The Design of Dipole and Monopole Antennas with Low Uncertainties

Martin J. Alexander and Martin J. Salter

Abstract— **Close agreement between the measured and predicted insertion loss between dipole antennas above a conducting ground plane has produced a calculable standard dipole antenna. Antenna factors of dipole antennas in the frequency range 30 MHz to 500 MHz have been determined to an uncertainty of ±0.1 dB. Though the design of the dipole is not new, the key achievements are: the use of a large standard ground plane, the use of the program NEC to obtain broadband results, careful design of antennas and supports and precision measurements. Insertion loss and antenna factor are calculated by two independent methods, numerical and analytical, and the results agree to better than ±0.05 dB. The NPL calculable dipole antenna was originally designed for electromagnetic compatibility (EMC) applications in the frequency range 30 MHz to 1 GHz, but it can be used wherever electric field strength of free-field signals needs to be precisely measured. The technique was applied to monopole antennas for which antenna factor was determined to an uncertainty of ±0.15 dB over the frequency range 10 MHz to 100 MHz. In this paper, traceability of antenna factor to the predicted value rather than a measured value is justified.**

Index Terms— **Antenna factor, calculable antenna, dipole antenna, E-field strength, electromagnetic compatibility (EMC) antenna, low uncertainty, monopole antenna, standard antenna.**

I. Introduction

IT IS POSSIBLE to measure the gain of standard gain horn antennas to uncertainties better than ±0.05 dB [1] by eliminating all signal paths except the direct path between two antennas. Below 1 GHz horn antennas become unmanageably large and it is more common to use half-wave dipole antennas. Dipole antennas have low gain. At VHF frequencies it is not possible to eliminate all signal paths, unless the antennas are placed unacceptably high above the ground. One strategy is to measure the properties of omni-directional type antennas above an electromagnetically well characterized metal plane.

For more than 20 years the National Institute of Standards and Technology (USA) has operated a calibration service [2] to measure antenna factors of dipole antennas in the frequency range 25 MHz to 1 GHz. In 1989 NPL built a calculable standard dipole antenna [3], [4] whose antenna factor is within ±0.1 dB of the theoretically predicted value. This has been verified by measurement over the frequency range 30 MHz to 500 MHz. Above 500 MHz the result is more sensitive to the dipole construction and the location of the antennas above the ground plane. So far the best uncertainty achieved for antenna factor at NPL at 1 GHz is ±0.4 dB, but the aim is to achieve ±0.1 dB.

A. Background

The background to this work was to make available to practitioners of ElectroMagnetic Compatibility (EMC) the means to reduce the uncertainties of their E-field measurements, starting with the frequency range 30 MHz to 1 GHz common in EMC Standards. Measurement uncertainties for EMC emission measurements can be of the order of ±5 dB, under well controlled measurement conditions. It is only very recently [5] that EMC standards have required the assessment of the uncertainty of measurement in relation to measurements meeting the pass/fail criteria for electrical products. A working group of CISPR/A is preparing a document for the evaluation of EMC uncertainties and the impact this will have on pass/fail limit levels. In the past, antenna factor uncertainties of ±2 dB were widely accepted, but increasingly there are demands for uncertainties of the order of ±0.5 dB. Knowing that antenna factor can change by up to 6 dB through mutual coupling to the ground plane, it is difficult to gain recognition of the fact that antenna factors can be measured with uncertainties as low as ±0.1 dB. To support our uncertainty claims to determine antenna factors accurately for any height above a good quality ground plane, a section of this paper has been devoted to justifying the technique employed.

II. Measurement of Antenna Factor

The key to the validation of the dipole antenna is the comparison of the predicted and measured site insertion loss (SIL). In this context SIL is defined as the ratio of the power received with the antenna input cables connected together to that received when the antennas are inserted and positioned apart above a ground plane for the same input power, Fig. 1. It is difficult to model the effect of a ground plane of finite area on the coupling between two antennas. If instead it can be shown that the measured SIL agrees with the value computed using an infinite ground plane, the adequacy of the finite plane is proved. The two antenna method was used. In the calculation of antenna factor the ground reflected signal is vectorially removed using Smith's formula [6].

A. NPL Ground Plane

NPL has an uncovered outdoor ground plane [4] of dimensions 60 m × 30 m. It is a continuously welded steel plate with a flatness of ±6 mm over 95% of its area. The equipment

Manuscript received June 20, 1996; revised October 1996.

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Publisher Item Identifier S 0018-9456(97)01610-0.

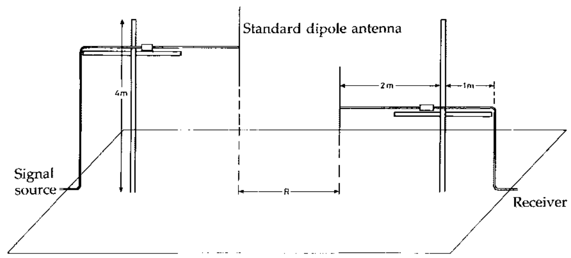
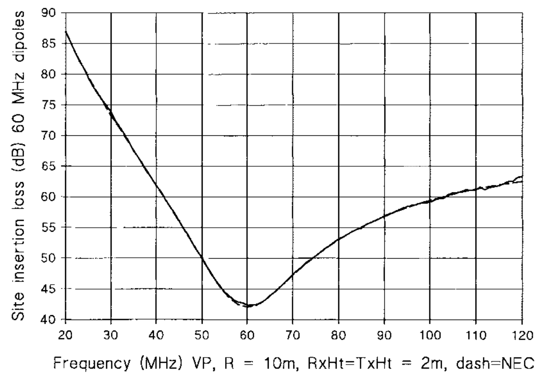
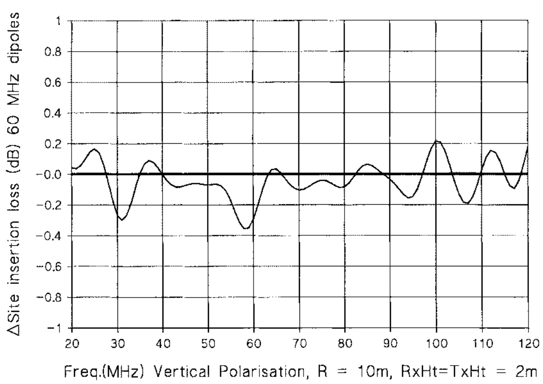


Fig. 1. Measurement set-up for site insertion loss. Two dipole antennas above a ground plane, fed by coaxial cable.



(a)



(b)

Fig. 2. (a) Site insertion loss for a pair of vertically polarized 60 MHz dipoles. Separation = 10 m, height = 2 m. Solid line is measured data and dashed line is NEC computed data. (b) Graph of difference between measured and computed results of (a).

cabin, built of timber and block is 45 m away from the centre of the ground plane. Trees are in excess of 50 m and other buildings more than 200 m away from the ground plane. It is ensured that unwanted reflections from antenna supports, trees and buildings give an insignificant contribution to the result. For frequency scanned measurements with vertically polarized antennas a peak to peak ripple of ± 0.3 dB shows on the SIL plot, which is caused by diffraction from the edges of the ground plane. When the surrounding soil is wet the edge currents are dissipated and the ripple is reduced to approximately ± 0.1 dB.

III. Calculation of Antenna Factor

The antenna factors can be calculated from the site insertion loss or simply from the properties of the dipole elements. NPL uses two independent methods of calculating the properties

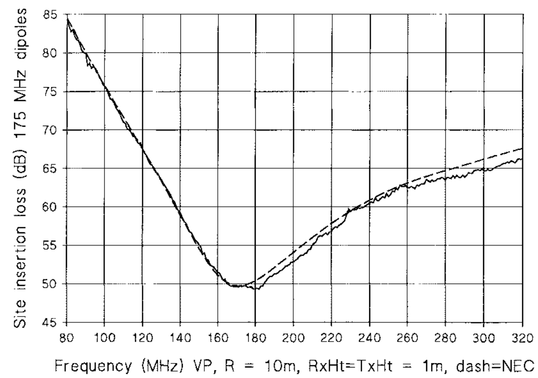


Fig. 3. Site insertion loss for a pair of vertically polarized 175 MHz dipoles. Separation = 10 m, height = 1 m. Solid line is measured data and dashed line is NEC computed data.

of linear dipole antennas and the coupling between a pair of such dipoles. The first is the program NEC [7] which uses the method of moments to solve an integral equation for the current on the dipole. The second is the induced emf method which assumes a sinusoidal current distribution on the dipole elements [8]. NPL calls this method SCD. It is only accurate when resonant dipole lengths of very thin wires are used. The two methods agree to less than ± 0.05 dB. NEC has the advantage that it accurately predicts the measured performance of the dipoles over a bandwidth of the order of 200%.

A. A Calculable Standard Dipole Antenna

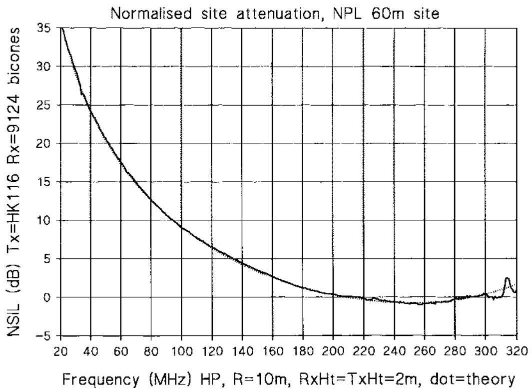
The dipole element parameters are calculated and then combined with the measured S-parameters of the antenna balun to give the antenna factor or the insertion loss between pairs of antennas. Antenna factor can be computed for free-space and any height and orientation above an infinitely large and perfectly conducting flat ground plane. The antenna factor of a horizontally polarized dipole antenna resonant at 30 MHz changes by 6 dB when raised in height from 1 m to 4 m above a metal plane. Such changes are fully calculable, including the 0.3 dB effect of the dipole tips drooping under their own weight.

B. Monopole Antennas

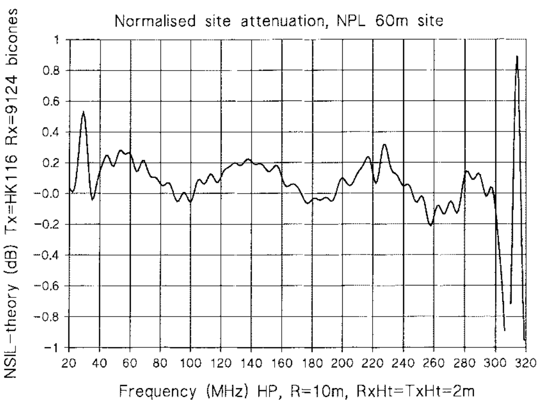
The same principle was applied to monopole antennas. Two one meter length metal rods were connected to N-type bulkhead connectors on the ground plane. The insertion loss between the two monopole antennas was measured and compared with the value predicted by NEC. The results agreed within ± 0.3 dB over the frequency range 10 MHz to 100 MHz, which implies that antenna factor is known to an uncertainty of ± 0.15 dB. Below 10 MHz the high input reactances of the pair of monopoles meant that the coupled signal was very small comparable with receiver noise. The aim is to make measurements down to 10 kHz, which will necessitate the use of transformer baluns.

C. Results

The measured insertion loss between two horizontally polarized dipole antennas agreed with the theoretically predicted value to better than ± 0.2 dB over the frequency



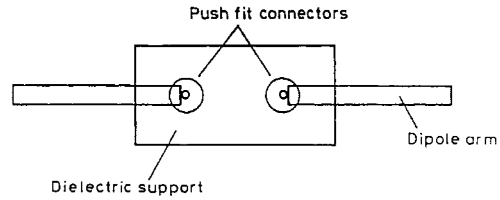
(a)



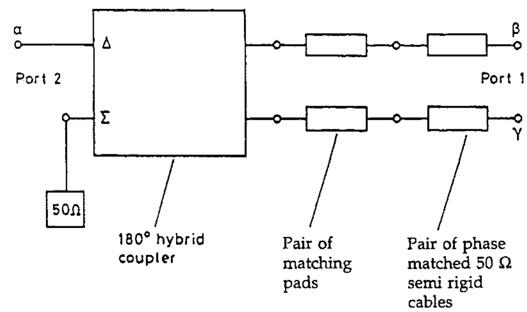
(b)

Fig. 4. (a) Normalized site insertion loss for a pair of horizontally polarized biconical antennas. Separation = 10 m, height = 2 m. Solid line is measured data and dotted line is simple far-field theory. Bicone types are Rohde & Schwarz HK116 and Schwarzbeck 9124. (b) Graph of difference between measured and computed results of (a).

range 20 MHz to 600 MHz. The best results apply to resonant dipoles and these are reported in [4]. The NEC calculations agree very well with the results of broadband measurements of coupling between two dipole antennas. It is well known that it is harder to achieve accuracy with vertically polarized measurements above a ground plane than with horizontally polarized measurements. A sample of results is given in Figs. 2 to 4. NPL uses 4 dipoles resonant at 60 MHz, 175 MHz, 400 MHz and 700 MHz to cover the frequency range 20 MHz to 1 GHz. Fig. 2(a) shows the insertion loss between two vertically polarized 60 MHz dipoles. The output cables were led horizontally 8 m behind the antennas before dropping to ground, to minimize reflections from the cables. Fig. 2(b) shows a difference of less than ±0.3 dB between the NEC and measured results, which is an exceptional achievement for vertically polarized measurements. Fig. 3 repeats this exercise using 175 MHz elements, showing a difference of 1 dB above 175 MHz. This could be because there are bigger reflections from the mast components at the higher frequencies. An investigation is required. Changes in received signal of up to ±0.2 dB have been noticed for vertically polarized measurements. This was caused by edge diffraction and appeared as a cycle on a swept frequency plot of insertion loss, which in come cases is possible to identify as a systematic error and therefore correct.



(a)



(b)

Fig. 5. (a) Dipole elements in dielectric support. (b) Schematic diagram of balun. Input port is α and ports β and γ are connected to dipole elements.

The results of Fig. 4(a) are for the normalized site insertion loss (NSIL) between two horizontally polarized biconical antennas, compared with the theoretical NSIL. The antennas were calibrated by the standard antenna method using the 60 MHz and 175 MHz elements and their computed broadband antenna factors, Fig. 4(b) shows a difference of less than ±0.3 dB between the measured and predicted results. This means that the antenna factors of each bicone are known to within ±0.15 dB of their true values for the operating frequency range of the antennas, 20 MHz to 300 MHz.

IV. Justification for Traceability to Calculated Antenna Factor

The question to answer is "how can one be sure that the predicted antenna factor gives the true value of the antenna factor (with its associated uncertainty)?". The scene can be set by contrasting the technique used here with the standard antenna used by NIST [2]. The NIST method is conceptually simple. Antenna factor, AF, is obtained by calculating the inverse of the effective length of a dipole element. For a very thin resonant dipole this is simply π/λ. The voltage, V_{out}, induced at the centre of the dipole by the incident field, E_{inc}, is measured. The field strength is found from the relation:

$$E_{\text{inc}} = AF \cdot V_{\text{out}}.$$

The known field can then be used to calibrate an antenna under test. The standard dipole comprises a wire dipole of resonant length with a Schottky diode at its centre. The diode is connected, via a short filter section and a length of high impedance lead, to a voltmeter. This method has been tried at NPL but uncertainties no better than ±0.5 dB were achieved. A special licence is required in the UK, available at a limited number of frequencies, to transmit the high field strengths required to generate sufficient voltage across the diode. Also there is no frequency selectivity so the measurement is susceptible to broadband RF interference. Advantages of this method are that the high impedance lead does not disturb the RF field and that the antenna element has a high input impedance so the antenna factor does not change with height above the ground plane.

The antenna design employed by NPL allows all measurements to be made at RF. Since the measurements are of power ratio, rather than absolute power or voltage, they can be highly accurate. The antenna comprises a 3 dB hybrid difference coupler which is detachable from the antenna elements to enable the S-parameters of the hybrid to be measured, Fig. 5. Antenna factor was chosen to be traceable to the computed value rather than a measured value. The objective is to measure antenna factor for which one needs a good quality test site The quality of the test site is determined by measuring it with a pair of antennas with known antenna factors. This creates a dilemma. The site is needed to measure the antenna, but the antenna has to be known in order to first measure the site. Fortunately the performance of a dipole antenna above an ideal ground plane can be calculated very accurately. If two identical dipoles are set up above a ground plane and the measured insertion loss is compared with the predicted insertion loss, the quality of the antennas and the test site can be assessed simultaneously, but cannot be deconvolved. With special care the majority of the measurements agreed to better than ± 0.1 dB.

Not only does this procedure confirm the quality of the NPL antennas and test site, but it confirms the accuracy of the analytical theory of dipoles [8] and of the NEC software [7].

When the antenna height is changed in the model, the change in measured antenna factor is accurately predicted. Measurements have been done at NPL using different combinations of heights and antenna separations, in the near-field as well as far-field, for 19 pairs of dipoles covering the frequency range 30 MHz to 600 MHz. All gave good agreement between measurement and prediction. The model can be relied on to fully account for mutual coupling. Traceability to the NPL calculable dipole antenna is to the predicted element antenna factor rather than the measured element antenna factor. Nevertheless the total antenna factor includes the measured balun loss.

A. Assessment of the Uncertainty of Antenna Factor

A comprehensive uncertainty budget for the measurement of site insertion loss, and hence antenna factor, can be found in reference [4]. An expanded total uncertainty, based on a standard uncertainty multiplied by a coverage factor of $k = 2$, was drawn up in the manner prescribed by the ISO Guide [9]. However the procedure described in this paper gives another route to quantifying the uncertainty of measurement. In cases where the model so closely predicts the measured result, one can place a lot of confidence in the model. This confidence can be translated into an assessment of uncertainty of measurement.

As the frequency is increased from 30 MHz to 500 MHz the biggest difference between measured and predicted insertion loss using the NPL ground plane is ± 0.2 dB. If the site were perfect the antennas take the maximum uncertainty. The ± 0.2 dB agreement can be apportioned between the two antennas. The two antennas were identical to within ± 0.05 dB. It is unlikely that the site is perfect, so antenna factor is known to better than ± 0.1 dB. If it were possible to measure to better than ± 0.1 dB, a systematic difference between measurement and theory may be revealed. Correcting for this would further reduce the uncertainties.

V. Further Work

The aim is to produce a standard dipole with the same uncertainty up to 1 GHz. The problem has been the dielectric element support which becomes large relative to the element length at 1 GHz. Also it is aimed to provide a calculable standard monopole antenna that operates down to 10 kHz. The problem to overcome is the lack of received signal below 10 MHz caused by the large mismatch of receive and transmit antennas. To date, antenna factor uncertainties of ± 0.4 dB and ± 1 dB have been achieved at 1 GHz and 10 kHz respectively. Another task is to overcome mast reflections at the higher frequencies for vertically polarized measurements. NPL currently offers customers uncertainty of ± 0.35 dB from 30 MHz to 500 MHz, ± 0.5 dB from 501 MHz to 700 MHz and ± 0.7 dB from 701 MHz to 1 GHz (however for directive antennas, such as log-periodic arrays, the uncertainty offered in the frequency range 701 MHz to 1 GHz is ± 0.5 dB). The aim is to achieve ± 0.3 dB from 30 MHz to 1 GHz. An international intercomparison of antenna factors is in progress, under the auspices of BIPM, similar to a European intercomparison [10] completed in 1995.

VI. Conclusions

Agreement of better than ± 0.2 dB between measured insertion loss and its theoretical prediction validates not only the antenna design but also the ground plane and the theory being applied. The usability of this dipole antenna design is considerably enhanced by the calculability of its broadband properties. With antenna factor uncertainties as low as ± 0.1 dB it is possible to measure radiated electric field strength to uncertainties of better than ± 0.2 dB, based on a standard uncertainty multiplied by a coverage factor of $k = 2$, providing a level of confidence of approximately 95%.

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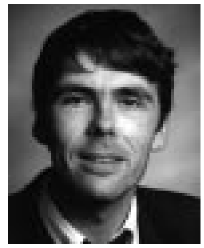

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