the divisor is two,
- standard deviations where the divisor is one, or
- mismatch uncertainty which has a U-shaped distribution and the semi range limit is divided by the square root of two.

The calculation given above for expanded uncertainty does not take account of any correlation between individual contributions. In practice there will inevitably be some correlation but given the nature of the measurements and the reliability of the estimates made for the magnitude of the contributions a more rigorous treatment of the calculation was not thought to be warranted.

The calculation used for mismatch uncertainty, U_M, is as follows:

$$U_M = 20\log\left(1 \pm |\Gamma_G| . |\Gamma_L|\right)$$

where Γ_G and Γ_L are the Voltage Reflection Coefficients of the source and load respectively.

The expanded uncertainties shown in the following tables are given to two places of decimal, however, in practice it is rarely necessary to quote more than one place of decimal, particularly for testing uncertainties. Since they are intended for guidance, the tables include all sources of uncertainty that might be expected in a typical test or calibration. Some of the factors are related to the experimental investigations reported in this document and these are highlighted. Other factors are determined by the lab's own equipment or set-up and these should be derived for each individual case.

Note that different uncertainty values may be reported for various sub-ranges of the total frequency span of the measurement or calibration. The sub-ranges chosen for the tables reflect the experience of this investigation.

5.2. AMN/LISN

5.2.1. Calibration - impedance

Source of Uncertainty	Divisor	Uncertainty ± % over frequency range:		
		9 to 25 kHz	25 kHz to 15 MHz	15 to 30 MHz
Impedance Measuring System	2	1.0	0.6	2.0
Coax to 3 pin Adaptor	√3	0.05	0.1	0.4
Output 50 ohm load (remote only)	√3	0.5	1.0	2.0
Effect of earth coupling	√3	0.05	0.1	0.3
Repeatability of measurement	1	0.1	0.2	0.3
Combined Standard Uncertainty		0.59	0.71	1.69
Expanded Uncertainty		1.17	1.41	3.37

5.2.2. Calibration - insertion loss

Source of Uncertainty	Divisor	Uncertainty ± dB over frequency range:		
		9 to 25 kHz	25 kHz to 15 MHz	15 to 30 MHz
Measuring System non-linearity	2	0.04	0.02	0.02
Measuring System resolution	√3	0.01	0.01	0.01
Loss of Coax to 3 pin Adaptor	√3	0.01	0.01	0.02
Effect of earth coupling	√3	0.00	0.01	0.1
Mismatch at receiver port	√2	0.02	0.01	0.02
Input voltage at EUT port	√2	0.03	0.09	0.12
Repeatability of measurement	1	0.01	0.02	0.05
Combined Standard Uncertainty		0.03	0.07	0.12
Expanded Uncertainty		0.07	0.14	0.23

For calculation of mismatch uncertainty the following values of VRC were used:

Device / Port	VRC over frequency range:		
	9 to 25 kHz	25 kHz to 15 MHz	15 to 30 MHz
Output of AMN/LISN	0.23	0.05	0.09
Input to measuring system	0.01	0.02	0.03

Comments on calibration contributions

Impedance

Impedance measuring system

The uncertainties given are appropriate to measuring systems that have traceable calibrations which demonstrate that they are within the manufacturer's specification.

Coaxial to 3 pin adaptor

These uncertainties are derived from the measurements made on the back-to-back pair of adaptors. It has been assumed that the impedance error (with respect to 50Ω) is additive for the two adaptors, however, the uncertainty value used is that for the back-to-back pair.

Output 50 W load

This uncertainty only applies to the measurement of the remote impedance and is due to the error in the load used with respect to 50 Ω, a VRC between 0.005 at 9 kHz and 0.01 at 30 MHz has been assumed.

Effect of earth coupling

This uncertainty has been estimated by observing the maximum variation in measured impedance when the earthing arrangements were changed, including the effect of handling the adaptor.

Repeatability of measurement

The values given are the standard uncertainty for 5 repeat measurements which includes disconnection and reconnection of the measuring system.

Insertion Loss

Measuring system non-linearity

The insertion loss of a LISN is normally less than 1 dB so that non-linearity will be low, the increased value below 25 kHz reflects the increase in insertion loss at these frequencies for some models of LISN.

Measuring system resolution

The values given are typical for a system where the range of attenuation is less than 10 dB.

Loss of Coax to 3 pin adaptor

Measurements on a back-to-back pair of adaptors gave a very low insertion loss which is treated as an uncertainty.

Effect of earth coupling

This uncertainty has been estimated by observing the maximum variation in measured insertion loss when the earthing arrangements were changed, including the effect of handling the adaptor.

Mismatch at receiver port

The output reflection coefficient for the LISN are typical values, the input reflection coefficient for the measuring system is usually only achievable if an attenuator of at least 6 dB is included.

Input voltage at EUT port

In the measurement of insertion loss the input is measured as a developed voltage across the actual impedance of the LISN and has no significant uncertainty due to impedance provided the Tee adaptor (e.g. a normal BNC Tee and the 3 pin to coaxial adaptor) is physically small. However, the difference in impedance between the measuring system and the 50Ω load will affect the voltage at the EUT port when these two are exchanged, as the method requires. A reflection coefficient of 0.01 has been assumed for both the 50 Ω load and the measuring system which gives the above uncertainty in the input voltage.

Repeatability of measurement

The values given are the standard uncertainty for 5 repeat measurements which includes disconnection and reconnection of the measuring system.

5.2.3. Tests

The uncertainties given in the following tables have been derived from an analysis of the test data obtained using the surrogate EUT constructed for this project. However, due to the diverse nature of real EUTs and the complexity of the RF coupling mechanisms, these budgets can only be considered as general guidance for the possible values of contributing uncertainties.

Two uncertainty examples are given, one for the use of an AMN/LISN earthed to a vertical ground plane and one with it earthed to a horizontal ground plane.

Horizontal ground plane, 3 cm long low impedance strap, 1 m mains lead at least 10 cm above ground plane

Source of Uncertainty	Divisor	Uncertainty ± dB over frequency range:		
		9 to 25 kHz	25 kHz to 15 MHz	15 to 30 MHz
Insertion Loss of LISN	2	0.07	0.14	0.23
Receiver Level Accuracy	√3	1.5	1.5	1.5
Coupling between LISN and Ground Plane	√3	0.0	0.10	0.5
Coupling between Mains Lead and GP	√3	0.0	0.10	2.0
Coupling between EUT and LISN	√3	0.0	0.10	0.5
Length of Earth Strap	√3	0.0	0.0	0.5
Effect of mains impedance	√3	1.0	0.0	0.0
Mismatch LISN to Receiver	√2	0.1	0.52	0.12
Repeatability of measurement	1	0.30	0.30	0.30
Combined Standard Uncertainty		1.09	0.97	1.56
Expanded Uncertainty		2.17	1.94	3.13

For calculation of mismatch uncertainty the following values of VRC were used:

Device / Port	VRC over frequency range		
	9 to 25 kHz	25 kHz to 15 MHz	15 to 30 MHz
Output of AMN/LISN	0.23	0.61	0.05
Input to Receiver	0.05	0.10	0.30

Vertical ground plane, 30 cm long low impedance strap, 1 m mains lead at least 10 cm from ground plane

Source of Uncertainty	Divisor	Uncertainty ± dB over frequency range:		
		9 to 25 kHz	25 kHz to 15 MHz	15 to 30 MHz
Insertion Loss of LISN	2	0.07	0.14	0.23
Receiver Level Accuracy	√3	1.5	1.5	1.5
Coupling between LISN and Ground Plane	√3	0.0	0.10	2.0
Coupling between Mains Lead and GP	√3	0.0	0.10	1.0
Coupling between EUT and LISN	√3	0.0	0.10	0.5
Length of Earth Strap	√3	0.0	0.0	5.0
Effect of mains impedance	√3	1.0	0.0	0.0
Mismatch LISN to Receiver	√2	0.1	0.52	0.12
Repeatability of measurement	1	0.30	0.30	0.30
Combined Standard Uncertainty		1.09	0.97	3.30
Expanded Uncertainty		2.17	1.94	6.59

For calculation of mismatch uncertainty the following values of VRC were used:

Device / Port	VRC over frequency range:		
	9 to 25 kHz	25 kHz to 15 MHz	15 to 30 MHz
Output of AMN/LISN	0.23	0.61	0.05
Input to Receiver	0.05	0.10	0.30

Comments on test contributions

AMN/LISN Insertion Loss:

This value is obtained from the calibration certificate for the unit and assumes that the insertion loss has been taken into account in the measurements.

Receiver Level Accuracy:

This value is taken from the specification for the receiver. Whilst it would be possible to correct the readings of the receiver, this is not normal practice and calibration serves to confirm compliance with the specification.

Coupling between the AMN/LISN and the ground plane:

All models could be bonded to the horizontal ground plane using a short earth strap of very low impedance. Provided the stand is not used the distance between the AMN/LISN and the ground plane is very similar for all units tested and will not vary significantly from one test to another.

The bonding to a vertical ground plane can vary considerably between units and the distance between the AMN/LISN and the ground plane is less likely to be controlled from one test to another than is the case for a horizontal ground plane. If the AMN/LISN is placed as close as possible to the ground plane the variation between units should not exceed 100 mm but this could still give a difference of ±2 dB.

Coupling between mains lead and ground plane:

While this uncertainty is not specifically a contribution of the AMN/LISN it is as a direct consequence of the design of all the units tested that the mains lead will be close to the horizontal ground plane when it leaves the AMN/LISN. The coupling to the ground plane will vary between units and give rise to uncertainty, particularly at frequencies where a resonance occurs.

In the vertical ground plane configuration the mains lead is less likely to be routed toward the ground plane and therefore the variation in coupling will probably be less.

Coupling between AMN/LISN and EUT

This effect is similar for both configurations, the uncertainty has been based on the assumption that the distance is within 1 cm of the specification requirement.

Length of earth strap

All of the units tested could be easily earthed to a horizontal ground plane with a short earth strap and providing this offers a low impedance, the uncertainty introduced by slightly different lengths will be low.

The likelihood of a long earth strap being used is greater when earthing to a vertical ground plane. While it is possible to arrange for the earthing post to be close to the ground plane by making the panel of the AMN/LISN face the plane, this is not very convenient and will probably increase the uncertainties due to coupling of the mains lead with the plane. The difference between using a 30 cm strap and a 60 cm strap was found to be as much as 15 dB worst case, however the uncertainty should be lower than this for most cases. One of the models tested has an earthing strip on the side panel which provides a very low impedance path, and gives rise to uncertainties similar to the horizontal ground plane case.

Effect of mains impedance

At frequencies up to approximately 25 kHz the isolation between the mains input and the EUT port is significantly lower than at higher frequencies. At low frequencies the effect of the mains impedance on the impedance at the EUT port has to be considered as an uncertainty. The values given for the uncertainty are based on the variations found in practice between the AMN/LISNs tested and not on an analysis of the impedances involved.

Mismatch between the AMN/LISN output and the receiver input

When the AMN/LISN is calibrated for insertion loss it is measured with the output terminated in a good match (VRC < 0.02) but when it is used for testing the receiver input VRC is likely to be considerably higher (> 0.3) if it is used without an attenuator. The mismatch uncertainty is dependent on both the AMN/LISN output impedance, which is a function of the EUT and can vary widely, and the receiver input impedance. The values given in the table are typical. When a receiver is used with no input attenuation its VRC will be substantially worse with a corresponding increase in uncertainty.

Repeatability of measurement

The figures given for repeatability assume that conditions, lead positions, and other variables remain substantially the same and is mainly due to receiver stability. Often the repeatability will be dominated by the stability of the EUT.

5.3. Absorbing clamp

5.3.1. Calibration

Source of Uncertainty	Divisor	Uncertainty ± dB over frequency range:			
		30 to 100 MHz	100 to 300 MHz	300 to 700 MHz	700 to 1000 MHz
Measuring System non-linearity	√3	0.3	0.3	0.3	0.3
Measuring System resolution	√3	0.2	0.2	0.2	0.2
Measuring System noise	√3	0.1	0.1	0.1	0.2
Effect of surroundings	√3	0.7	0.3	0.1	0.1
Effect of wire cross section	√3	0.5	0.5	0.5	0.5
Effect of length of wire	√3	0.3	0.3	0.3	0.3
Effect of fixed absorbers	√3	0.3	0.2	0.1	0.1
Effect of size of reference plane	√3	0.2	0.2	0.1	0.1
Effect of position of wire in clamp	√3	0.1	0.2	0.3	0.6
Effect of coupling to output cable	√3	0.2	0.2	0.2	0.2
Mismatch at wire input	√2	0.23	0.21	0.19	0.18
Mismatch at clamp output	√2	0.15	0.15	0.15	0.15
Repeatability of measurement	1	0.1	0.1	0.1	0.1
Combined Standard Uncertainty		0.66	0.54	0.50	0.59
Expanded Uncertainty (k = 2)		1.31	1.07	1.01	1.19

For calculation of the mismatch uncertainty the following values of Voltage Reflection Coefficient (VRC) were used:

Device / Port	VRC over frequency range:			
	30 to 100 MHz	100 to 300 MHz	300 to 700 MHz	700 to 1000 MHz
Output of Source (10 dB attenuator)	0.02	0.03	0.03	0.03
Input to wire	0.9	0.8	0.75	0.7
Output of Absorbing Clamp	0.6	0.6	0.6	0.6
Input to measuring system	0.03	0.03	0.03	0.03

<u>Comments on calibration contributions</u>

Measuring system non-linearity

This uncertainty is obtained from information on the calibration of the measuring system. If a spectrum analyser is used in sweep mode then the uncertainty must be obtained from a calibration that is performed in sweep mode.

Measuring system resolution

This should be a relatively insignificant contribution to the uncertainty but needs to be considered.

Measuring system noise

If a spectrum analyser is used in max hold mode then the measurement will be offset by half the noise envelope which will be different with the clamp in and out of circuit.. Checks should be carried out to measure the effect of this offset and if relatively small (<0.2 dB) it can be treated as an uncertainty. Whilst corrections can be made to allow for the noise offset this is not recommended, steps should be taken to minimise the effect of signal noise.

Effect of Surroundings

The uncertainties given in the example are for a laboratory environment where the presence of large metal objects, such as steel used in the construction of the building RSJs, cannot be avoided. However, all other measures are taken to ensure that metal objects and the operator are at least 1 m from the clamp and wire. If measurement are made in an area free of large metal objects to a distance of at least 2 m then this uncertainty can be reduced to ±0.3 below 300 MHz and ±0.1 above this frequency.

Effect of Wire Cross Section

Since CISPR 16-1 gives a range for the cross sectional area of the wire different calibration laboratories could use different sizes of wire. The uncertainty is derived from comparing results for a 2.5 mm^2 wire and a 1 mm^2 wire.

Effect of length of wire

This also is not clearly defined and therefore gives rise to an uncertainty. The value given was obtained from measurements made with different lengths of wire. The effect will be considerably more if fixed absorbers are not used.

Effect of fixed absorbers

CISPR 16-1 recommends that a second clamp is used as a fixed absorber. The uncertainty given represents the difference between using a clamp and the use of clamp-on ferrites as an alternative.

Effect of size of reference plane

The reference plane suggested in CISPR 16 is the wall of a screened room or a 2.5 m x 2.5 m metal sheet. It is more convenient to construct a reference plane from two sheets with dimensions of 2 m x 1 m giving a 2 m x 2 m sheet. The uncertainty represents the difference found when the sheet size is increased.

Effect of position of wire in clamp

Two of the clamps tested were provided with guides that restricted the wire movement to within ±5 mm of the centre position, for the third clamp this is approximately ±10 mm. The uncertainty given is appropriate to controlling the position with an additional guide to within ±1 mm.

Effect of coupling to output cable

The uncertainty given is based on the output cable being fitted with two or more clip on ferrites at each end of the cable and the cable being perpendicular to the wire.

Mismatch at wire input

The uncertainties given are for typical reflection coefficients for the wire input and the 10 dB attenuator, which includes the attenuated match of the source. The mismatch uncertainty will be reduced if an attenuator with lower VRC is used.

Mismatch at clamp output

Again this is for typical values of the clamp output and the 6 dB attenuator in combination with the match of the measuring system input attenuated by 6 dB.

Repeatability of measurement

The value given is a typical standard uncertainty obtained when the whole measurement process is repeated 5 times (standard deviation divided by the square root of 5) .

5.3.2. Use in a normal laboratory environment

Source of Uncertainty	Divisor	Uncertainty ± dB over frequency range:			
		30 to 100 MHz	100 to 300 MHz	300 to 700 MHz	700 to 1000 MHz
Correction Factor of Absorbing Clamp	2	1.31	1.07	1.01	1.17
Receiver Level Accuracy	√3	1.5	1.5	1.5	1.5
Effect of surroundings	√3	0.7	0.3	0.1	0.1
Effect of mains lead cross section	√3	0.0	0.0	0.0	0.0
Effect of position of lead in clamp	√3	0.1	0.2	0.3	0.6
Effect of length of mains lead	√3	0.3	0.2	0.1	0.1
Effect of position of fixed absorber	√3	0.3	0.3	0.3	0.3
Effect of coupling to output cable	√3	0.2	0.2	0.2	0.2
Effect of clamp impedance	√3	0.0	0.0	0.5	1.0
Mismatch at clamp output	√2	0.51	0.75	0.98	1.44
Repeatability of measurement	1	0.3	0.3	0.3	0.3
Combined Standard Uncertainty		1.28	1.23	1.32	1.65
Expanded Uncertainty (*k* = 2)		2.56	2.45	2.64	3.86

For calculation of the mismatch uncertainty the following values of Voltage Reflection Coefficient (VRC) were used, assuming no attenuator between clamps and receiver:

Device / Port	VRC over frequency range:			
	30 to 100 MHz	100 to 300 MHz	300 to 700 MHz	700 to 1000 MHz
Output of Absorbing Clamp	0.6	0.6	0.6	0.6
Input to measuring system	0.1	0.15	0.2	0.3

5.3.3. Use in a screened room

Source of Uncertainty	Divisor	Uncertainty ± dB over frequency range:			
		30 to 100 MHz	100 to 300 MHz	300 to 700 MHz	700 to 1000 MHz
Correction Factor of Absorbing Clamp	2	1.31	1.07	1.01	1.19
Receiver Level Accuracy	√3	1.5	1.5	1.5	1.5
Effect of surroundings	√3	5.0	1.0	0.2	0.1
Effect of mains lead cross section	√3	0.0	0.0	0.0	0.0
Effect of position of lead in clamp	√3	0.1	0.2	0.3	0.6
Effect of length of mains lead	√3	0.3	0.2	0.1	0.1
Effect of fixed absorber	√3	0.3	0.3	0.3	0.3
Effect of coupling to output cable	√3	0.3	0.2	0.2	0.2
Effect of clamp impedance	√3	0.0	0.0	0.5	1.0
Mismatch at clamp output	√2	0.51	0.75	0.98	1.44
Repeatability of measurement	1	0.3	0.3	0.3	0.3
Combined Standard Uncertainty		3.13	1.35	1.32	1.65
Expanded Uncertainty (*k* = 2)		6.26	2.69	2.65	3.30

<u>Comments on test contributions</u>

Clamp correction factor

This value is obtained from the calibration certificate for the absorbing clamp and assumes that the results have been corrected.

Receiver level accuracy

This value is taken from the specification for the receiver. Whilst it would be possible to correct the readings of the receiver, this is not normal practice and calibration serves to confirm compliance with the specification.

Effect of surroundings

The uncertainty for normal laboratory conditions apply to a laboratory area that has some metal framework in its construction and the possibility of screened rooms being within 2m of the test setup. If measurements are made without these factor being present then the uncertainty below 300 MHz could be reduced, probably to half the values given. The uncertainties applicable to a screened room would need to be increased for unlined rooms but it would be difficult to quantify this, the recommendations given in 4.3.3 should be followed so that uncertainties for measurements near to the test limits can be reduced.

Effect of mains lead cross section

This is not considered to be a contribution to the test uncertainties since the mains lead is part of the EUT.

Effect of position of lead in the clamp

This effect was found to vary according the model of clamp. The values given in the budget represent the clamps that are provided with guides that keep the lead approximately in the centre of the clamp.

Effect of length of mains lead

The length of the mains lead is specified in the appropriate EMC standards but only as “about” 6m. Varying this length will have some affect but will be relatively small if fixed absorbers (or a second clamp) are placed on the lead, as recommended by the standard. The values given in the tables apply to the use of a fixed absorbers.

Effect of the position of fixed absorbers

The distance between the EUT and the fixed absorbers is only a recommended distance so that some variation is possible. The values given are appropriate to positioning the fixed absorbers within 40 cm of the specified distance.

Effect of coupling to output cable

Provided the output cable is perpendicular to the mains lead the effect of any coupling was found to be not greater than the values given in the tables.

Effect of clamp impedance

At frequencies up to 300 MHz the impedance presented by the clamps to the EUT conforms with CISPR 16 requirement for the three clamps tested and therefore there is no uncertainty applicable. At frequencies above 300 MHz the reactive component of all three clamps does not meet CISPR requirements (see 4.1.2). The consequence of this is that different models of clamp will give different values for the disturbance power due to their different impedance. The uncertainty this introduces will be dependent on the source impedance of the disturbing source. The values given in the table are judgements based only on the differences found between the three clamps tested and not a study of the physics of the phenomenon.

Mismatch at clamp output

This uncertainty will vary considerably with frequency and the characteristics of the measuring receiver. The values given are typical values applicable for when there is no attenuator at the clamp output (if an attenuator is used the uncertainties will be similar to those given in calibration example table 5.3.1). However, in some cases the uncertainty could be considerably greater, in particular if the receiver is used with no input attenuation.

Random

The values given for random contributions are typical standard deviations that would be applicable to making only one measurement. If necessary this contribution could be reduced to an insignificant value if repeat measurements are made. This would normally be done when an emission is measured that is close to the specification limit.

6. Comparing calibrations by different laboratories

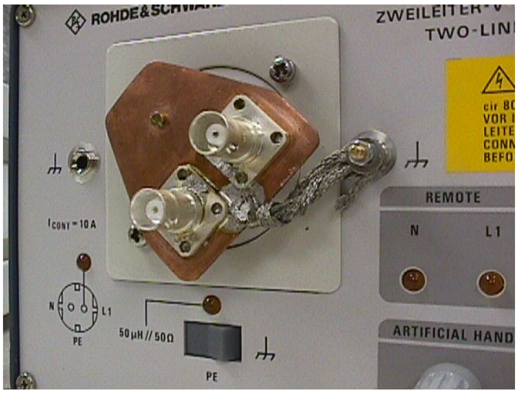
Calibrations of two absorbing clamps and one AMN/LISN were made by both the participating organisations, Schaffner-Chase EMC and the National Physical Laboratory. The calibrations were made using the best practices that had been established during the investigation stage of the project. The results were then compared to establish any variances and to see if the uncertainty estimates were reasonable and valid.

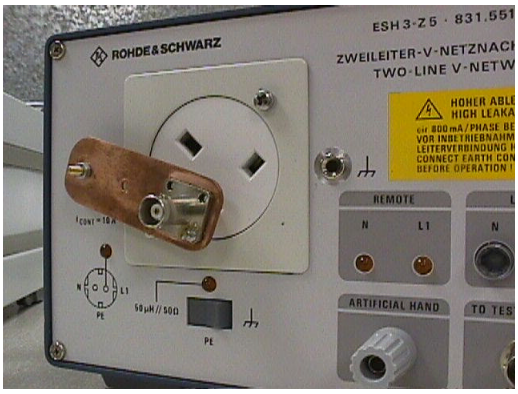
6.1. AMN/LISNs

Unit #2 was calibrated for impedance and insertion loss under the following conditions:

- The adaptors used were manufactured by each laboratory: NPL used a three pin adaptor with an earthing strap to the chassis earth socket (Figure 48 (a)); Schaffner-Chase used a single pin adaptor with a plate to the chassis earth socket (Figure 48 (b))
- The impedance was measured with the mains input open circuit
- The insertion loss was measured according to 3.3.3 from effectively a zero impedance source
- Similar impedance analysers (HP4192A/94A) and vector network analysers (HP8753A) were used in each laboratory

The results of the measurements are shown in Figure 49 and Figure 50.



(a)


(b)

Figure 48 - The adaptors used: (a) NPL, (b) Schaffner-Chase

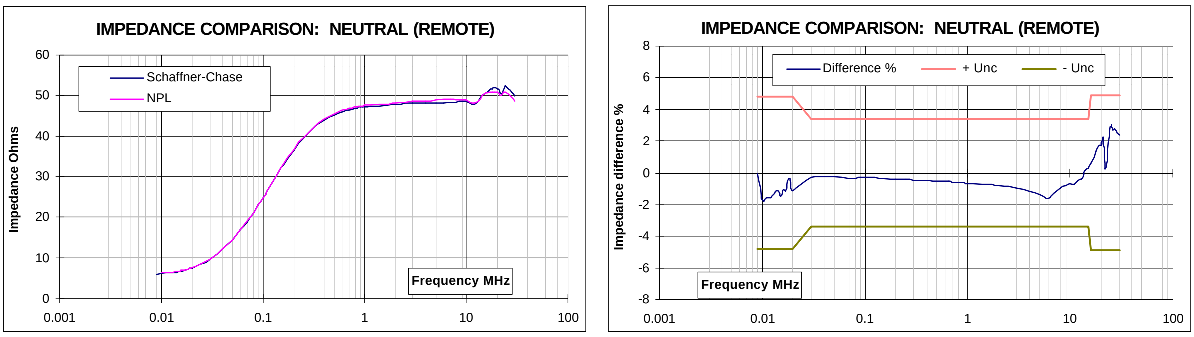


Figure 49 - Neutral line input impedance: comparison NPL - Schaffner Chase

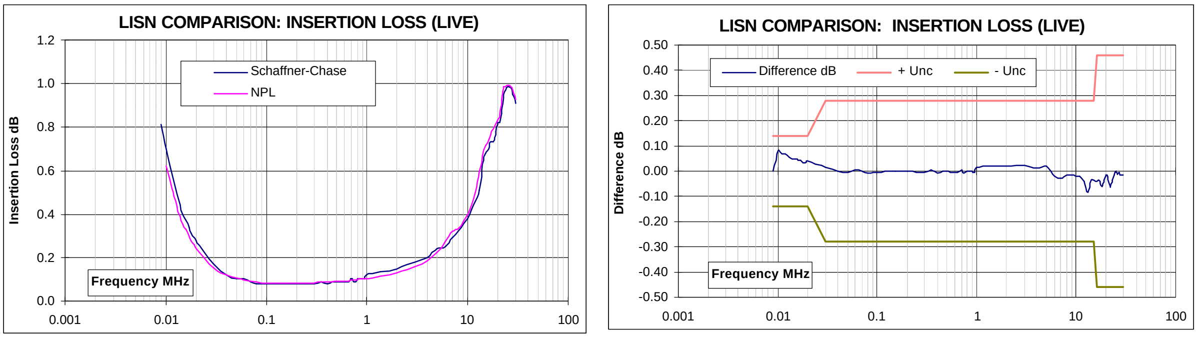


Figure 50 - Live line insertion loss: comparison NPL - Schaffner Chase

6.1.1. Observations

The results show good agreement between the laboratories, the results for the other lines not shown here were very similar. The differences in impedance are generally less than 2% which could be accounted for in the uncertainty of the measuring instruments alone. Since the measurements were made with different designs of adaptors it is clear that these are not a significant contribution to uncertainty. The assumptions made about the symmetry of a back-to-back pair referred to in 3.3.1 are supported. The difference in insertion loss measurements are all less than 0.1 dB which is insignificant in the context of other uncertainties involved in the use of LISNs.

6.2. Absorbing clamps

Absorbing clamps #1 and #2 were calibrated for insertion loss under the following conditions.

- The measurements were made using the procedure as recommended by CISPR 16-1:1993
- The wire cross section was 1.5 mm^2
- The wire was held in the centre of the clamp using an additional guide
- Ten clip on ferrites (Fair-Rite 2643-164151) were used on the wire at 4 m from the reference plane
- The output cable had ferrites at both ends and was perpendicular to the wire
- The measurements were made in an open area above a concrete ground
- The reference plane size was 2m x 2m
- A 6dB attenuator was used at the clamp output
- Spectrum analysers in max hold mode were used at both laboratories

The results of the measurement are shown in Figure 51. The first graph shows the measured insertion loss for each absorbing clamp and each laboratory; the second shows the difference between each laboratory with the estimated uncertainty for each laboratory summed.

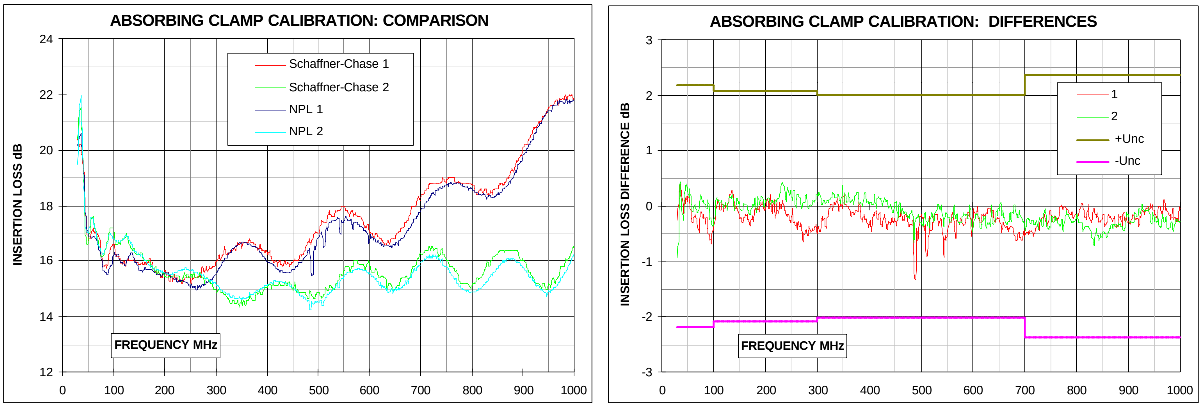


Figure 51 - Clamp insertion loss: comparison NPL - Schaffner Chase

6.2.1. Observations

Again the results show good agreement between the two laboratories for both models of clamp. The differences are generally less than 0.5 dB with the occasional spike up to 1 dB different but all within the combined estimated uncertainty for both sets of measurements.

6.3. General conclusions

The results for both the AMN/LISN and the clamps demonstrate that the calibration techniques are reproducible between laboratories within the estimated uncertainty. It would, though, be inappropriate to conclude from this result that the uncertainties could be reduced since both laboratories used substantially the same procedure and equipment configuration so that systematic differences were minimised.

7. References

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