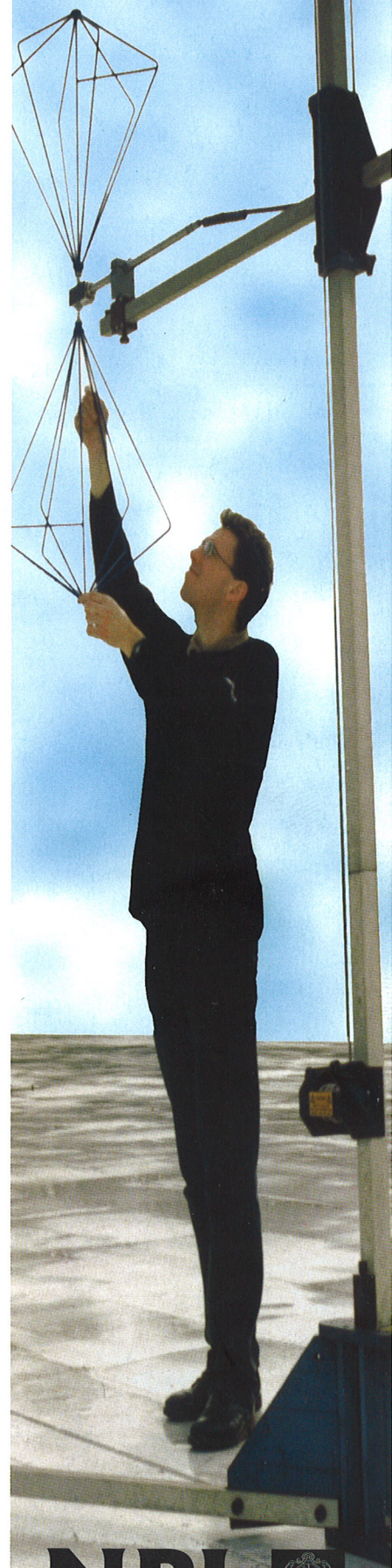


*Measurement  
Good Practice Guide*

**Calibration and Use of  
EMC Antennas**

*M.J. Alexander*

**No. 4**



**NPL**   
National Physical Laboratory

# Measurement Good Practice Guide No 4

## Calibration and Use of EMC Antennas

Martin J Alexander

National Physical Laboratory

**Abstract:** This document addresses the calibration of EMC antennas in the frequency range 30 Hz to 40 GHz. Guidance is given on the assessment of uncertainties in their use for EMC radiated emission measurements. The National Physical Laboratory operates calibration services for the measurement of antenna factors of monopole, loop, dipole, biconical, log-periodic, bilog and horn antennas which are used for emission testing on open area test sites and in fully anechoic chambers.

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The objectives of *Competing Precisely* are:

- to demonstrate the contribution accurate measurement can make towards improving industrial competitiveness and compliance with standards and regulations
- to support the development and application of good measurement practice by providing a practical 'toolkit' that companies can use to improve measurement quality
- to back this up with access to local and national sources of measurement expertise and services.

For more information on *Competing Precisely*, contact Gareth Francis on 0181-943 6329 (e-mail: [gmf@npl.co.uk](mailto:gmf@npl.co.uk)) or by post at National Physical Laboratory, Teddington, Middlesex TW11 0LW.

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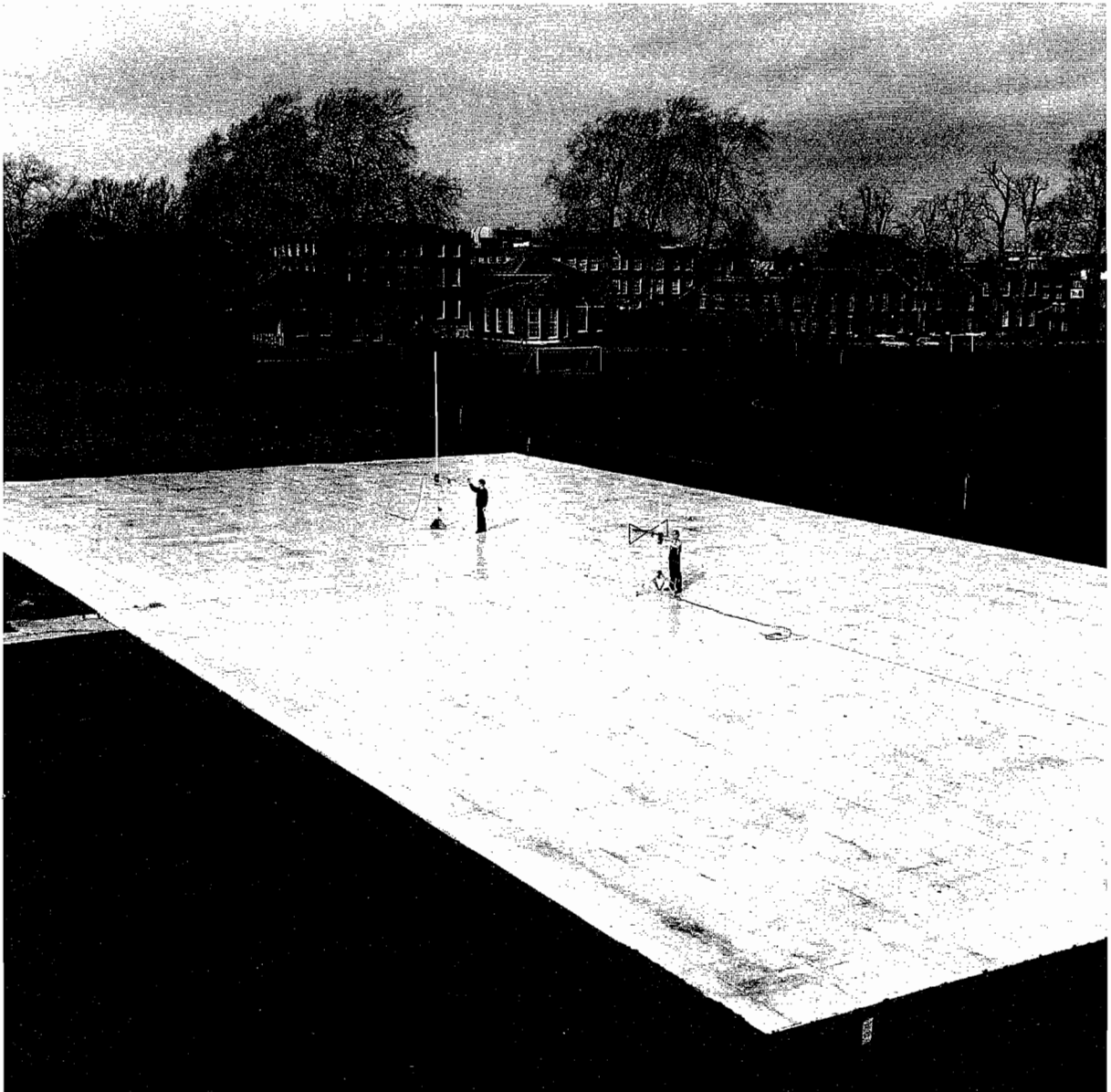


**Plate 1: 60 m x 30 m sheet steel ground plane on the NPL site**

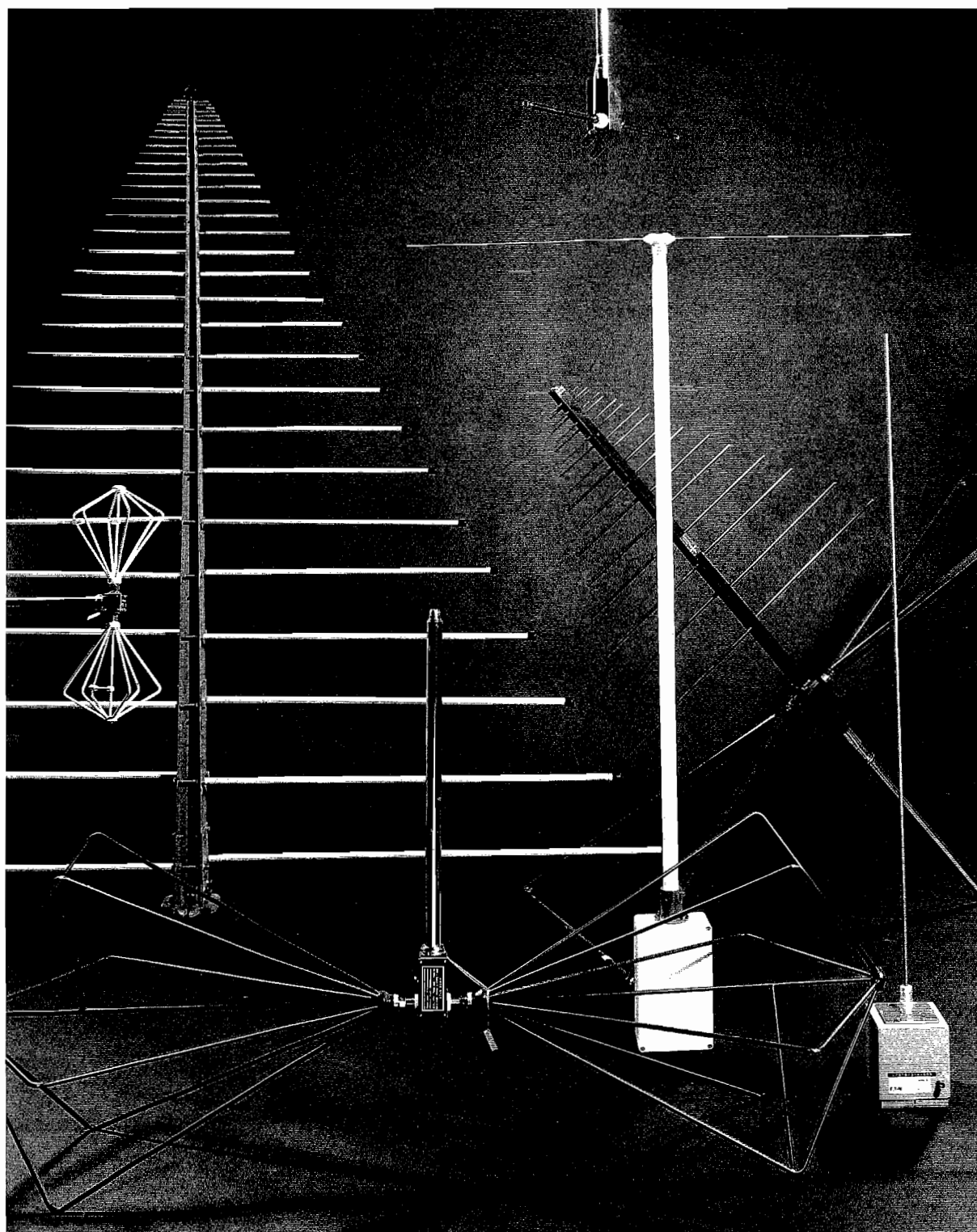


**Plate 2: Ensemble of EMC Antennas: Biconical, LPDA, bilog, rod, standard dipole**

# 1. Introduction

## 1.1. Scope

This document addresses the calibration of EMC antennas in the frequency range 30 Hz to 40 GHz. Guidance is given on the assessment of uncertainties in their use for EMC radiated emission measurements. NPL operates a calibration service for the measurement of *antenna factors* of monopole, dipole, biconical, log-periodic (LPDAs), bilog and horn antennas which are used for emission testing on *open area test sites* (OATS) and in *fully anechoic* chambers.

Conical log-spiral, rod and loop antennas which are mainly used in testing to Defence Standards are also calibrated at NPL. The use of antennas at a distance of 1 m from the emitter in screened rooms is a special case, for which calibrations and measurement uncertainties are addressed.

## 1.2. The National Physical Laboratory

NPL's mission is to satisfy the nation's current and future needs for measurement standards; to seek new ways in which the improved use of measurement can contribute to UK competitiveness, and to serve customers world wide with an expanding range of high quality scientific services.

We aim to fulfil this mission by:

- playing a full and leading role in world metrology through the work of the International Bureau of Weights and Measures (BIPM), particularly the increasingly important series of international comparisons being organised by its Consultative Committees. NPL is also committed to the work of international standardisation bodies, to EUROMET and to the key European standards organisations.
- maintaining and improving a diverse range of some 200 calibration and testing services (e.g. mass, frequency, resistance, antenna gain) to meet the needs of industrial and other users in the UK as well as customers overseas for whom NPL may be able to offer a capability not available from their own standards laboratory;
- concentrating more than ever before on best practice, technology transfer and the solving of industrial measurement challenges by working through more than 40 clubs and

specialised technical forums, issuing guidance notes and reports, conducting contract research and providing seminars, workshops, and training.

This Guide is an example of technology transfer and good practice support provided by NPL. It provides a fitting introduction to the NPL calibration and testing facility that includes one of the world's best free field antenna ranges, using a 60 m by 30 m contiguously welded sheet steel ground plane.

This Guide is an updated version of the NPL "Handbook on EMC Antenna Calibration and Uncertainties", 1995.

## 2. Summary

Measurements of radiated emissions in the frequency range 30 MHz to 1 GHz and above is a requirement of Electromagnetic Compatibility (EMC) standards. EMC is the ability of electrical equipment to coexist without mutual electromagnetic interference. The European Community EMC Directive<sup>1</sup> broadened the scope for EMC testing. The main reason for improving the methods of calibrating antennas was to reduce the uncertainty of EMC measurements, which will enable industry to save resources by specifying tighter manufacturing tolerances to achieve the required EMC protection. One component of the uncertainty budget for an emission test is the performance of the test site as gauged by the measurement of *Site Attenuation* using a pair of antennas.

Current standards for EMC emission testing require measurements to be made more accurately than in the past. For example the current CISPR Document 16<sup>2</sup> now requires antenna factor to be measured to an uncertainty of  $\pm 1$  dB or less. This contrasts with the  $\pm 2$  dB which is commonly accepted from antenna manufacturer's at the time of writing this document. Calculations of uncertainty of measurement are required in Test Reports produced by EMC laboratories which are accredited under an internationally accepted accreditation scheme. This requirement is spelled out in ISO/IEC Guide 25 and in EN 45001<sup>3</sup>. Uncertainty calculations should be performed in accordance with the requirements in the ISO Guide<sup>4</sup>. The UK Accreditation Service, UKAS, has published document NIS81<sup>5</sup> which gives guidance on the calculation of uncertainty in the specific case of EMC, in which the magnitudes of uncertainty are typically larger than in most applications in RF & Microwave metrology. An example of an uncertainty budget for the NPL calculable standard dipole antenna is given in Ref. 6.

Recently CISPR documents have made more positive statements on the importance of uncertainties of measurement. Notably, EuroNorm prEN 50222 (IEC 1996) states that limits have been set taking into account typical uncertainties and that measurement uncertainty must be evaluated and made available on request. It is hoped that, as the contributions to the uncertainty of emission measurements become better understood and quantified, the staff of more laboratories will be encouraged to include all known contributions in their uncertainty budgets. This will put the calculation of uncertainties on a more scientific footing. It will help to ensure that European trading partners are offering their services on equal terms.

This Guide is concerned with the minimisation of the uncertainty contribution of the antenna in EMC emission testing. A working group of CISPR/A is expected to complete a review by the end of 1997 of methods of antenna calibration and site evaluation in the frequency range 30 MHz to 1 GHz. The decisions of this group will be incorporated into CISPR Publication 16 and are reflected in this Guide.

When assembling an uncertainty budget for an emission test, the antenna contribution is not merely the uncertainty of measurement of antenna factor stated in the certificate of calibration. This could be  $\pm 0.2$  dB. Because of the interaction of the antenna with the emission test environment there may be other uncertainty contributions which amount to several decibels. Whilst some systematic errors are amenable to correction, others would require costly characterisation of the antenna and are usually left as uncertainty components. In practice the total uncertainty contribution of an antenna in an EMC emission test can economically be kept to less than  $\pm 2$  dB. A detailed calibration certificate, such as that from NPL, quantifies the main contributions.

Emission testing on OATS is performed to a prescription laid down by CISPR. The receiving antenna is set 10 m away from the equipment under test (EUT) - the FCC uses 3 m. The antenna is scanned in height in order to avoid destructive interference between the direct and ground reflected signals. The maximum signal in the height scan range 1 m to 4 m is noted. This method was adopted because of the omni-directional properties of practical antennas for this frequency range: a well defined ground plane makes the measurement more reproducible. However, from a metrology point of view the ground plane is the cause of several sources of uncertainty. This is explained in Appendix 1.

In order to reduce the uncertainty contribution of the antenna to the measured field strength it is necessary to understand the emission test method and the properties of the antenna. The height above ground of the maximum signal will vary with frequency. There are three

properties of the antenna which affect its output voltage, in response to a field at a pre-defined distance from the EUT. First, the antenna factor varies with height. Second, the radiation pattern affects the proportions of signal received directly from the EUT and via reflection from the ground plane. Third, the *phase centre* of LPDAs changes with frequency. Descriptions of these properties are further developed in Section 4.

The output voltage of the antenna is related to the strength of the field in which it is immersed by the antenna factor (AF). When calibrating the antenna one could argue that its gain, or antenna factor, should be measured for every *height maximum* at every frequency and polar direction (see *boresight*) because no two antenna factors will be the same. The more practicable solution is to measure an “optimum” antenna factor and to account for the variations caused by these three properties as uncertainty terms. The optimum AF is a single value to be used regardless of measurement geometry, including phase centre. In practice the optimum AF is the *free-space antenna factor*. By default EMC antennas are calibrated in their *boresight* direction.

Mutual coupling of the antenna with the ground plane can affect the measured antenna factor by several decibels. This effect is ignored for broadband antennas by the ANSI standard for the calibration of EMC antennas<sup>7</sup>, which has been adopted as the model in CISPR Document 16 up to the 1996 edition. It recommends a method of calibration that includes significant ground coupling in the antenna factor. In order to improve upon this method, NPL has developed new methods of measuring the free-space antenna factor. This has been made possible by the development of the NPL calculable standard dipole antenna<sup>6</sup> which is accurate to better than  $\pm 0.2$  dB over a broad frequency band.

Some antenna manufacturers distinguish, in their certificates of calibration, between antenna factors for measurements at 3 m distance and at 10 m distance. This distinction is based on the premise that measurements made in the near-field of an EUT require an antenna that has been calibrated in the near-field of a source antenna. In contrast CISPR/A is reviewing the idea that the appropriate calibration of antennas for emission testing is the free-space antenna factor and that this applies equally to a distance of 3 m as it does to 10 m. This is the position taken by NPL which is currently studying the uncertainties in the use of the two types of antenna factor for 3 m measurements, see Appendix 3.

There are many proprietary models of antenna which have undesirable, but avoidable, properties in addition to the less than ideal intrinsic properties referred to above. These are balun-imbalance in tuneable dipole and biconical antennas, and resonances in LPDAs. These

properties can be unstable, depending on cable layout and usage of the antenna. NPL has developed tests to determine approximately the additional uncertainties that such antennas will introduce when used for emission testing. Fortunately there are commercial models available which are largely free of such defects. It is to be hoped that as the EMC community becomes aware of the disadvantages of using unsatisfactory antennas they will be phased out of use.

Test houses can obtain traceability of antenna factor to national standards by self-calibrating an antenna through substitution against a transfer standard which has been calibrated at an accredited laboratory. However the test house needs to be aware of the requirements for a high quality test site and of the pitfalls they may encounter in the calibration of antennas: for traceability to be claimed it is necessary to have the calibration method approved by NAMAS<sup>9</sup>. This is explained more fully in Section 6.

This Guide is aimed at technical users of antennas who wish to get the best out of a traceability exercise, particularly when using the services offered by NPL, and who wish to minimise the uncertainties of their radiated emission measurements. Typical uncertainties in the use of EMC antennas are included in the text. Allied services at NPL handle calibrations of field probes over the frequency range 30 Hz to 40 GHz, which are used to test for field uniformity in EMC immunity tests.

### **3. The role of a Standards Laboratory in EMC antenna calibration**

The role of a standards laboratory in the reduction of uncertainties in radiated emission testing is twofold. First, to develop a method for measuring an optimum value of antenna factor at each frequency that will result in the minimum uncertainty of measurement in an emission test. Second, to evaluate the properties of the antennas to establish the uncertainty limits attributable to each characteristic that causes the antenna factor to vary from its ideal value during an emission test. The ideal value is that which gives the true E-field strength for the measured output voltage of the antenna. The evaluation of antenna characteristics requires expertise and a high quality site to determine precise uncertainty limits for each characteristic. Unrealistically high limits will unacceptably increase the overall uncertainty of an emission test. Refer to Section 4.

OATS which are designed for radiated emission conformance testing may not meet the stringent requirements required for antenna calibration. An antenna range specifically for the calibration of EMC antennas was built at NPL, the UK's national standards laboratory. It is

described in Section 7. This site is widely regarded throughout Europe as a National Standard Site. The significance of this is that measurements on other sites can be compared with measurements on a standard site which is known to approximate very closely to the *ideal site*.

Two distinct methods of testing are 1) on a 10 m OATS employing height scanning of the receive antenna and 2) in a fully lined anechoic chamber. Some anechoic chambers have a ground plane on the floor instead of absorber - for the purposes of this article such facilities will also be treated in the same way as an OATS. NPL is examining improved methods of emission testing and this includes investigation of the properties of absorber lined rooms.

With the introduction of improved absorbing materials for anechoic chambers, their use for emission testing looks very promising. The intended CISPR acceptability criterion for site imperfections is  $\pm 1$  dB, CISPR 16-1<sup>2</sup> Annex M. Calculations suggest that even if this were increased to the overall CISPR criterion of  $\pm 4$  dB to allow for wall reflections, the overall uncertainty of an emission test in a fully anechoic 3 m chamber compares favourably with the overall uncertainty on a 10 m OATS. This is because no height scanning is involved and the three sources of antenna uncertainty, referred to in Para. 5 of Section 2, disappear (distance to phase centre can be corrected for). Just as important is the fact that the metrology is more rational because only the direct emission is being measured and not an unwanted signal from the ground, this point is amplified in Section 4. The appropriate calibration of antennas for use in fully anechoic chambers is a measurement of their *free-space AFs* - see Section 8.1. The acceptability of the use of anechoic chambers as "alternative test sites" is under discussion within CISPR. A draft standard for the use of Fully Anechoic Chambers was issued to National Committees in November 1996 by CENLEC SC210A/WG4. For completeness, specification limits should be revised for measurements made in chambers and in GTEM cells.

Methods of antenna calibration developed at NPL are fully compatible with the methods recommended by the standards making bodies, recognising that the purpose of such calibrations is to minimise the measurement uncertainties of emission tests done in the manner laid down by these standards. The method<sup>7</sup> adopted by the standards bodies using height scanning was a practical solution to the variation in quality of ground planes on different sites. The reduction in uncertainties achievable by this method is limited. NPL has been able to improve on this method because its ground plane is of a proven high quality. Further information on the evolution of the EMC measurement services at NPL are given in Refs. 10 and 11.

## 4. Uncertainties in the use of antennas

### 4.1. Antenna related uncertainties in emission testing

The uncertainty associated with the measurement of antenna factor is quoted in all calibration certificates. Ref. 7 gives an example of an uncertainty budget, showing how the total uncertainty has been calculated.

Additionally there are uncertainties associated with the method used for emission testing. These have been extensively researched at NPL and techniques have been developed for calibrating antennas that give the lowest overall measurement uncertainty for a given method of emission test. The three variable properties of an antenna introduced in Section 2 are now quantified as uncertainty terms that are additional to the uncertainty given foremost in the calibration certificate for antenna factor.

The first is the variation of antenna factor with height in the height scan range 1 m to 4 m. This can be as much as 6 dB for a horizontally polarised resonant dipole antenna at 30 MHz, see Fig. 1. The effect is much smaller for vertical polarisation and can generally be ignored for heights above 0.4 wavelengths, see Fig. 2. For a horizontally polarised biconical antenna it is typically 1.8 dB above 55 MHz, see Fig. 3. NPL has developed a method to halve this uncertainty, as explained in Appendix A1.4.

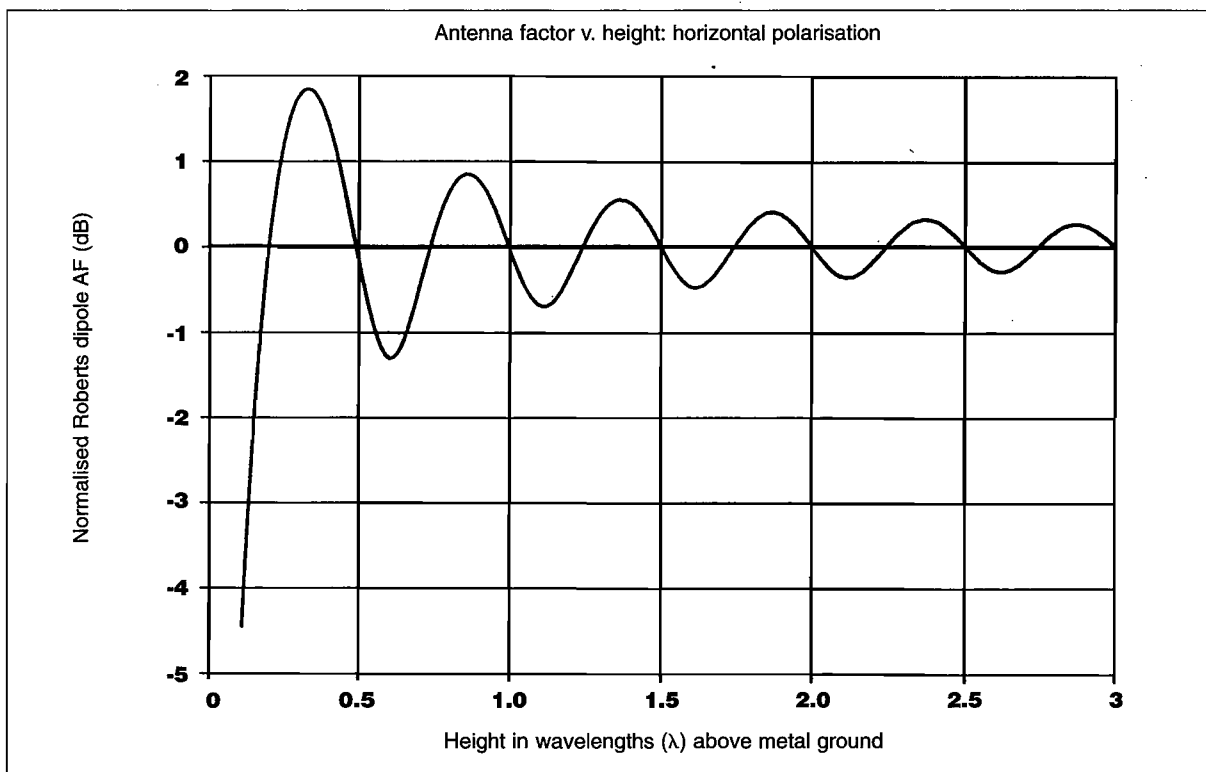


**Figure 1:**

**Variation of AF with height for a horizontally polarised resonant dipole antenna**

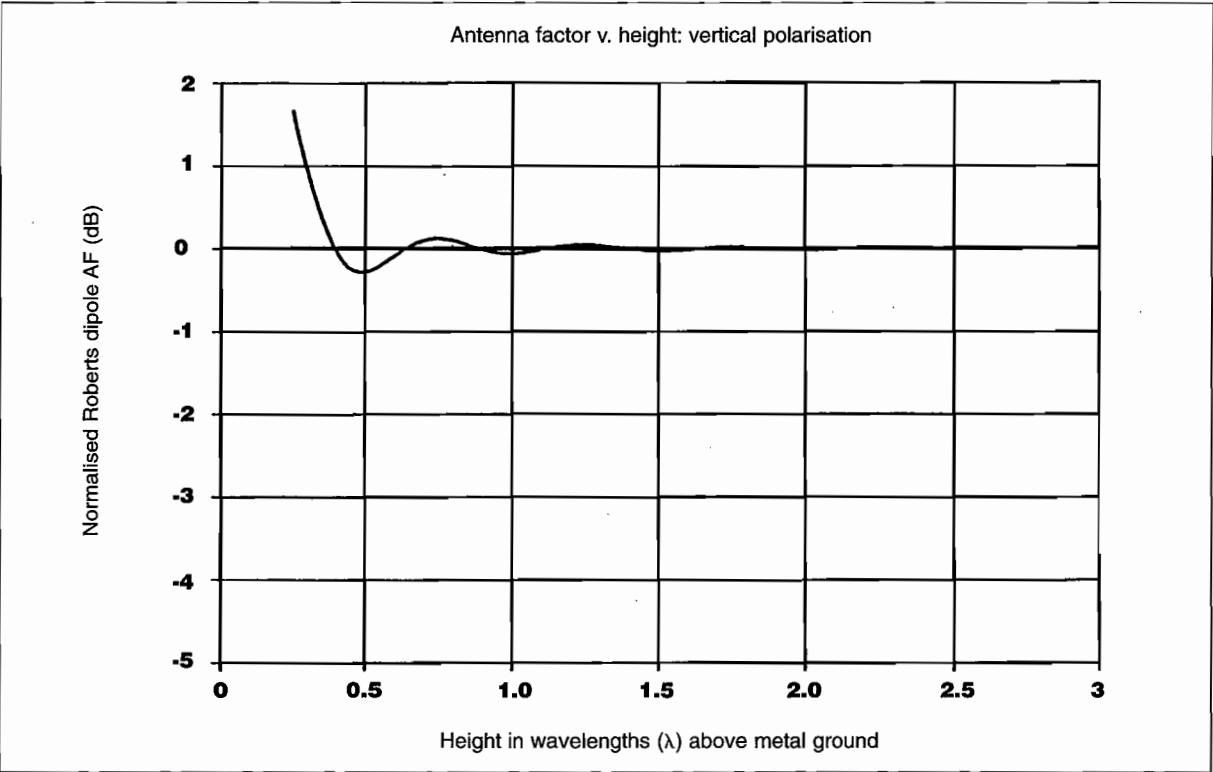


**Figure 2:**  
**Variation of AF with height for a vertically polarised resonant dipole antenna**

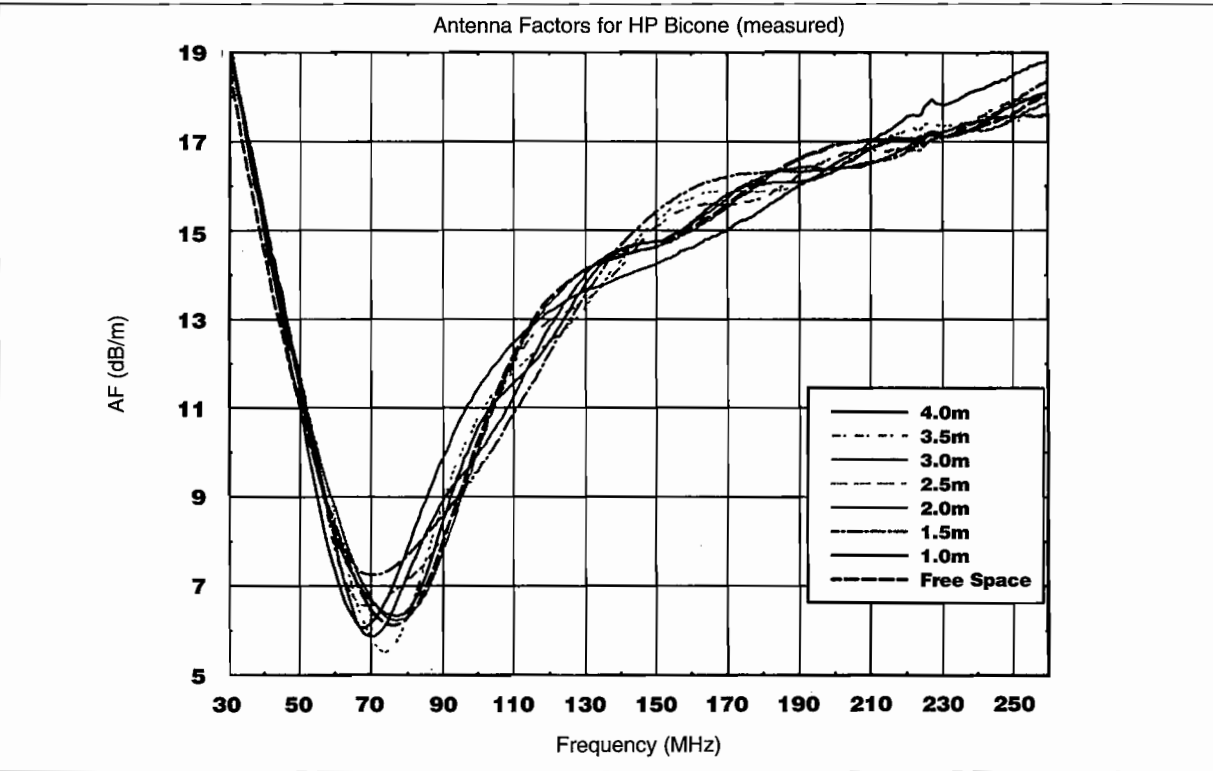


**Figure 3:**  
**Antenna factor measured at heights 1 - 4 m every 0.5 m, and in free-space**

The second uncertainty term arises from the directivity of the antenna. Antenna factor is measured for the boresight direction of the antenna. When a vertically polarised dipole or biconical antenna is scanned in height above a ground plane the received signal is reduced because the EUT is no longer in the boresight direction. This is especially the case for an LPDA (any polarisation) for which this uncertainty term can be as much as + 2 dB on a 3 m OATS, ie the measured signal is 2 dB less than would be measured by a dipole antenna.

The third uncertainty term arises from the variation of *phase centre* with frequency of a LPDA. This term is more significant when the antenna is used over a ground plane because the signal strength of the combined direct and reflected rays varies more rapidly across the length of the antenna than for a single ray in free-space. The method for correcting for phase centre in such conditions is given in Appendix A1.3. In free-space the uncertainty for a commonly used LPDA of length 1.4 m is  $\pm 2$  dB at the ends of its frequency band on a 3 m range, assuming the phase centre is fixed at the mechanical centre of the antenna. The uncertainty is reduced to  $\pm 0.6$  dB for a 10 m range. The uncertainties are greater when the measurements are made over a ground plane.

There are further uncertainty terms associated with the design of antennas, which can be as great as  $\pm 15$  dB. This problem has caught many operators unaware, wasting man-days of effort, especially when using such antennas for site validation. Some models of tuneable dipole and biconical antennas have poorly balanced baluns. Some LPDAs have uncharacteristic resonances. These problems are described in Section 5.

#### 4.2. Uncertainties in the measurement of normalised site attenuation

The uncertainties of Section 4.1 are potentially doubled when doing NSA measurements because the insertion loss between *two* antennas is measured. The method of measuring NSA defined in Table G1 of CISPR 16-1<sup>2</sup> requires that one antenna be placed at a fixed height of 1 m and the other is height scanned from 1 m to 4 m. Refer to the caution on this method in Appendix 3. Calibrating the fixed antenna for its particular height and polarisation is possible, see Appendix 5, so that the uncertainty term for antenna factor variation with height for this antenna is eliminated. For vertically polarised NSA measurements, uncertainty contributions from cable reflections of  $\pm 1$  dB per antenna can be reduced substantially by routing the cable horizontally behind the antenna for several metres before dropping vertically to ground, see Fig. 4.

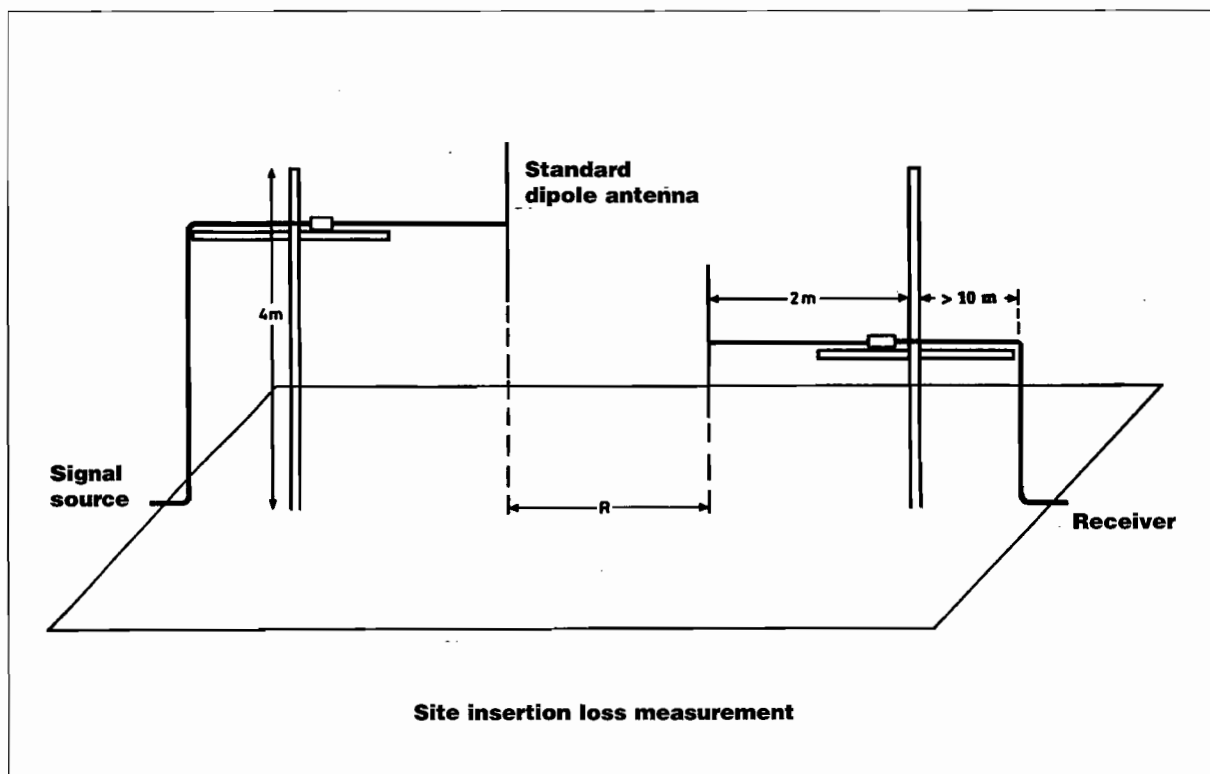


**Figure 4:**  
**Schematic layout for site attenuation measurement**

## 5. Problems encountered in calibrations for customers.

It is not uncommon for antennas to develop faults, even the most recently manufactured ones. Current antenna factors no longer apply to the faulty antenna and this can lead to wrong field levels being reported in Emission Conformance Test Reports. A common fault is a loose internal electrical connection. Often the customer can discover this by measuring its reflection coefficient, but this is a good reason for sending antennas regularly to a Calibration Laboratory, especially when traceability to a national standard needs to be demonstrated.

Many models of biconical antennas have been found to have a serious balun imbalance. This causes unwanted current to flow on the outer conductor of the input cable, see Appendix A1.5. The same problem is found on some tuned dipole antennas, especially when used with off-tuned element lengths for the purpose of broadbanding. The radiation from the cable interferes with the field from the EUT being measured. In the worst cases the signal is nearly cancelled. The effect is most pronounced when the input cable is laid out parallel to

and in proximity to the antenna elements. This is a particularly serious fault for tuneable dipole sets, considered by many operators as their most accurate reference antennas. Antennas are being redesigned as manufacturers become aware of this fact. Fig. 5 shows the change in signal strength when a vertically polarised biconical antenna, exposed to an incident field, is inverted.

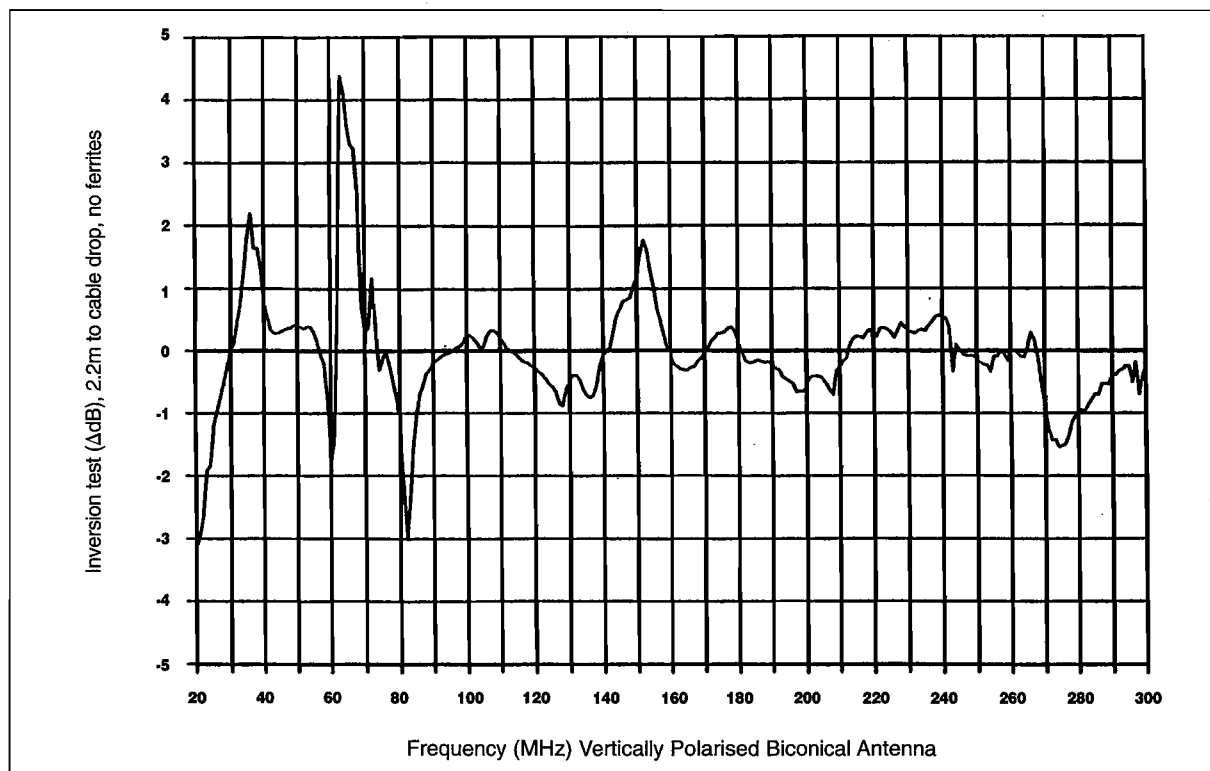


**Figure 5:**  
**Balun imbalance of a high power biconical antenna**

The most common design of biconical antenna element can be considered to be built around a wire dipole of total length approximately 1.4 m, see Fig. 6a. The standardised dimensions were set in MIL-STD-461<sup>12</sup>. There are two wire “cages” either side of the balun. At approximately 287 MHz there is an internal resonance which can increase the antenna factor by up to 8 dB over a narrow bandwidth. This undesirable effect was cured by Schwarzbeck by attaching a bar to one of the six wires on each cage as illustrated in Fig. 6b, which pushes the frequency of the resonance above 300 MHz, the top operating frequency of a bicone. One model of antenna has 3 bars on alternating wires, which removes the 287 MHz resonance but unfortunately introduces another resonance at 217 MHz. Another model of antenna has hinges at the 3 bends on each of the 6 wires to make it collapsible and therefore portable. The hinges give intermittent contact and can cause many unstable narrow band resonances.

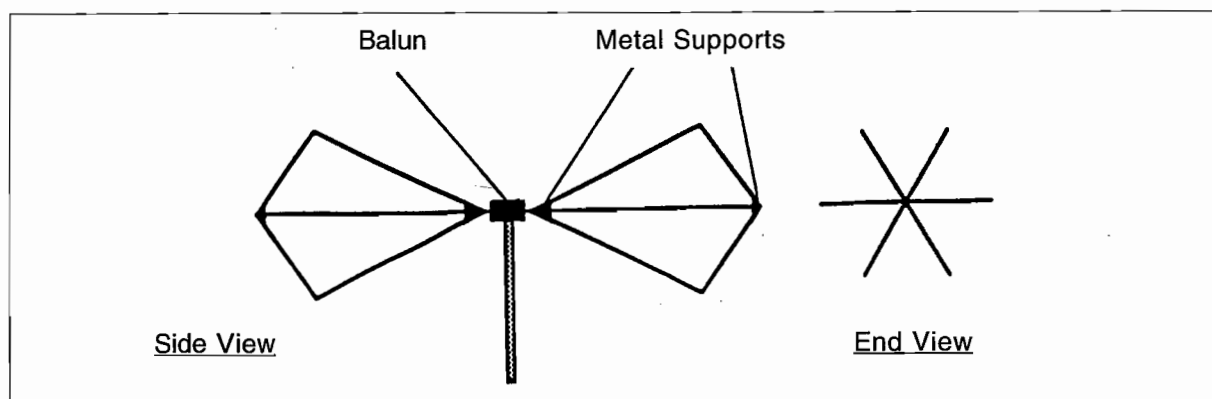


**Figure 6a:**  
**Schematic diagram of skeletal biconical antenna as used for EMC measurements**

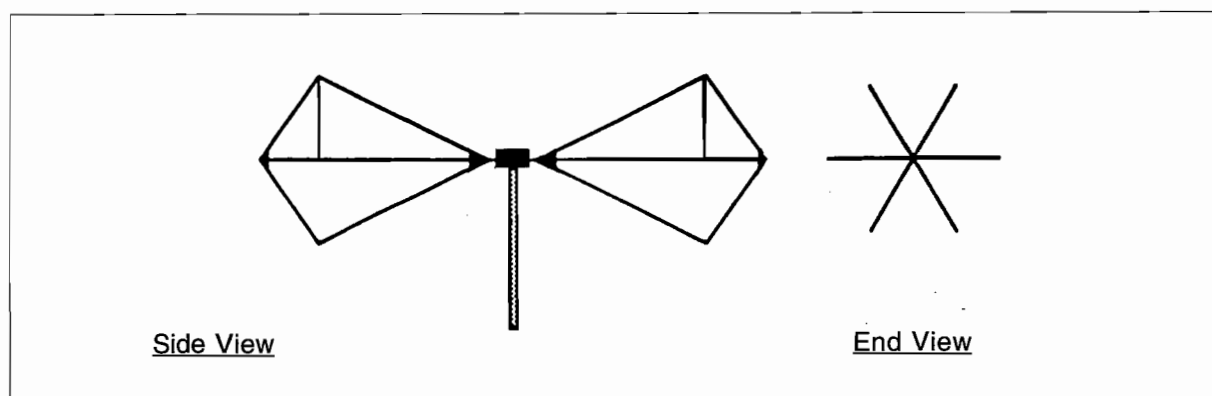


**Figure 6b:**  
**Skeletal biconical antenna with bar to suppress resonance at ~287 MHz**

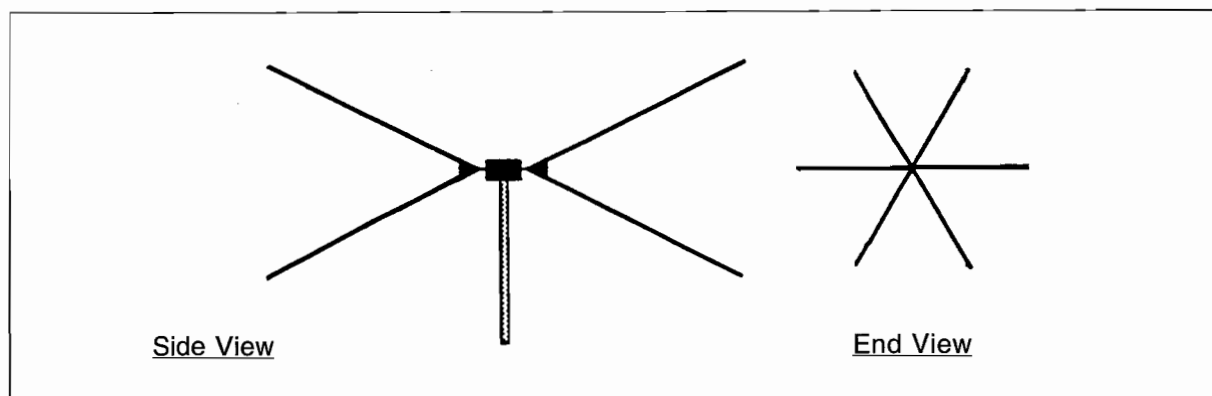


**Figure 6c:**  
**Collapsible form of skeletal biconical antenna, with locking screws at apex of cones**

The commercial collapsible design shown in Fig. 6c has been found to have a reproducible performance and is recommended. The electrical performance is very similar to the bicone of Fig. 6b, but the antenna factor is lower and better behaved above 260 MHz. Also being an open structure it does not suffer from an internal resonance in free-space. Fig. 7 compares the antenna factors using the conventional and collapsible biconical elements. There is a small resonance at around 120 MHz when the antenna is horizontally polarised at a height of 1 m above a ground plane, but this is not a problem as the height is usually greater than 1 m in an emission measurement. The use of collapsible elements is to be encouraged for portability. A conventional bicone cage has a large volume for its weight and can be much more costly to transport than a collapsible bicone.

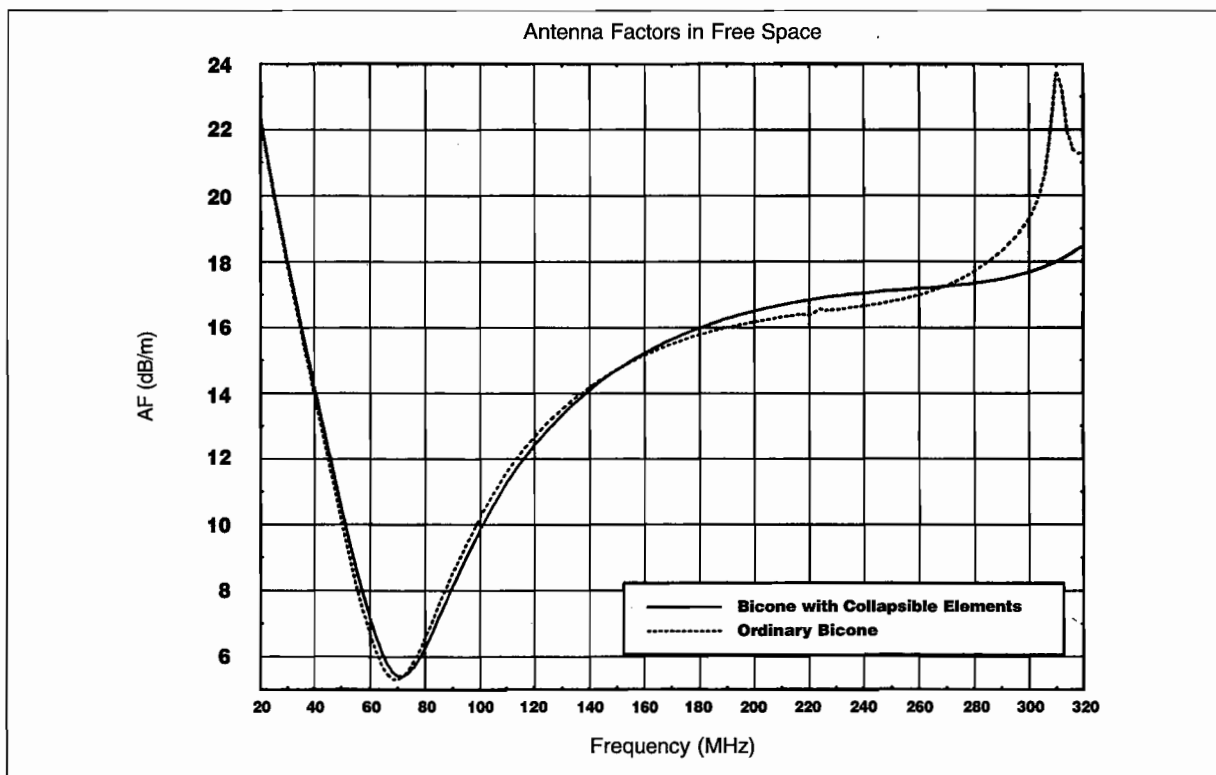


**Figure 7:**  
**Comparison of computed antenna factors for conventional and collapsible bicones.**

Another antenna design problem leads to large resonances in the response of LPDAs. These resonances are narrowband and can be typically 10 dB in magnitude. They do not usually show on new antennas but appear unexpectedly during use. They are associated with a breakdown in RF contact between the dipole elements and the main shaft or transmission line of the antenna. The breakdown can occur if the element does not have a tight fit on the shaft or if a metal oxide film builds up. Black powder deposits have been observed at the contact points of customers' antennas. This has been associated with input powers of tens of watts

used in susceptibility testing, causing electrical arcing on a particular make of antenna. It is recommended that such antennas are limited for receiving use only.

It is important regularly to check the performance of such antennas for the onset of resonances. The dipole elements can be removed and cleaned, restoring the antenna to its correct performance. Nevertheless, this does not always work and a full reconstruction of the antenna may be needed. There are models of LPDA for which attention has been paid to the mechanical construction, for example with welded elements, that do not suffer from this problem.

## **6. Self calibration using transfer standards**

An EMC test house can designate an antenna as a transfer standard. For traceability to national standards to be claimed, the transfer standard must be calibrated by a laboratory with the appropriate accreditation for antenna calibration, for example NAMAS accreditation in the UK. The test house can then calibrate its own antennas by substitution with the transfer standard, in other words by using the standard antenna method. In order for the secondary antennas to be traceable to national standards two fundamental points need to be observed. The transfer standard should only be used for calibrations, or handled so that its NAMAS calibration is not invalidated. The second point is that the method of calibration should be acceptable to an Accreditation Body and that the additional uncertainties imparted to the secondary antennas shall be agreed by the assessor.

The test house needs to be aware of the problems with performing antenna calibrations. If the three antenna method is used, the measurement site needs to be of a high quality - traceability can be claimed if the site attenuation is measured by a NAMAS accredited laboratory. ANSI C63.5<sup>7</sup> does not recommend calibrations using vertical polarisation because of problems with accuracy. The draft version of CISPR Document 16, due to be available in 1998, deals comprehensively with the issue of antenna calibration and the quality of the site required.

Special care is needed in the calibration of problem antennas described in Section 5. When using the substitution method accurate calibrations can only be obtained when the transfer antenna is of the same construction as the secondary antenna. For example there would be additional uncertainty terms if a tuneable dipole were used to calibrate a biconical antenna or if a transfer LPDA was not an identical model to the secondary LPDA.

NPL measures free-space antenna factor of biconical antennas using vertical polarisation, as discussed in Section 8.1. Very few test houses can do accurate calibrations using vertical polarisation. If a customer requires an antenna calibrated for transfer purposes employing horizontal polarisation, this should be stated and a horizontally polarised calibration will be provided. If the customer has a 6 m mast, NPL can provide a calibration at 6 m which gives antennas factors close to the free-space value, see Section 8.1. LPDAs are calibrated in free space conditions. It is difficult to measure boresight AF of an LPDA at a fixed height above a ground plane, but this is not essential because the antenna factor changes by no more than an estimated  $\pm 0.4$  dB for heights above 1 m. This applies to an LPDA with bottom frequency of 200 MHz placed above a ground plane.

## 7. The measurement facility at NPL

The open-field EMC antenna calibration facility at NPL has gained wide acceptance as a National Standard Open-field Site. It has the largest continuous ground plane in Europe designed specifically for antenna calibration. The ground plane is welded sheet steel of dimensions 60 m by 30 m. 95% of the area is flat to within  $\pm 6$  mm and 100% to within  $\pm 11$  mm<sup>6</sup>. The site has no weather proof cover, which could compromise accuracy. The centre axis is 45 m away from the control building (constructed with a minimum of metal parts) and 50 m away from nearest trees, so that unwanted reflections are negligible. As a measure of the quality of the site, the insertion loss between two horizontally polarised resonant dipole antennas differs from theoretical prediction to less than  $\pm 0.1$  dB in the frequency range 30 MHz to 300 MHz. This level of agreement confirms the quality of both the site and the NPL calculable standard dipole antenna. At 1 GHz the difference increases to  $\pm 0.3$  dB, which is attributed to the calculability of the dipoles rather than to site imperfections: at 1 GHz the dipole feed region is larger as a proportion of dipole element length. A receiver with a linearity of  $\pm 0.01$  dB over a dynamic range of 100 dB was used for these measurements.

A comparison of measurement and theory is required by CISPR<sup>2</sup> to validate a site, though the CISPR criterion for site errors in NSA is  $\pm 1$  dB. NPL's calculable standard dipole antenna<sup>6</sup> is accurate to  $\pm 0.1$  dB over the frequency range 20 MHz to 500 MHz and  $\pm 0.2$  dB from 501 MHz to 1 GHz. The best measurement uncertainties currently offered for customer calibrations are shown in Appendix 5. They are proportionally higher at 1 GHz because of the extra uncertainties in setting up the antennas and reflections from supporting structures.

The facility is equipped with a turntable and the full capability for performing radiated emission tests. Radiation patterns, in amplitude and phase, can be measured. The location of the phase centre of antennas can be determined. The service is not restricted to EMC antennas. Enquiries are welcome for the measurement of any type of antenna in the frequency range 10 kHz to 5 GHz whose aperture size is less than about 2 m (rod antennas below 10 kHz are measured in a GTEM cell). Examples are broadcast antennas, including mobile communications, and antenna arrays used as gain standards. The range is available for hire with or without the measuring equipment.

Staff at NPL have expert knowledge of the performance of most types of EMC antennas on the market. Some 25 different models of biconical antenna and 25 models of LPDAs have been measured to date. Some 6 different models of tuneable dipole sets have been measured. Unexpected performance characteristics on some models of antenna are known and the staff are alerted to identify these and to advise the customer accordingly.

Between 1993 and 1995 NPL led an intercomparison of antenna factors in 10 European countries and chose antenna models which were stable and could be relied upon to give reproducible performances. Two different models of biconical antenna, two models of LPDA, one tuneable dipole and one short broadband dipole were circulated to 15 laboratories. The report<sup>13</sup> concludes that most well equipped laboratories are capable of calibrating to an uncertainty of  $\pm 1$  dB and those with facilities designed for antenna calibration should be capable of achieving better than  $\pm 0.5$  dB.

NPL has a fully lined anechoic chamber used for calibrating horn and spiral antennas at frequencies above 1 GHz. The chamber can also be used for calibrating LPDAs when necessary.

Though NPL does not currently do routine radiated emission conformance testing, it has all the facilities for doing so. NPL has an impartial status with respect to EMC testing and can provide a second opinion for radiated emission measurements.

## **8. Types of calibration available at NPL**

Most organisations have a Quality System under which instruments have to be regularly calibrated. There is a range of possible calibrations for any one antenna. In order for the customer to get the lowest possible uncertainty of measurement the calibration can be tailored

to the way the customer uses the antenna. If the antenna is used horizontally polarised at a fixed height above a ground plane, antenna factors can be provided for that height, eliminating the component of uncertainty that takes account of variation of antenna factor with height. NPL can measure antenna factors for most conditions and also offers a service for lower uncertainties, typically  $\pm 0.5$  dB, for which an extra charge is levied.

The available calibrations are allocated service numbers in the leaflet "EMC antenna calibration services at NPL". The version of this list at the time of publication of this Guide is reproduced in Appendix 5. The services are briefly described below to enable the customer to choose the calibration appropriate to his requirements. Antennas are calibrated in the far-field of a source.

### 8.1. Calibration of broadband dipole and biconical antennas

For an antenna to be used at a fixed height above a ground plane and horizontally polarised for a measurement of site attenuation, the lowest uncertainties are obtained by calibrating it at that height. NPL offers a standard service for calibration at heights of 1 m, 1.5 m, 2 m, 2.5 m, 3 m, 3.5 m and 4 m in steps of 1 MHz across the operating frequency range of the antenna. Other heights are available on request. Antenna factor measured in this way is designated in the list of Services as AF#m, where # is the height in metres. An antenna intended for use by a customer as a transfer standard can be calibrated by NPL at a height of 6 m which gives antenna factors close to the free-space value.

For a biconical antenna scanned in height from 1 m to 4 m it is feasible to store in a computer the antenna factors for a sufficient number of heights across the operating frequency range and to call up the appropriate value at each measurement point. However most operators have a calibration for one physical setting of the antenna and apply this to all the heights and polarisations used in the emission test (called the optimum AF in Section 2). If a 2-m-height-horizontal calibration, AF<sub>2m</sub>, is used for a height scanned test, the additional height related uncertainty is  $\pm 2$  dB, see Appendix A1.4. This is more than twice that of the calibration uncertainty and dominates the overall uncertainty of measurement.

NPL has made extensive measurements of different models of biconical antenna in the height range 1 m to 4 m and has developed a method of measuring the quasi free-space antenna factor, AF<sub>FS</sub>. It is shown that AF<sub>FS</sub> is approximately the mean of the antenna factors as they vary over the height scan range, see Fig. 3. This allows the height related uncertainty to be reduced to  $\pm 1$  dB. Some models can yield less than  $\pm 0.6$  dB over most of the operating

frequency range. If a height related uncertainty of  $\pm 1$  dB is added in quadrature to a calibration uncertainty of  $\pm 1$  dB, the total is only  $\pm 1.4$  dB, a considerable reduction over the 2 m height method. NPL has built a calculable biconical antenna whose measured antenna factors in free-space and at any height above a ground plane agree to better than  $\pm 0.3$  dB of the predicted value<sup>14</sup>. This work led to the recommendation of the use of collapsible elements for ease of storage and portability.

For highest accuracy it is recommended that antennas, especially tuned dipoles, are calibrated at distances of  $2l$  or greater from the source antenna. In the case of short dipole antennas operating down to 30 MHz a distance one wavelength, or 10 m, is sufficient, see Appendix A3.1. This includes biconical antennas below 60 MHz. A separation of  $l$  is possible because the antenna aperture is small compared with a wavelength and the antenna input impedance is highly reactive, for which mutual coupling effects are negligible.

Free-space antenna factors are measured by default unless the customer requests a horizontally polarised calibration. The correct antenna factor to use in fully lined anechoic chambers is  $AF_{FS}$ ; even if there are significant reflections in the chamber, causing the reading to vary by as much as  $\pm 6$  dB, the mutual coupling of the antenna to the walls of the chamber is considerably damped.

All baluns are tested for imbalances. If the imbalance causes an error of greater than  $\pm 0.5$  dB when the antenna is illuminated with a vertically polarised plane wave the balance test will be recorded in the certificate and the possible uncertainties quantified.

## 8.2. Calibration of tuneable dipole antennas

For an introduction to the tuneable dipole antenna see Appendix 2. Resonant antennas are available on the market as a “tuneable dipole set” which comprises one to four baluns with telescopic dipole antennas that can be tuned to resonant lengths in the frequency range 26 MHz to 1000 MHz. It is strongly recommended that only antennas with near-perfect baluns are used as reference antennas. This is essential if the customer wants to use calibrations with the lowest uncertainties available at NPL and to claim low uncertainties in the application of the antennas.

The antenna factor of a dipole resonant at 30 MHz changes by 6 dB when scanned in height from 1 m to 4 m. The change rapidly decreases with frequency and above 500 MHz it is less than  $\pm 0.3$  dB. NPL can calibrate tuneable dipole antennas for any height and polarisation

requested by the customer. A standard service is offered in which the dipole set is calibrated horizontally polarised at 24 frequencies (listed in Appendix 5) at a height of 2 m above a large conducting ground plane.

Correction tables are supplied in NPL Report DES 131<sup>15</sup> to enable interpolation to other frequencies. First the antenna factor is corrected to the free-space value and then it is corrected for the new height. There is an additional uncertainty associated with the use of such corrections because they are derived assuming a certain antenna input impedance. Each model of dipole set has its unique scattering parameters and a margin of uncertainty has been allowed so that the corrections are valid for most models. To reduce the uncertainty of interpolation the antenna should first be tuned to free-space resonance. This is defined by the input impedance of an antenna element in free-space whose length has been adjusted until the reactance term is zero. If the manual for the customer's antenna specifies tuning to exactly half a wavelength, the customer will be asked to state whether this is the length to be used or whether the NPL estimated resonant length is preferred. For exact half wavelength dipoles there will be a greater uncertainty in applying the correction factors in DES 131.

The additional uncertainties when the correction factors are used for resonant dipoles range from to  $\pm 1$  dB at 30 MHz to  $\pm 0.3$  dB at 300 MHz. The customer may request calibrations at additional heights and frequencies to gain confidence in the application of the corrections, possibly enabling the uncertainties to be reduced. Heights of 1 m and 1.5 m at 50 MHz, 90 MHz and 180 MHz are recommended because, taken with the 2 m measurement, they give the full spread of antenna factor versus height.

### 8.3. Calibration of LPDAs, spirals and bilog antennas

LPDAs and conical log-spiral antennas are calibrated over their operating frequency range at intervals of 2 MHz. They are illuminated by a source antenna positioned at a sufficient distance to ensure an adequate approximation to far-field conditions. In the method used at NPL, the antennas are positioned above RF absorbing material, creating a quasi free-space environment. The dimensions of the LPDA are measured and fitted to a polynomial to derive phase centre positions. These calculated phase centres are used in the three antenna method to derive the antenna factors.

The calculated distance of the phase centre from the tip of the central column of the antenna is tabulated in the NPL certificate at frequency intervals of 20 MHz. These phase centre positions can be used to correct for field strength at the measurement distance, eg 3 m or

10 m, see Appendix A1.3. Alternatively, values of antenna factor with reference to the mechanical centre of the LPDA for a given distance from the EUT can be supplied on request for a small charge. These are only strictly valid for facilities with absorber on the floor. The mechanical condition of LPDAs should be checked, before submitting them for calibration, and any bent elements straightened and all elements screwed tight. Appendix A3.3 warns the reader of the large errors that occur with the mis-use of antenna factors measured by the SAE ARP958 method.

Most LPDAs are constructed with the two half elements in echelon. This causes a decrease in cross-polar performance that is worst at the higher frequencies where the displacement of the two elements from a straight line is a greater proportion of the element length. The CISPR 16-1 criterion of 20 dB for cross-polar discrimination is too severe for some popular models of LPDA. Whilst this level may be achieved below 500 MHz it can range from just on 20 dB to as low as 14 dB at 1 GHz for different models. It may be that design improvements will be needed.

A simple test of the ellipticity of spiral antennas is done by taking the difference of the responses to a linearly polarised LPDA when oriented horizontally and vertically polarised. When using spiral antennas for emission testing, it is assumed that the field from the equipment under test is linearly polarised, in which case 3 dB has to be added to the antenna factor measured for circularly polarised fields.

For LPDAs that operate below 150 MHz the fixed height method of calibrating biconical antennas might be used. The antenna factor is computed using the LPDA phase centre positions. The bilog antenna is a hybrid of an LPDA and a biconical antenna which covers the entire frequency range 30 MHz to 1 GHz. The cutoff frequency of the log-periodic section is determined by the longest “log” element. There is one much larger element just behind this that works down to the lowest frequency of operation. At NPL bilog antennas are calibrated in two stages using the methods of Sections 8.1 and 8.3.

#### **8.4. Calibration of rod antennas**

Rod antennas are commonly used for radiated emission measurements in the frequency range 10 kHz to 30 MHz. Most models have a telescopic monopole, which can be set to a length of 41” as specified in military standards. The most widely used method of calibrating rod antennas is by a closed circuit measurement<sup>16</sup>, substituting the rod for a capacitor of about 10 pF. Some rod antennas have a vestigial ground plane of dimensions approximately

0.6 m x 0.6 m. However the true interaction of the rod antenna (including monopole, vestigial ground plane and amplifier box) with the site ground plane is not possible to simulate with a capacitor. In most cases the capacitor method is accurate to within  $\pm 2$  dB but breaks down above about 15 MHz.

NPL has developed a technique for the calibration of rod antennas up to 2 m in length in free-field conditions, from 100 Hz to 100 MHz or higher. The base of the rod antenna unit is placed near the middle of and in contact with the 60 m x 30 m metal ground plane on the NPL site. It is illuminated by a field from a transmitting monopole antenna approximately 20 m away. The transmitted field is very small below 5 MHz so for calibrations down to 100 Hz a parallel plate line is set up about twice the height of the rod. The antenna factor is determined by substitution with a standard rod antenna whose antenna factors are calculable. On request from the customer the rod antenna can be calibrated with its vestigial ground plane, sometimes called a "counterpoise", mounted on a tripod. At the time of writing, the uncertainties associated with the calibration of rod antennas in a large GTEM cell are being investigated.

Antenna factors derived by the above methods can be used to give the E-field strength in free-field conditions, and as argued in Appendix 3 will accurately measure the field-vector at a near-field distance, such as 1 m. However most applications of rod antennas are in screened rooms, whose size dictates that there are no longer free-field conditions, in other words the room is operating below its cut-off frequency. In this case E-field magnitude as conventionally understood is not being measured and special steps are needed to derive E-field magnitude which can be related to free-field emissions. Significant progress has been made in quantifying this relationship and is discussed in Appendix 4.

### **8.5. Calibration of horn antennas**

Horn antennas and conical log-spiral antennas operating at frequencies above 1 GHz are calibrated inside a NPL 10 m fully anechoic chamber. The 3 antenna technique is used with an uncertainty of better than  $\pm 0.8$  dB. The apparent gain, antenna factor and reflection coefficient of coaxially and waveguide fed antennas can be measured. The gain can be measured for any antenna separation between 1 m and 4 m.

It is important that customers carefully check the connectors on their antennas before sending them in for calibration as worn or damaged connectors may seriously affect the measurements' results: in some cases calibrating the antenna may not be possible. The use

of antennas with SMA connectors in situations where repeated connection and disconnection occurs should be avoided, as these connectors have poor repeatability and are easily worn out.

## 9. Calibration interval

The recommended interval for the recalibration of antennas by a NAMAS accredited laboratory is 2 years. This interval is under review and depends on the repeatability of the calibrations of a given antenna. Guidelines agreed by NAMAS<sup>9</sup> recommend that regular intermediate checks should be performed. A mechanical check should be performed each time an antenna is used. This will ensure that the RF connector is in good condition and that the antenna elements are firmly affixed and are not bent out of shape. The user should regularly check the input match and do a functional check using a stable noise source or measure the insertion loss between two antennas for a defined set-up. These measurements should be made immediately after the antenna has been calibrated to provide reference data for subsequent checks. The user may prefer to do an internal antenna calibration as a repeatability check to ensure that the antenna performance has not changed since it was last measured with an identical set-up.

The cost of a reliable calibration and exhaustive measurements of antenna properties, such as balun imbalance, can be quite high. In particular for dipole sets, which are used as reference antennas, the cost can be almost of the cost of replacing the set. It is false to assume that it is more cost effective to replace the antenna rather than have it recalibrated. First, not all manufacturers issue antennas with antenna factors measured to acceptable precision: typically  $\pm 2$  dB is offered. Secondly, some manufacturers appear not be aware of deficiencies in the performance of their antennas. A very old antenna stored away may be a better quality antenna than some currently for sale. There are more than 25 different types of proprietary biconical antennas and 25 different types of LPDAs. NPL has measured the particular characteristics of most of these and has the experience to assess new designs.

If, during the course of a calibration at NPL it is found that the antenna has a large balun imbalance, the customer will be contacted and advised that it is not worth proceeding with the calibration. If calibration is requested, there will be a warning in the certificate of large additional uncertainties when the antenna is used for emission conformance testing. For cases where the balun is usable over part of its operating frequency range, the faulty range will be identified. See Appendix A1.5. NPL is authorised by the manufacturer to repair one model of antenna in order to restore its balance.

For a customer whose antenna has been fully calibrated at NPL, an alternative service may be considered. This is aimed at tuneable dipole sets as a means of reducing the number of measurements. The measurement of two dipoles per balun (at the extremes of its frequency band) will confirm whether the antenna has changed since its last calibration. The extension of the telescopic dipole elements is not known to cause any unrepeatability. In this way 24 frequencies can be cut down to eight (for a 4 balun set). A full calibration will be necessary if the customer requests a lower measurement uncertainty than quoted for the original calibration. This service with a subset of measurements is listed as services S1 and S2 in Appendix 5. A Calibration Certificate will be issued which states that the calibration in the previous certificate is still valid. If the antenna performance is found to have changed by more than  $\pm 0.3$  dB the customer will be informed and invited to request a full calibration.

## **10. The NPL certificate**

### **10.1. Contents of the certificate**

The antenna factors of broadband antennas are measured up to 5 GHz at intervals of no greater than 2 MHz. The full set of factors is plotted in graphical form in an NPL certificate of calibration, and also in tabular form at a frequency interval of approximately 20 MHz as appropriate to the operating frequency range of the antenna. The uncertainty of these antenna factors, within the frequency limits stated in the certificate, is stated to a confidence level of not less than 95% ( $k = 2$ ). Also, plotted are the return loss values. Full sets of antenna factors, complex reflection coefficient and return loss can be requested as ASCII files on a DOS formatted 3+” floppy disk.

The certificate also gives guidance on the uncertainty terms to be included when the antenna is used for emission testing or test site validation. Various sources of uncertainty are quantified. Warnings are included in the case of excessive deviations of antenna performance from that which is normal for that model of antenna, drawing on an accumulation of data from the measurement of many antennas.

It is the practice at NPL to measure complex reflection coefficients when calibrating an antenna. This information enables the customer to perform a mismatch correction, but it does require the customer to measure the complex reflection coefficient of the receiver and the complex S-parameters of the cable connecting the receiver to the antenna. In view of the relatively large uncertainties involved in emission testing it is generally not thought worth

calculating the mismatch corrections. The magnitude of complex  $S_{11}$ , expressed as return loss, is sufficient for the estimation of mismatch uncertainties. An NPL certificate does advise the use of a padding attenuator between the antenna and the receiver to minimise mismatch errors.

If an antenna is found to give an unacceptable performance it is deemed to be faulty and a letter will be sent to the customer describing the problem. The customer will be charged proportionally according to the amount of work carried out up to the point that the fault was identified.

## **10.2. Interpretation of uncertainties in certificates**

The uncertainty of calibration is just one term in the uncertainty budget of an emission test. Antenna factors of tuneable dipole and biconical antennas vary by typically  $\pm 2$  dB with height above a ground plane, see Section 7.2. Some EMC standards require that the antenna is scanned in height to search for the signal maximum. LPDA antennas have uncertainty terms associated with the variation of phase centre with frequency and with polar variation or directivity. Unbalanced antennas can exhibit large errors when the output cable is aligned with the antenna elements. The NPL certificate attempts to quantify these uncertainty terms for guidance. Not all terms should be included in the uncertainty budget for a particular test. For example for horizontal polarisation a bicone with free-space antenna factors has an uncertainty of  $\pm 0.6$  dB for height variation whereas this is zero for a vertically polarised antenna above a height of 1.5 m. But for vertically polarised measurements there is an uncertainty of  $\pm 1$  dB caused by reflections from a cable that is about 0.6 m away from the antenna and aligned with it - the magnitude of  $\pm 1$  dB was found by measurement. This is a separate error from balun imbalance. For LPDAs the phase centre error is small for 10 m sites but significant for 3 m sites and up to 5 dB for a separation of 1 m in screened rooms. The phase centre can be precisely corrected for measurements made in fully anechoic chambers.

Guidance on the addition of the uncertainty terms is given in the NAMAS document NIS81<sup>5</sup>.

## 11. Procedure for requesting calibrations

Measurements are normally completed within one week of the agreed start date, though it may be 2 weeks for dipole sets, allowing for the weather. We offer a fast turn round of one or two days if required, but if this involves reorganising our schedule an extra charge may be levied. A calibration is normally requested by phone or fax to the personnel listed below (these arrangements do not apply to loop and horn antennas which are dealt with by separate services, see Appendix 5). A customer chooses the calibration service required from Appendix 5, or special calibrations can be arranged by telephone. The next calibration date available will be given, or a "fast" date arranged, and an instant quotation if the request is for a standard service. A Firm Price Agreement form and Conditions of Service will be sent to the customer who will send a purchase order with the signed FPA. *Please mark this for the attention of the personal name of the sender.*

The customer is expected to identify and remedy any problems with antennas before sending them for calibration, such as those associated with LPDAs in Section 5. If the customer prefers, NPL can do this for a fee with no guarantee of being able to repair it. Sometimes inspection of the dipole elements reveals they are loose and tightening them cures the problem; this will be done free of charge.

NPL will not normally repair antennas, for example a faulty amplifier on an active rod antenna or a faulty power supply. The customer should check that the antenna is in working order before sending it to NPL. If a fault is found NPL will contact the customer and recommend a course of action, such as returning the rod antenna to the manufacturer - the customer will be charged the proportion of the calibration fee to cover the work already completed. If NPL is requested to proceed with the repair the additional fee for this will be agreed by the customer.

Because of the size and fragility of some EMC antennas many customers prefer to deliver and collect them. Alternatively, if they are appropriately packed, they can be delivered to the Goods-In department at NPL. For transport in the UK mainland there is a return charge of typically £8 (in 1996) up to 10 kg. (+ 30p/kg above 10 kg) for the courier service, including insurance.

Please apply for a quotation and calibration date to:

K I Pharaoh  
National Physical Laboratory  
Teddington  
Middlesex, UK  
TW11 0LW  
tel. 0181-943 6796

or

M J Alexander  
tel. 0181-943 7175

For calibrations of horn antennas above 1 GHz, contact D G Gentle on tel. 0181-943 6717.

For calibrations of loop antennas and field strength meters, contact K P Holland on tel. 0181-943 6947.

The FAX number for all the above contacts is 0181-943 7176.

The brochure on antenna calibration is reproduced on the NPL web site  
<http://www.npl.co.uk/npl/cetm/antenna.html>

## 12. Glossary

|                |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |
|----------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| antenna factor | antenna factor (AF) is the ratio of the E-field in which the antenna is immersed to the voltage across the load at its output. It is assumed that the field is uniform in amplitude and phase across the aperture of the antenna (ie a plane wave). Antenna Factor is proportional to frequency and inversely proportional to the square root of realised Antenna Gain.                                                                                                                           |
| boresight      | the boresight direction of an antenna is mechanically defined and is generally the direction of maximum gain. It would be possible to calibrate antenna factor for other polar angles so that the effects of directivity could be compensated by calculation. However this would require measurement of amplitude and phase so that the direct and ground reflected signal could be correctly combined. It is not considered practicable to do this so only boresight antenna factor is measured. |
| civil EMC      | an example of a specification for civil EMC radiated emission measurements is European Standard EN 50081-1 "EMC - Generic emission standard Part 1: Residential, commercial and light industry"                                                                                                                                                                                                                                                                                                   |
| CISPR          | Comité International Spécial des Perturbations Radioélectriques. International Special Committee on Radio Interference. Issues Documents with which, in most part, European EMC Standards, or EuroNorms, conform.                                                                                                                                                                                                                                                                                 |
| FCC            | Federal Communications Commission, USA. Testing to American Standards is only allowable if the test site has been accepted by the FCC.                                                                                                                                                                                                                                                                                                                                                            |
| free-space AF  | $AF_{FS}$ is the antenna factor of the antenna when it is removed so far from other conducting surfaces that mutual coupling of the antenna to these surfaces is negligible.                                                                                                                                                                                                                                                                                                                      |
| fully anechoic | a fully anechoic room has absorbing material on all surfaces. This is in contrast to a semi-anechoic chamber where the floor is deliberately left uncovered to simulate the ground plane of an open-field site.                                                                                                                                                                                                                                                                                   |
| height max.    | The height maximum is the height at which the maximum signal is recorded when the receive antenna is scanned in height from 1 m to 4 m,                                                                                                                                                                                                                                                                                                                                                           |

according to CISPR 16-1. This is to avoid destructive interference between direct and ground reflected rays from the source to the antenna.

|                      |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |
|----------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| ideal site           | The ideal test site is a mathematical half-space, free of obstacles and bounded by a perfectly flat and perfectly conducting ground plane of infinite extent, acting as an ideal reflector of electromagnetic waves in the frequency range under consideration.                                                                                                                                                                                                                                                                                                       |
| LPDA                 | Log-Periodic Dipole Array antenna. A series of half-wave dipole elements tuned to increasing frequencies are spaced logarithmically along a transmission line to create a broadband antenna. The bandwidth is determined by the lengths of the shortest and longest elements.                                                                                                                                                                                                                                                                                         |
| open area test sites | a flat open area site which has a large metallic ground. Potential scatterers such as buildings, trees, power lines and fences are sufficiently far away to cause insignificant change to the intended signal                                                                                                                                                                                                                                                                                                                                                         |
| phase centre         | Knowing the antenna factor at the position (phase centre) on the antenna of the active element at a given frequency is necessary for the accurate measurement of field strength. It is common practice for the antenna factor to be given in relation to the mechanical centre of an LPDA. See Appendix 1.3. If the AF is not related to the phase centre information in the certificate of calibration, one has to be sure that the antenna has been calibrated with a sufficient separation from the source for the phase centre uncertainty term to be negligible. |
| plane wave           | a field with a wave impedance of $377 \Omega$ that is uniform in amplitude and phase across the aperture of the antenna.                                                                                                                                                                                                                                                                                                                                                                                                                                              |
| site attenuation     | is the ratio of the power input to a matched balanced dipole-like antenna to that at the output of a similar antenna for specified polarisation, separation and heights above a flat reflecting ground plane.                                                                                                                                                                                                                                                                                                                                                         |
| NSA                  | normalised site attenuation is site attenuation minus the antenna factors of the transmit and receiving antennas.                                                                                                                                                                                                                                                                                                                                                                                                                                                     |

### 13. References

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- 4 Guide to the Expression of Uncertainty in Measurement  
International Organisation for Standardization, Geneva, Switzerland, 1995.
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- 8 American National Standards Institute, ANSI C63.4:1992.  
Methods of measurement of radio noise emissions from low-voltage electrical and electronic equipment in the range 9 kHz to 40 GHz.
- 9 NAMAS is the National Measurement and Accreditation Service, operating under UKAS, the United Kingdom Accreditation Service. Address: UKAS, Teddington, Middlesex, TW11 0LW, England. Tel: 081-943 7140, Fax: 081-943 7134.
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## **Appendix 1**

### **Background to uncertainties in emission testing**

#### **A1.1 Emission testing in screened rooms above the first resonant frequency**

In the early days of EMC testing, a lot of the measurements were carried out in screened rooms which acted like resonant cavities. Because of the high Q-factor of the rooms the uncertainties in measured field strength could be of the order of  $\pm 30$  dB. At best the measurement served to identify the frequency of emission and to show up differences between one EUT and another measured in the same way. A displacement of the antenna of the order of 10 cm could cause the received signal to vary by 20 dB. In this scenario it did not matter much if the uncertainty in the antenna factor (AF) was of the order of  $\pm 3$  dB. Some military testing still employs unlined rooms, though there is now a trend towards using anechoic material to dampen the resonances.

These days better quality control demands that some sort of calibration is performed, if only to prove that the antenna is working as the manufacturer intended. The trend is to use absorbing material to lower the Q-factor of screened rooms. In this case antenna factor uncertainty can be an important contribution to the overall uncertainty budget. Calibrations of antennas for use at distances of 1 m from the EUT and associated uncertainties are discussed in Appendix 3. Measurements in screened rooms below the first resonant frequency are discussed in Appendix 4.

#### **A1.2 Errors inherent in measurements above a ground plane**

The use of a ground plane on an OATS was an important step forward in getting better reproducibility of measurement from one site to another. A lot of work was done from the late 1970s to improve the quality of test sites. If the intention of an emission measurement is to measure the emission directly from an EUT, metrologically the CISPR method<sup>2</sup> introduces two error terms which are not recorded in the uncertainty budget. The most important of these two errors arises from the ground reflection. The antenna has to be scanned in height (usually 1 m to 4 m) to avoid destructive interference of direct ray and the ground reflected ray. When they combine in-phase to give a signal maximum the direct signal is enhanced by between 4 dB and 5.8 dB. An inconsistency arises at 30 MHz where a signal maximum cannot be obtained in the limited height scan range for horizontal polarisation: whereas over most of the frequency range the signal is 5 dB higher, the reading at 30 MHz is 12 dB down from this general higher value. The second error is that the distance between the EUT and the height scanned antenna is greater than the specified distance. The distance error is significant for a 3 m site. These error terms should have been included in the setting

of the specification limits, but it is doubtful that they were rigorously taken into account. A reminder of this problem helps the argument for the adoption of fully anechoic chambers.

### A1.3 Assessment of uncertainty arising from phase centre position on LPDAs

The antenna factor for an LPDA should be given at the phase centre position at each frequency. In an NPL certificate the AF is tabulated with three columns: Frequency, Antenna Factor and Phase Centre. The certificated uncertainty for AF only applies when the phase centre is positioned at the required separation distance,  $R$ , from the source (eg 10 m) at each frequency. If the antenna position is not adjusted with frequency, a correction should be made to the recorded field strength (at the phase centre position) to give its value at distance  $R$  from the source. For distances of greater than one wavelength from the antenna a fall-off of the field proportional to the inverse of the distance can be assumed. The correction factor,  $C_R$  dB, is added to the field strength, equation 1. The fourth column of the AF table can be this correction factor  $C_R$ , with additional columns for each separation  $R$ .

$$C_R = 20 \log [(R + P_f - d)/R] \dots\dots\dots 1$$

E-field strength is given by equation 2:

$$E_f = V_f + AF_{FS}(f) + C_R \dots\dots\dots 2$$

where:

$f$  = frequency, (MHz).

$R$  = the required separation from the source to the reference point, (m).

$P_f$  = phase centre position as a function of frequency, (m from tip).

$d$  = distance of the reference point from the antenna tip, (m).

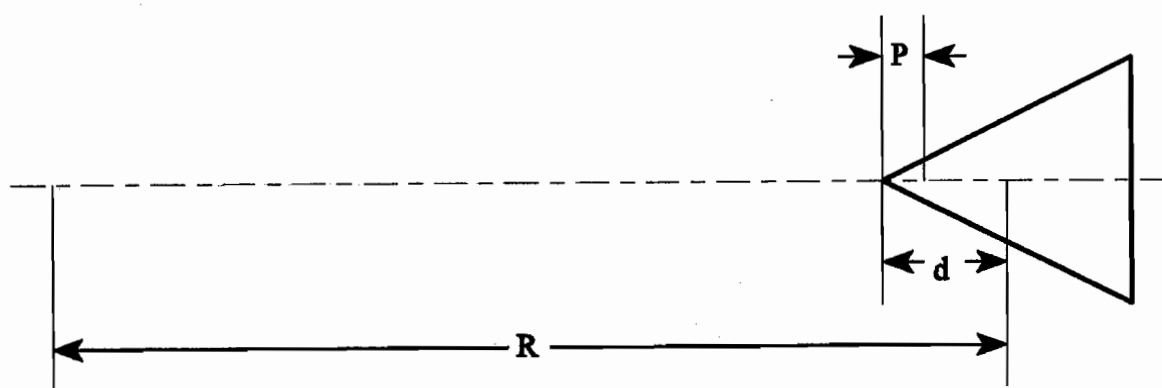
$E_f$  = E-field at distance  $R$  from source (dBV/m).

$V_f$  = voltage at output of antenna at frequency  $f$  (dBV).

$AF_{FS}(f)$  = antenna factor (free space) for E-field at the phase centre, (dB/m).

**Table A1.3 Example LPDA antenna factors. Correction assumes reference is 0.3 m from tip**

| Frequency<br>MHz | Antenna Factor at<br>phase centre, dB/m | Phase centre,<br>distance from tip, m | Correction factor<br>for 3 m distance,<br>dB |
|------------------|-----------------------------------------|---------------------------------------|----------------------------------------------|
| 200              | 11.1                                    | 0.60                                  | 0.83                                         |
| 400              | 15.2                                    | 0.30                                  | 0.00                                         |
| 1000             | 24.0                                    | 0.10                                  | -0.60                                        |

**Diagram showing the distance, R, from a source to the reference point on an LPDA**

For measurements made over a ground plane this correction has to be calculated using the difference<sup>7,17</sup> in  $E_{Dmax}$  for the distances to the phase and mechanical centres of the antenna. If this procedure is not adopted a fixed phase centre can be chosen as the centre of the antenna. This will weight the error evenly at the ends of the operating frequency band. The uncertainty calculated in this way applies to fully anechoic chambers or above a ground plane at heights giving signal maxima. The uncertainty is greater at other heights, especially near signal minima. The fixed phase centre may be chosen as the point half way between the positions on the antenna which correspond to the phase centres for the two ends of the antenna's operating frequency band. For example for an LPDA of length 0.6 m and an operating frequency range of 200 MHz to 1 GHz, this method gives a fixed phase centre for this antenna at 0.35 m from the antenna's tip, and the uncertainty in the antenna factor at the ends of the band is  $\pm 0.2$  dB for a separation of  $R = 10$  m from the source. For  $R = 3$  m the uncertainty increases to  $\pm 0.8$  dB.

#### **A1.4 Improved methods of calibrating EMC antennas**

At the time of writing, the most widely used method of calibrating biconical antennas is that described in ANSI Standard C63.5<sup>7</sup>. This gives an approximate calibration for a horizontally polarised antenna at a height of 2 m above a conducting ground plane. Historically this became an accepted method because it allows for imperfections in the ground plane and is an accessible method for the general EMC operator. Because this method employs height scanning there is a common misconception that it yields the appropriate antenna factors for emissions measured using height scanning. This method has been thoroughly investigated at NPL where an improved method has been devised. In the NPL method both transmit and receive antennas are fixed in height and the frequency is stepped over the operating bandwidth of the antenna. Let us call the antenna factor obtained by the this method  $AF_{2m}$ . This is the AF that gives least uncertainty when the operator uses the antenna fixed at that height.

However for height scanning applications, the antenna factor varies at different rates at each frequency in the operating frequency range of the antenna. For practical reasons in emission testing it is preferred to use just one value of antenna factor at each frequency. If the value is  $AF_{2m}$ , the height related uncertainty is just less than  $\pm 2$  dB. However if free-space antenna factor is chosen, the height related uncertainty is almost halved. Measurements at NPL have verified this and have confirmed that the free-space antenna factor results in the least uncertainty as explained in Section 8.1.

#### **A1.5 Unbalanced baluns, a major source of uncertainty**

A major source of measurement uncertainty for biconical antennas is unwanted currents set up on the outer conductor (or braid) of the coaxial feed line. These are caused by poorly balanced baluns. Using two such antennas to measure NSA can make it impossible to get the site to meet the CISPR NSA criterion, Annex M<sup>2</sup>. The problem is that radiation from the braid currents destructively interferes with radiation from the antenna. By reciprocity the same is true for reception. There has arisen the mistaken belief that the antenna has a preferred polarity when vertically polarised, ie with one particular biconical element pointing skywards, and that if the antenna is calibrated and then used in this orientation the problem is solved.

In fact the problem is caused by the interaction of the antenna with its feed cable and is dependent on the exact cable layout, the main factor being the distance between cable and antenna. It can be reduced by extending the cables at least 10 m behind the antennas before they are allowed to be parallel to the antenna element axis. For horizontal polarisation the distance can be minimal providing the cable is laid orthogonally to the antenna. Ferrites are commonly used to reduce braid currents, though it is mistakenly thought by some to completely cure the problem. NPL uses ferrite clamps on the half inch diameter cable in all cases where balun imbalance is suspected, either Chomerics Type B2024-OAO or Fairite 2643102002 beads, but have not researched the best possible ferrite.

Antennas are commercially available which have perfect balance and operators are encouraged to use these.

#### **A1.6 Background to the work of CISPR/A ad-hoc group on antenna calibration**

A group of 8 experts was formed in September 1993 to improve the CISPR procedures for calibrating antennas and evaluating OATS. The group comprised members from Australia, Germany, Japan, the Netherlands, the USA and the UK. It was agreed that a higher quality OATS was required for calibrating antennas and this was called a CALTS or calibration test site. A paper on progress<sup>18</sup> was presented at the 1995 Zurich Symposium. The group proposed the use of methods to rigorously calculate the mutual coupling between two dipole antennas so that this could be compared with measurement as a means of validating the quality of a test site. It also proposed the use of free-space antenna factors as the default factor for the characterisation of EMC antennas. Uncertainty margins associated with the performance of antennas above a ground plane were quantified. The CALTS document<sup>19</sup> was sent to the IEC Secretariat in April 1997 for publication as a Committee Draft for Voting (CDV). This document will be discussed<sup>20</sup> at the IEEE EMC Symposium in August 1997.



## Appendix 2 Background to the tuneable dipole antenna

The antenna that is recommended by CISPR and the FCC as a reference antenna for measurement of normalised site attenuation<sup>2</sup> is the resonant dipole antenna. A tuneable dipole enables a broadband balun to be used with telescopic elements which can be set to resonant lengths at any frequency within the bandwidth of the balun. Resonant dipole antennas are favoured by the standards making bodies because it is straight forward to calculate their antenna factors. This makes it possible to design an antenna which is calculable with reasonable accuracy; a detailed design is given by ANSI<sup>7</sup>. This design and the references to it in CISPR 16-1 assume that free-space antenna factor is used. No account is taken of mutual coupling in these calculations of NSA. This can cause errors of several decibels at the lower frequencies. Attempts have been made to issue correction factors to allow for mutual coupling but these do not represent a rigorous solution.

It is possible to eliminate these errors by using readily available methods for calculating NSA including all mutual coupling effects. These methods are due to be published in the updated CISPR 16 Part 1. The method requires an antenna with detachable dipole elements so that the balun loss can be accurately measured. This will be specified in the CISPR document. NPL has produced a version of this antenna which is marketed, with software, by Chase EMC Ltd<sup>21,7</sup>.

Another role of the CISPR standard dipole antenna is to act as arbiter for emission measurements which are close to the specification limits and which have been made with broadband antennas. Because of this role, resonant antennas are often calibrated with lower uncertainties than broadband antennas. One problem is that the measurements can only be made one frequency at a time because the dipole length has to be adjusted for each new frequency. It is neither economic nor practicable to calibrate the dipole set at every frequency of use. The minimum number of frequencies recommended by CISPR<sup>2</sup>, Table G1, is 24. These are listed here in Appendix 5, Table 1. For intermediate frequencies the intention is to interpolate the antenna factor. Though this can be done with reasonable accuracy for free-space antenna factors, it cannot be done in the presence of a ground plane. This is because the electrical height (height of antenna in wavelengths above ground) changes with frequency. NPL have issued Tables<sup>15</sup> of corrections to allow interpolation of antenna factors between frequencies at any height.

The recommended method of calibrating resonant dipoles requires that they are set horizontally polarised at a height of 2 m above a conducting ground plane. However,

resonant dipole antennas are more sensitive than any other type of antenna to mutual coupling effects. As a consequence, when the dipoles are used at heights other than 2 m or for vertical polarisation, the measurement uncertainty is greater than for other types of antenna. Mutual coupling to the ground plane is much less for vertically polarised dipoles. The reason that horizontal polarisation is used for calibration is that measurement uncertainties associated with vertical measurements are greater due to site effects.

It has to be said that practitioners of EMC favour the use of broadband antennas and there is a strong case<sup>14</sup> for their acceptance in place of tuneable dipoles. The most important is that swept frequency measurements of NSA can be performed, essential for a proper validation of a site. Tables G2 and G3 in Ref. 3, which give NSA for tuneable dipole antennas, take no account of mutual coupling. This results in errors of up to  $\pm 0.8$  dB, additional to the AF calibration uncertainty, for the tabulated antenna geometries and frequencies in the range 30 MHz to 45 MHz. Nowadays biconical antennas can be calibrated to uncertainties of less than  $\pm 0.5$  dB. Antenna factor for a biconical antenna does not change significantly with height below 55 MHz because it is a high impedance short dipole in this range. Also NSA measurements can be performed using fixed heights in the frequency range 30 MHz to 300 MHz, eliminating the height uncertainty altogether - above 300 MHz the effect can be made negligible with the appropriate choice of height scan range.

## Appendix 3

### Measurement of field-strength in the near-field of an EUT

#### A3.1 Measurement of absolute field strength

Users of antennas sometimes request a special calibration of an antenna for measurements at a distance of 3 m from the EUT at frequencies above 30 MHz. The position currently taken by NPL is that free-space antenna factor, measured in the far-field of a source, is appropriate for measurements at 3 m. Some antenna manufacturers give two sets of antenna factors, one for 3 m and one for 10 m, measured using the ANSI C63.5 method. The reason for this is that there are near-field effects and mutual coupling between closely spaced antennas. The practice of calibrating antennas at a separation of 1 m is discussed in Section A3.3.

EMC dipole-like antennas have dimensions which are not much larger than half a wavelength,  $\lambda/2$ . Near-field effects can dominate the reading for distances less than  $\lambda/2$  from a radiating source and for uncertainty budget purposes they should be quantified for distances of less than  $\lambda/2$  from the source. In simple terms the near-field effects can be described as: (1) field strength variation by a  $1/r^2$  term<sup>22</sup> in addition to the  $1/r$  distance term, (2) an amplitude and phase taper of the emitted field throughout the volume of the antenna and (3) the effect of the proximity of the EUT on the current distribution on the antenna elements. The latter is a mutual coupling effect. There is also the possibility that the proximity of the antenna has an effect on the field emitted by the EUT.

If the field were to be extrapolated from a distance of 3 m (from the EUT) to the far-field there would be an error of 1 dB at 30 MHz, dropping to 0.2 dB at 75 MHz.

There are two problems with the ANSI method of calibration, described in Section A3.2, which give rise to an uncertainty of the order of  $\pm 0.5$  dB in the field strength of a small source at 3 m distance. This error was found by modelling, comparing the E-field at a point in space to the field registered by the biconical antenna. Studies at NPL have shown that in the case of the collapsible biconical antenna a free-space calibration gives a similar order of uncertainty. A free-space calibration is preferred because only one set of AFs is needed for all distances greater than 3 m. The use of free-space antenna factors is being recommended to CISPR/A WG1.

### **A3.2 Comment on ANSI C63.5 method of calibration**

The variation of 1.8 dB of antenna factor with height causes a problem with the accurate calibration of biconical antennas by the ANSI method<sup>7</sup>. One of the three antennas has to be used at a fixed height and as the height scanned antenna. Therefore one is trying to solve for four unknowns from three measurements. The calculation of antenna factors assumes only three unknowns, so the antenna factor of all three antennas is in error. The solution is to do the measurement all three antennas at fixed heights above the ground plane.

Additionally the formula, used to obtain antenna factors from the measured site attenuation between pair of antennas, does not include near-field terms and so does not give a rigorously defined antenna factor at 30 MHz when using a separation distance of 3 m.

Another problem with calibrating antennas-in-close-proximity by the three-antenna method is that mutual coupling between two antennas is built into the antenna factor, yet in an emission test the coupling is between one antenna and the EUT.

However the use of ANSI NSA values in Table 1 of Ref. 8, which do not include near-field terms, was found to be consistent with the method of calibrating antennas at  $R = 3$  m in ANSI C63.5. This was done by running a computer simulation of the ANSI method.

### **A3.3 Calibration with 1 m separation according to SAE ARP958**

In Appendix A1.1 the background is given to the choice of a 1 m separation between the antenna and the EUT in order to ensure better reproducibility of the measured field strength in an adverse measurement environment. At best the measurement was a prescription to compare the emission of different EUTs in a repeatable manner so that they could be passed or failed against a given specification limit. This was seen as a more important criterion than achieving an accurate measure of absolute field strength. However it resulted in the adoption of the ARP958<sup>16</sup> method for measuring the "1 m gain" of an antenna, whose equivalent for the purposes of this document is labelled "1 m AF<sub>ARP</sub>". This procedure is called up in standards such as MIL-STD-461<sup>12</sup>.

In 1968 the American Society of Automotive Engineers produced document SAE ARP958 which gave a method for calibrating conical log-spiral antennas operating above 200 MHz for testing EUTs at a distance of 1 m. The method did not take the variation of phase centre with frequency into account and could result in an error in the measurement of absolute field

strength of up to 1 dB for an antenna 0.8 m in length at 200 MHz. The error decreased to zero at 1 GHz corresponding to the reference plane at the tip of the antenna. This assumed the measurement was made in free-space conditions, so the error could increase if there was a ground reflection. The document states that the calibration is of “1 m AF<sub>ARP</sub>” which is not intended to give absolute field strength. In 1992 the document was revised to include the calibration of biconical antennas from 20 MHz.

The problem with this procedure is that it uses the same calibration method and equations as for a calibration in the far-field, which clearly results in errors at 30 MHz for which 1 m is a tenth of a wavelength ( $< \lambda/10$ ). The formula for deriving gain takes no account of the fact that at 20 MHz an antenna separation of 1 m is 0.07 wavelengths and is therefore truly in the near-field. “1 m AF<sub>ARP</sub>” is approximately 2 dB higher than the AF<sub>FS</sub> above 50 MHz, 2 dB lower at 30 MHz and 5 dB lower at 20 MHz which implies that the uncertainty in the measurement of absolute field strength could be 5 dB. Also the antenna under test will have built into its antenna factors the effects of coupling to the source antenna. When the source antenna is replaced by an EUT the coupling will be different and the antenna factor will not be wholly valid.

This is an example of a calibration procedure which results in antenna factors to be used for only one type of set-up, i.e. when making measurements with the tip of the antenna placed 1 m from the EUT. If the “1 m AFs” of a 0.8 m long spiral antenna were mistakenly used to measure an EUT at a distance of 10 m (in free-space) the field strength could be in error by 4 dB. If an antenna has to be used at different distances it would be sensible to use just the free-space antenna factors and correct the distance by the phase centre value at each frequency. The other point to note about free-space antenna factor is that it is a unique property of the antenna, giving the E-field strength of a plane wave, and not dependent on its proximity to other conducting bodies.

NPL research<sup>23</sup> on the reduction of uncertainties of 1 m measurements in screened rooms showed that uncertainties of typically  $\pm 30$  dB can be reduced to the target of  $\pm 6$  dB for frequencies above 30 MHz by partially lining the room with RF absorbing material. The EUT size was limited to 1 m<sup>3</sup> and the distance to the antenna increased to 2 m. Under these conditions the correct antenna factor to use was AF<sub>FS</sub>. These findings have been recommended as a basis for modifying the UK Defence Standard 59-41. There is therefore less incentive to research the uncertainties in measuring absolute field strength using a biconical antenna 1 m away from an EUT.

### A3.4 Conclusions

Free-space antenna factor is the preferred factor for converting the output voltage of an antenna into the absolute field strength of the field in which the antenna is immersed.  $AF_{FS}$  is a well defined property of the antenna, independent of its surroundings. When the antenna is used to make a measurement,  $AF_{FS}$  is the best starting point to quantify the field, for which the uncertainties of deviations from the free-space assumption can be assessed. There is little advantage in uncertainty terms in using  $AF_{3m}$  compared with using  $AF_{FS}$  at 3 m.

When assessing the uncertainty of measurement in the near-field it is important to know what the aim of the measurement is. Is it a) to measure the output voltage of the antenna as a means of comparing the performance of different EUTs, or is it b) to measure absolute field strength radiated by a specific EUT? In the latter case the method of calibration of the antenna contributes to the uncertainty of absolute field strength and there will be an additional uncertainty in the extrapolation of the field to greater distances.

The current position of NPL and NAMAS is that the antenna should be calibrated in the normal way for  $AF_{FS}$ . Measurement of  $AF_{FS}$  enables test houses using the same method to compare results of measurements using different models of antenna of the same type, eg biconicals. However NPL can calibrate to ANSI C63.5 and ARP958 if customers specifically request it.

## **Appendix 4    Emission measurements in screened rooms operating below cut-off**

Screened rooms of approximate size 6 m x 4 m and 2.5 m high are commonly used for emission measurements to Defence Standards. For frequencies below 30 MHz any absorber present may not be very effective so the room may be considered to be undamped. Also rooms of this size will be operating below the cavity cut-off frequency. This means that the radiated field from the EUT is not propagating and is likely to differ in magnitude from the field measured at the same distance in free-space.

Standards like MIL-STD-461<sup>12</sup> specify methods<sup>16</sup> of calibrating antennas for use at a distance of 1 m. However this method involves calibrating an antenna in open space, for subsequent use in a screened room. If one makes the assumption that a meaningful measurement of an EUT is one that gives the magnitude of radiated field strength when the EUT is operating in open space, a special calibration of the antenna for use in a screened room is required.

An appropriate method of calibration was investigated<sup>23</sup>. In this investigation a distance of 2 m was used between the antenna and the EUT, but the method equally applies for 1 m. A rod antenna was used to measure a 10 cm diameter spherical dipole emitter, both on an OATS and in a screened room. The difference between the measurements was used to correct a subsequent measurement of an EUT in a screened room to give the field that would have been obtained if the EUT had been measured on an OATS. It was necessary to also use a loop antenna to measure the spherical dipole. Furthermore it was necessary to replace the spherical dipole with an emitting loop and to measure its field with a rod and a loop antenna in the screened room and on the OATS. The correction factor that applies to the EUT depends on whether the EUT is primarily an E-field source or an H-field source.

The full procedure is described in References 24 and 25. It was found that the field radiated by the EUT in open space differed by about 10 dB from the field measured in a screened room operating below its cut-off frequency, when simply using the free-space antenna factors of the rod and loop antennas. When the above procedure was followed, the field measured in the room agreed, after correction, to within about 2 dB of the field measured on an OATS.



## Appendix 5    Guide to choosing the right calibration

The choice of calibration is governed by the final measurement uncertainty that the user of the antenna expects to achieve. Different laboratories accredited for antenna calibration offer different uncertainties. It is important to confirm the best measurement uncertainty when inquiring about antenna calibration. Additional to the achievable measurement uncertainty there are uncertainty terms associated with the properties of the antennas, referred to in the following paragraph. These can be minimised if the calibration is tailored to the eventual use of the antenna.

Using the currently recommended methods<sup>7</sup> of calibration, it is possible to have an error of 5 dB<sup>15</sup> in E-field strength at 1 m height using a dipole tuned to resonance at 30 MHz, if the user is not aware of the effect of mutual coupling that a ground plane has on the antenna factor. The variation in AF caused by the ground plane could be treated as a correctable error but, for broadband antennas, this implies calibrations at every height at every frequency. For emission testing using height scanning a compromise is to use free-space antenna factor at all heights, for reasons given in Section 8.1. However for site attenuation measurements one of the antennas will be at a fixed height. The uncertainty of measurement can be reduced by approximately  $\pm 1$  dB by having that biconical antenna calibrated at the relevant height and polarisation. The same applies to the calibration of a transfer standard biconical antenna, see Section 6.

It is vital to discriminate between a calibration of antenna factors for the purpose of emission testing and a calibration for the purpose of measuring NSA for a separation of 3 m according to ANSI C63.4<sup>8</sup>. The latter calibration does not give true antenna factors but only a means of comparing measured NSA with the theoretical NSA figures in ANSI C63.4.

The following tables summarise the range of antenna factors which can be measured at NPL. Table 1 is for measurement uncertainties of in the region of  $\pm 1$  dB and Table 2 is for uncertainties in the region of  $\pm 0.5$  dB.

## EMC antenna calibration services at NPL

**Table 1**

| Antenna type             | Type of calibration, see Service number                                                                                                                                                                                                                      | Service No. |
|--------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------|
| biconical & short dipole | AFfs 20 MHz to 300 MHz, $\pm 0.9$ dB<br>AF2m 20 MHz to 300 MHz $\pm 0.9$ dB                                                                                                                                                                                  | 1<br>2      |
| log (LPDA)               | AFfs 250 to 1300 MHz, $\pm 1$ dB;<br>100 to 249 MHz, $\pm 1$ to $\pm 1.5$ dB                                                                                                                                                                                 | 3           |
| bilog & †                | AFfs 30 to 1100 MHz, $\pm 1.2$ dB                                                                                                                                                                                                                            | 4           |
| log (spiral)             | AFfs 200 MHz to 1 GHz, $\pm 1.5$ dB<br>AFfs 1 GHz to 18 GHz, $\pm 1.3$ dB                                                                                                                                                                                    | 5<br>D1     |
| dipole set               | AF2m at 30, 35, 40, 45, 50, 60, 70, 80, 90, 100, 120, 140, 160, 180, 200, 250, 300, 400, 500, 600, 700, 800, 900 and 1000 MHz.<br>30 to 500 MHz, $\pm 0.5$ dB; 501 MHz to 700 MHz, $\pm 0.7$ dB; 701 MHz to 1 GHz, $\pm 1.0$ dB, surcharge for heights > 2 m | 6           |
| rods§                    | 100 Hz to 10 MHz, $\pm 1.5$ dB;<br>11 MHz to 100 MHz, $\pm 1$ dB                                                                                                                                                                                             | 7           |
| loops                    | 100 Hz to 100 MHz, $\pm 1$ dB                                                                                                                                                                                                                                | L1          |

### Notes:

The uncertainty is based on a standard uncertainty multiplied by a coverage factor of  $k = 2$ , providing a level of confidence of approximately 95%. All calibrations include measurement of return loss. Bicones, tuneable dipoles and bilogs are tested for balun imbalance. Broadband antennas are calibrated by stepped frequency technique using an interval of 1 MHz for biconical antennas and 2 MHz for log antennas.

AFfs is free-space antenna factor which is the recommended parameter.

AF2m is antenna factor for horizontal polarisation at height of 2 m above ground plane.

† includes LPDA operating from 80 MHz to 1.3 GHz.

§ rods are calibrated in free-field conditions, not by replacing the monopole with a capacitor.

The uncertainties may be increased (a) for antennas which show significant balun imbalance, (b) in the region of sharp antenna factor resonances and (c) where the polarisation of spiral antennas is not perfectly circular. Antenna factors for log-periodic dipole arrays (LPDA) are referred to the phase centre. Additionally values can be supplied with reference to the mechanical centre of the LPDA.

## EMC antenna calibration services at NPL

**Table 2 - lower uncertainties**

| Antenna type           | Type of calibration                                                                                                                                                                                                                    | Service No. |
|------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------|
| biconical short dipole | 20 MHz to 300 MHz, $\pm 0.5$ dB                                                                                                                                                                                                        | 8           |
| biconical              | AF per additional height in 0.5 m increments<br>AF#m where # is an arbitrary height for either polarisation                                                                                                                            | 9<br>10     |
| biconical              | AFfs 200 MHz to 1.2 GHz, $\pm 0.5$ dB                                                                                                                                                                                                  | 11          |
| bilog & †              | AFfs 30 to 1100 MHz, $\pm 0.7$ dB<br>(† 80 - 200 MHz $\pm 1$ dB)                                                                                                                                                                       | 12          |
| log (LPDA)             | AFfs 80 MHz to 5 GHz, $\pm 0.5$ dB, the uncertainty may be increased up to $\pm 1$ dB at the lowest operating frequency, because an LPDA acts more like a dipole                                                                       | 13          |
| log spiral             | AFfs 200 MHz to 1 GHz, $\pm 1$ dB                                                                                                                                                                                                      | 14          |
| dipole set             | AF2m, frequencies as service 6.<br>Uncertainties: 30 to 500 MHz, $\pm 0.35$ dB;<br>501 MHz to 700 MHz, $\pm 0.5$ dB;<br>701 MHz to 1 GHz, $\pm 0.7$ dB. Above 1 GHz please apply for quotation. There is a surcharge for heights > 2 m | 15          |
| dipole set             | sub-set of services 6, 13                                                                                                                                                                                                              | S1, S2      |
| ridged guide           | AFfs and apparent gain,<br>1 GHz to 18 GHz, $\pm 0.8$ dB                                                                                                                                                                               | D2          |
| horns                  | AFfs and apparent gain,<br>18 GHz to 40 GHz                                                                                                                                                                                            | D3          |

\quotes\services: September 1996

Notes: the notes for Table 1 also apply to Table 2.

The services in Table 2 are not recommended for antennas with significant balun imbalance. At some frequencies biconical and short dipole antennas with perfect baluns can be calibrated at spot frequencies to the same uncertainties as dipole antennas in service 15. Antennas can be calibrated to ANSI C63.5 or SAE ARP958 procedures on request.

The recommended interval between re-calibrations is no greater than 2 years. Prices apply for calibrations arranged by appointment. Measurements are normally completed within one week of the agreed start date, though it may be 2 weeks for dipole sets, allowing for the weather. We offer a fast turn round of 2 days if required, not limited to calibration periods, for which an extra charge may be levied. Please inquire about price reductions for volume work. For a full calibration of a dipole set, tables of correction factors for interpolation to other frequencies and heights are supplied.

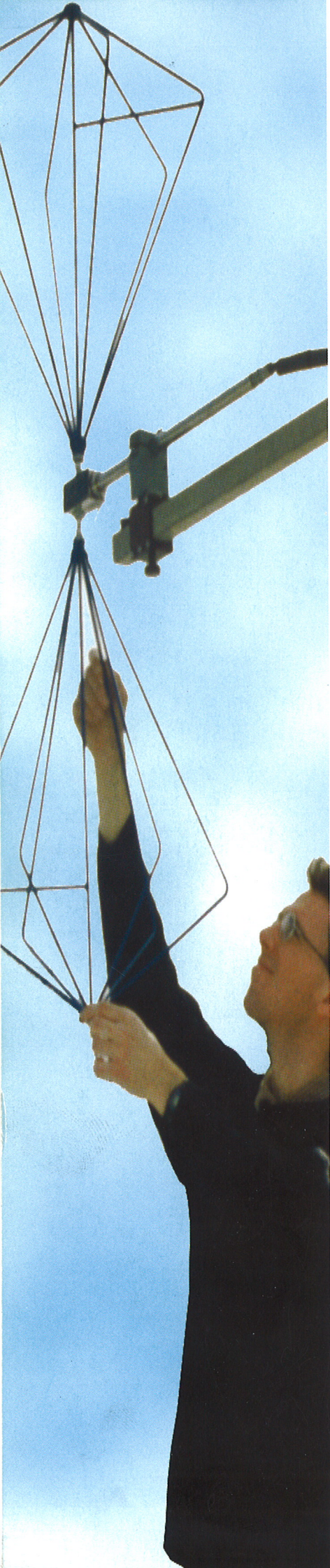
Enquiries are welcome for the measurement of any type of antenna in the frequency range 100 Hz to 5 GHz whose aperture size is no more than a few wavelengths and is less than about 2 m across. Examples are broadcast antennas, including mobile communications, and antenna arrays used as gain standards. The facility is equipped with a turntable and the full capability for performing radiated emission tests. Radiation patterns, in amplitude and phase, can be measured. The phase centre or position of the active elements on log-periodic dipole array antennas can be measured.

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email: [mja@npl.co.uk](mailto:mja@npl.co.uk). For horn antennas please contact D G Gentle (tel. 0181-943 6717) and for loop antennas and field probes contact K P Holland (tel. 0181-943 6947), fax as above.

<http://www.npl.co.uk/npl/cetm/antenna.html>



*Recommended sale price £15.00*