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Investigation into the Errors Introduced by Using Multiple E Field Probes Concurrently

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Abstract: Measurement of the E field component of a RF electromagnetic field at a single point using electric field probes is well understood. However, using a single probe to measure the E field at a number of points in space is time consuming and the results are at different actual times. A multiple probe array may be considered in order to achieve a “snapshot” measurement of all test points concurrently but, since each probe itself distorts the field, measurement error is introduced. This error has been investigated by experimental and modelling techniques, using a range of field scattering bodies and antennas, to determine if it can be limited sufficiently to make the use of multiple probes viable.

Background

There are a number of applications that would benefit from the ability to accurately measure the E field at a number of points in space simultaneously. For example, evaluating the uniformity of field intensity used to illuminate equipment undergoing electromagnetic compatibility (EMC) radiated immunity tests, or when experimentally measuring transmission antenna radiating patterns. Measuring each point individually introduces a time delay factor, which may be significant where varying or transitory fields are being monitored. Where knowledge of the frequency values of the signals comprising the field is not required, measurements can be made using field probes that combine both antenna elements and detector circuits together in a single unit. Although not capable of the same degree of sensitivity as dipoles, horns or other “standard” antennas, field probes take advantage of a small-volume, integrated form and lack of external electrical connection to minimise the distortion of the field being measured. Some distortion introduced by the presence of field probes is, however, inevitable.

The purpose of this study was to determine the degree of field distortion caused by a hypothetical E field probe in order to see whether using an array of such probes to measure a number of points in space simultaneously would introduce significant errors, compared to using a single probe in isolation at each point sequentially. Commercially available E field probes state typical accuracies of around 1dB (see [Holaday] [ETS-Lindgren] [Amplifier Research] product references), and with this in mind an error of 1dB or better, due to the presence of an array of probes, is appropriate for the E field probe array proposed in this paper.

Sources of measurement error

The presence of a conducting body in an electric field causes distortion of the field. In the case of a metallic body such as a field probe, a significant proportion of the distortion is caused by scattering i.e. reflection of the incident wave. Depending on the surface properties of the body, such scattering may be specular (e.g. from a mirrored surface) or random (e.g. diffuse reflection from a rough surface). The re-radiated fields combine with the source field,
establishing interference patterns and thus altering the intensity of the field at points throughout the field.

Distortion is also caused where the body absorbs energy from the incident wave which then, by some mechanism, causes a new field to be radiated. For a metallic body, surface currents induced by the incident field will themselves cause fields to be radiated, the pattern and orientation of which will be dependent on the “shape” of the surface currents.

These effects are iterative, and become increasingly complex where more than one body exists within the field. A flowchart indicating the interaction between two such bodies has been presented [Figure 1, Elsherbeni]. In order to investigate the properties of field probes, this has been expanded to include the special case where the bodies contain antenna elements, which have scattering, absorption and re-radiation properties that can be separated from those of the body itself, relating as they do to currents flowing in both the antenna structures and the connected load circuitry.

![Flowchart](image)

Figure 1 Flowchart for analysing two-body scattering proposed by Elsherbeni and Harmid, expanded to include the case where bodies contain antenna structures.

**Experimental methods**

The effect of field scattering by the probe bodies has been investigated by experimentation with the setup shown in Figure 2. The measurement of an E field using a probe in isolation is compared with measurements taken in the presence of a range of differently sized scattering objects, detailed in Table 1, placed at a number of increasing separation distances from the probe.
Figure 2 Test setup for evaluating the effect of nearby objects on $E$ field measurements with the fixed distance between the field generator and test point probe position being $d = 3m$ and the variable distance between probe and neighbours being $s m$.

<table>
<thead>
<tr>
<th>Object</th>
<th>Size</th>
<th>Construction</th>
<th>Separation $(s)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cube, $l = 100mm$</td>
<td>Metal box</td>
<td>0.3m</td>
</tr>
<tr>
<td>2</td>
<td>Cube, $l = 50mm$</td>
<td>Metal box</td>
<td>0.5m</td>
</tr>
<tr>
<td>3</td>
<td>Diameter $h = 15mm$</td>
<td>Length $l = 100mm$</td>
<td>1.0m</td>
</tr>
<tr>
<td>4</td>
<td>Cube, $l = 120mm$</td>
<td>100mm metal box with ferrite covering</td>
<td></td>
</tr>
</tbody>
</table>

Table 1 Test objects and their separation distances from the probe.

The $E$ field was generated by a 30MHz – 2GHz broadband noise source (York EMC Services Comparison Noise Emitter model CNEV+) fitted with a monopole antenna, and measured at point $d = 3m$ away using a dipole antenna fitted with two 20mm long elements. Using a broadband noise source meant that the full measurement frequency range was excited, so that sweeping the source signal was unnecessary. In order to reduce the noise content of the signal, the results were averaged over 25 samples.

Tests were performed inside a fully anechoic chamber in order to mimic a free-space environment. The source, probes and test objects were mounted on low $\varepsilon_r$ polystyrene stands, present during both test runs, in order to minimise any $E$ field distortion affecting the results. Using this setup, adequate measurements to 2GHz were achieved.

**Experimental results**

The results for the $E$ field strength from the measurements made with the source and receive antennas vertically polarized (i.e. the scattering objects broadside to the antenna) are shown in Figures 3 to 5, with increasing separation of the neighbouring scattering object from the
central test probe. It is results for the deviation of the $E$ field from the situation where there is no neighbour present, that are given.

Figure 3 Deviation of the $E$ field strength due to the presence of nearby test objects, where the separation between probe and objects $s = 0.3$ m.
These results indicate that the size of the nearby probe influences the degree of disturbance (a larger object leads to a greater disturbance) and that the separation influences the degree of deviation (the further the neighbouring object is from the central probe the weaker the disturbance). Furthermore the separation affects the periodicity of the constructive / destructive pattern effects at the measurement point.

An example of the interference caused by the scattering from a nearby object is shown in Figure 6, which considers the test setup shown as an approximation of the multipath propagation between two horizontally polarized dipoles over a reflecting ground plane. The phase inversion associated with ground-plane reflections of horizontally polarized waves leads to maxima (where the waves at the observation point are in-phase) when the difference between path lengths is an half-integer number of wavelengths ($n_{\text{max}}$). Similarly, minima (where the waves at the observation point are in anti-phase) occur when the path length difference equals an integer multiple of wavelengths ($n_{\text{min}}$), e.g. (referring to Figure 6).

$$\text{Maxima } (f) = \frac{c}{\lambda_{\text{difference}}} = \frac{cn_{\text{max}}}{2((P_1+P_2)-d)} \text{ Hz} [\text{Equation 1a}]$$

$$\text{Minima } (f) = \frac{c}{\lambda_{\text{difference}}} = \frac{cn_{\text{min}}}{((P_1+P_2)-d)} \text{ Hz} [\text{Equation 1b}]$$

In practice, the effect will be the sum of all interactions between all reflecting points on the object surface. As such, a fully descriptive closed-form analytical solution is difficult to achieve, although formulae for simplified models involving pairs of scattering bodies of various types have been presented [Allen, 2005] [Hui, 2004]. However, by calculating the
difference between the direct and reflected path lengths (in this example from the nearest point of the scattering object) it can be confirmed that the frequency spacing between the interference peaks and nulls decreases as the separation increases. Also, since the intensity of the interfering field reaching the probe will increase with the size and proximity of the scattering objects, smaller, more distant objects will result in smaller amplitude peaks and nulls.

![Diagram showing multipath propagation](image)

**Figure 6** Calculations for predicted frequencies of maxima/minima in received signal due to multipath propagation (due to reflections from the leading edge only). The distance between the field generator and test point probe position is \( d = 3 \, \text{m} \).

The results indicate that, up to a frequency of 2GHz, a disturbance of <1dB could be achieved with a probe size of 50mm\(^3\) or smaller, with the minimum practical enclosure size as a target. Construction of field probes for this kind of application should therefore favour a small footprint facing the source, with a shape designed to scatter any reflections as broadly as possibly, exploiting length in order to achieve the necessary volume for the probe circuitry (e.g. cylindrical shape).

The test frequency range for the experiment was limited due to the equipment available. Further experimentation to determine the effects between 2-6GHz is planned.
Modelling methods

As with scattering of the field by the probe bodies, the interaction between antenna elements is iterative, with the net effect being the sum of all reflections and transmission from all parts of the antennas involved. A closed-form analytical solution is therefore difficult to achieve, although formulae for simplified models involving pairs of half-wave dipoles have been proposed [Kazemipour & Begaud, 2002]. Numerical modelling has therefore been used to investigate the interaction between the antennas. Modelling has been performed using the NEC-2 software, which uses the Method of Moments (MoM) technique [Kraus & Fleisch 1999]. This is particularly suited to problems such as this, involving elementary wires, currents and fields in homogenous environments. The response to an incident $E$ field of a single probe in isolation is calculated, and then comparing to the numerical results obtained when the probe is the central object in an array (see Figure 7).

![Figure 7 Model arrangement of source, receive and array dipoles. NEC E field results are presented later for a plane cutting this figure centrally containing the source and central probe dipole.](image)

The probes have been modelled as electric dipoles, comprising perfectly conducting rods with simplified Shottky detector diode circuit equivalents at the centre load points, a method previously used successfully to analytically and numerically study and predict the operation of electric dipole field probes [Kanda & Driver, 1987]. The dipole rod length and the resistive component of the Shottky diode model are altered in order to evaluate the effect of mutual impedance on the result. Realistic values for dipole length and load are used to determine the sensitivity of an actual antenna/detector pair, after normalisation to the incident $E$ field intensity.
One method of describing the interaction between antennas is through their mutual impedance. In the example shown (see Figure 8) this can be defined as the voltage \( Z_{12}I_2 \) induced in Antenna 1 as a result of the secondary field generated by Antenna 2, due to the current \( I_2 \) induced in Antenna 2 by a common incident electromagnetic field.

By examination of Figure 8, it can be seen that increasing the load resistances \( Z_{L1}, \ Z_{L2} \) will minimise the effect of mutual impedances \( Z_{12}, \ Z_{21} \) on the voltages developed across the loads, \( V_1 \) and \( V_2 \) respectively and thus reduce the error. For the field probes being investigated, the antenna loads are typically Schottky detector diodes whose sensitivity and impedance characteristics are bias-current tuned.

The diode detector loads have been represented in the NEC-2 model as single-segment parallel R/C networks (see Figure 9) with variable values of resistance \( R_j \). For a typical Schottky detector diode (e.g. Agilent HSMS-286x series), \( R_s = 6\Omega, \ C_j = 0.18pF \) and \( R_j = 8.33 \times 10^{-5} \frac{nT}{(I_b + I_s)} \), where \( n = 1.08, \ T = \text{temperature (K)}, \ I_s = 5 \times 10^{-8}A \) (saturation current) and \( I_b \) = bias current. From this a bias current of 1μA gives \( R_j = 26k\Omega \), zero-bias gives \( R_j = 540k\Omega \) and 1mA bias gives \( R_j \approx 27\Omega \). The simulations have been performed using \( R_j \) values of 50Ω and 250kΩ.

To establish the same physical conditions, in the NEC-2 simulation, as the experimental investigation, an \( E \) field was generated using a current-driven dipole, at a distance \( d = 3m \) from the probe array by (see Figure 7). A comparison was made of the voltage developed across the dipole load in the presence of this \( E \) field, between a single probe in isolation and
the same probe surrounded by eight identical antennas in a 0.5m × 0.5m grid array where the separation between the centres of the dipoles is given by \( s = 0.5 \) m.

**Modelling results**

An \( \mathbf{E} \) field plot for the NEC-2 numerically generated results, for the full probe array is shown in Figure 10, for a section defined by the plane containing the source and central probe dipoles (see Figure 7). The source antenna is visible at the top of the plot, with the cross-section through the generated \( \mathbf{E} \) field clearly showing the toroidal pattern of intensity for a radiating electric dipole [Kraus & Fleisch 1999]. Individual antennas comprising the receive array are visible at the bottom of the plot, parallel to the \( y \) axis. Those antennas in the plane of the plot clearly show interaction with the \( \mathbf{E} \) field as a localised disturbance in the field intensity.
The normalised response from a 40mm dipole probe (a pair of 20mm elements) with a 50Ω diode detector, in isolation and in the presence of the probe array is shown in Figure 11 while in Figure 12 a 250kΩ diode detector is employed.
In Figure 13 the difference between the single probe and array responses for both load resistance values are plotted in closer detail. Figure 13 indicates that the array introduces a
maximum error approaching +/-0.8dB around a frequency region close to the 40mm dipole’s half-wave resonance (assuming effective dipole length is 0.9 of the actual length, $\lambda/2 = 4.17$GHz).

![Graph](image)

Figure 13 Deviation versus frequency due to the presence of the array of 40mm (two 20mm element) dipoles, with 50$\Omega$ and 250k$\Omega$ detector diode models

Repeating the numerical simulation with an increased load resistance does not significantly reduce the array error (see Figure 13), although a higher detector voltage is achieved for a given incident $E$ field intensity (comparing Figures 11 & 12).

The simulation was repeated using a 10mm dipole (two 5mm elements) and the results are presented in Figures 14 and 15 for the 50$\Omega$ and 250k$\Omega$ diode detector loads respectively. At 6GHz, each 5mm element is still less than $\lambda/10$, thereby satisfying the criteria for an electrically short antenna, and so exhibiting an almost flat frequency response (see Figure 14). (Note that the 1GHz period ripples seen are due to interpolation errors in the $E$ field normalisation calculation). In each case, the error introduced by the array appears to be greatly reduced in comparison to the 40mm dipole probes, with the single probe responses almost indistinguishable from the corresponding response in an array.
Figure 14. Normalised transfer function against frequency of the 10mm (two 5mm elements) dipole, with a 50Ω detector diode model. The single and multiple probe response curves lie on top of each other.

Figure 15. Normalised transfer function against frequency of the 10mm (two 5mm elements) dipole, with a 250kΩ detector diode model. The single and multiple probe response curves lie on top of each other.

In Figure 16 the difference between the single probe and array responses for both load resistance values are plotted. Figure 16 indicates that the array now introduces a maximum error approaching +/-0.008dB.
This represents a significant improvement over the longer dipole model. As the electrically shorter 10mm dipoles are less efficient receivers and transmitters, compared to the 40mm dipoles operating around their $\lambda/2$ point, the mutual coupling between them is greatly reduced and consequently the error introduced is also reduced.

The 10mm dipoles remain electrically short across the frequency range examined and so exhibit very low antenna resistance $R_t$, where $R_t$ for an electrically short dipole of length $l$ is given by

$$R_t = 80\pi^2 \left( \frac{l}{2} \right) \left( \frac{I_{av}}{I_0} \right)^2 \text{ and where } \left( \frac{I_{av}}{I_0} \right) \approx \left( \frac{1}{2} \right) \text{ for an electrically short dipole} \quad \text{[Equation 2]}$$

and the terms $I_{av}$ and $I_0$ describe the current distribution along the length of each dipole element [Kraus & Fleisch, 1999]. For an electrically short dipole with approximately linear current distribution, the average current $I_0$ is $\frac{1}{2}$.

For example, where $l$ is one-tenth the minimum wavelength $\lambda$, the maximum value of $R_t$ is $2\Omega$. As a result, increasing $R_t$, beyond a few $10’s$ of Ohms does not significantly reduce the array-related error. However, increasing the load resistance presented by the detector circuit does increase the $V_{Out}/E_{Field}$ sensitivity and contributes to a much flatter frequency response overall from the probe (comparing Figures 14 & 15).

**Conclusions**

This study has shown that it is a practical solution to use an array of multiple field probes to measure the RF $E$ field intensity at many points over an area. With careful selection of the probe size, antenna configuration and array spacing, the errors relating to field distortion by the probes can be minimised to an order similar to the inherent measurement error of a typical commercially available probe.
References


Kanda M, Driver L D: An Isotropic Electric-Field Probe with Tapered Resistive Dipoles for Broad-Band Use, 100kHz to 18GHz, IEEE Transactions on Microwave Theory and Techniques, Vol. MTT-35, No 2, February 1987

Kazemipour A, Begaud X: A Simple Closed-Form Formula for the Mutual Impedance of Dipoles, Microwave and Optical Technology Letters, Vol. 34, No 5, September 2002


Allen O E: Modeling General Purpose Antennas as Minimum-Scattering Antennas, IEEE 0-7803-8883-6/05, 2005, p47-50


CNEV+ 9kHz to 3.5GHz York EMC Services Ltd battery-powered broadband radiating reference noise source.  
http://www.yorkemc.co.uk/instrumentation/cnev+/  

Agilent HSMS-286x datasheet  
http://www.avagotech.com/docs/AV02-1388EN  

Holaday 10kHz-1GHz battery powered isotropic field probe, 64x64x64mm cube plus antenna radomes.  

ETS-Lindgren HI 6005 isotropic E field probe Freq 100kHz to 6GHz  
http://www.ets-lindgren.com/page/?i=HI-6005

Amplifier Research FL7006/kit 100kHz-6GHz isotropic E field probe  