Image and Return Current Modeling of PCB Traces for Radiated Emissions.

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Abstract: This paper establishes that the image current spread induced on a ground plane by a balanced PCB trace is several times wider than the return current spread of an unbalanced PCB trace. The magnitude of the image current, unlike that of the return current, is not only very small but it also has a non-uniform flow pattern similar to eddy current in a transformer. Therefore, the combined radiated emission levels of a balanced trace and image current is always higher than that of an unbalanced trace and sometimes higher than that of an isolated balanced trace. Radiated emission measurements for an isolated balanced trace loop without a ground plane, a balanced trace loop over a ground plane, and an unbalanced trace over a ground plane were made. The resulting radiated emissions data are presented as Cartesian and polar plots. The variation of current spread levels with respect to spread width is also investigated.

I. INTRODUCTION

A circuit loop formed by traces in a PCB is called a balanced trace if the ground plane is not a part of a circuit loop (Fig. 1), and it is called an unbalanced trace if the ground plane is a part of a circuit loop (Fig. 2).

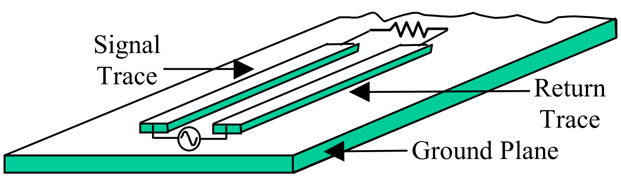

Figure 1. A Balanced Trace circuit loop over a Ground Plane
(Ground Plane is isolated from Traces)

The current of a balanced trace induced on the adjacent ground plane is defined as image current in this paper. This definition should not be confused with image current as explained in "method of images" for solving antenna ground reflection problems [1,2]. The circuit loop current of an unbalanced trace flowing on a ground plane is called return current. The width of the image or return current is always wider than that of the trace current [3,4], and the image current width is always wider than the return current width (Fig 3,4). The center area enclosed by the image current is therefore smaller than the area enclosed by trace current. This paper examines image and return current characteristics for current spread and distribution density. The current spread levels for different ground spread widths were measured using a current probe. The variation of current spread levels with respect to spread width is discussed. The effect of image and return current on the trace current radiation is studied.

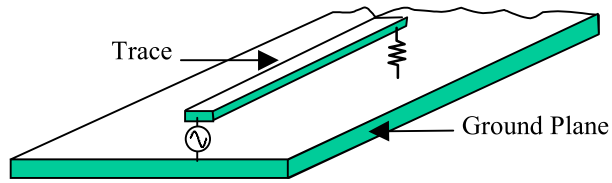

Figure 2. An Unbalanced Trace
(Current is Path is through Ground Plane)

Radiated emission levels for an isolated balanced trace loop without a ground plane, a balanced trace loop over a ground plane, and an unbalanced trace over a ground plane were measured in a 3 m absorber-lined shielded chamber. Measurement data are presented and discussed.

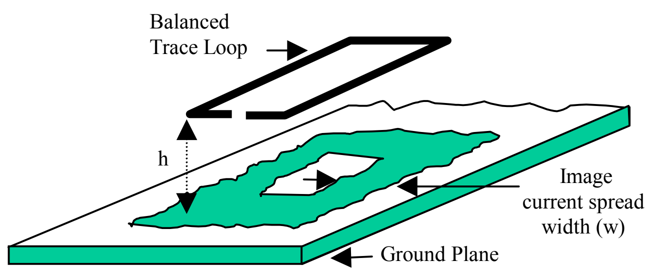

Figure 3. Image current loop formed by a balanced trace.

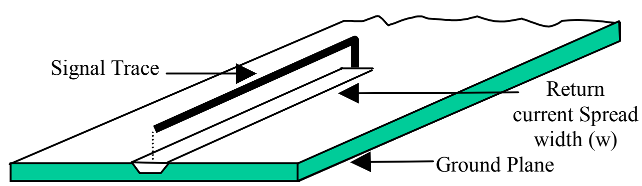

Figure 4. Return current spread of an unbalanced trace

II. BASIC ASSUMPTIONS

The field distribution on the trace and on the ground plane is similar to TEM or quasi-TEM mode. Ground layer current flows in a direction opposite to trace current. The radiated field of ground current and trace current can be superposed to obtain a complete radiating pattern. The trace or ground current refers to high frequency current (>20 MHz and < 2 GHz).

III. CURRENT SPREAD IN BALANCED TRACE

In any closed circuit, current tends to flow through the path of least impedance. Unlike the trace current flow, which is restricted to trace cross sectional area, the image current tends to flow through the least impedance path forming a current loop independent of trace loop. Image loop current is generally oppositely directed to trace loop current, but their phase relationship cannot be assumed to be 180^o out of phase. Current density and distribution in an image loop also differ from that of a trace loop. In any perfectly conducting plane, the least impedance path is a wider path therefore, the current spread of image current is wider than that in a trace loop. The center area enclosed by the image current is smaller than the area enclosed by trace current (Fig. 3). Therefore, radiation from a trace loop is always greater than image current loop radiation.

When the separation distance between two parallel rectangular traces of a balanced trace is very small (Fig. 1), most current tends to flow on inner sides of the traces (where they face each other) and the current flow are oppositely directed. Little current flow occurs on all other sides of the trace, therefore, the image current becomes negligible [3,4,5].

IV. CURRENT SPREAD IN UNBALANCED TRACE

The ground plane return current tends to follow the trace current and the currents are equal in magnitude and opposite in direction. The characteristics of ground current spread are documented in several publications. Current spread becomes wider, as the trace width (w) to dielectric thickness (h) ratio decreases and narrower as w/h ratio increases (Fig. 3). When w/h is ratio is very large ($w/h \rightarrow \propto$), the current concentrates at the bottom of the trace, and the return current spread on the ground plane becomes equal to the trace width [4,5,6,7]. Because current density and distribution in any cross sectional area of the trace and ground plane under the trace is the same, (Fig. 4) the trace and ground inductance must be equal, ideally no radiation is produced.

V. CURRENT SPREAD AND RADIATED EMISSIONS

The radiated field intensity at any observation point in space and time (P) is a vector sum of all the rays reaching that point. The rays add or subtract depending on their magnitude and phase relationship, but fields of the image and trace current or return and trace current arriving at point P (Fig. 5) do not completely cancel due to following reasons:

(1) For a typical signal trace, image or return current spread is always wider than trace current width. Wider traces have lower inductance and therefore develop lower noise voltage across the inductance. Lower noise voltages generate lower radiation levels. Therefore, radiation rays from image or return current arriving at point P will have lower magnitude levels than radiation rays from the trace.

(2) For a balanced signal trace, the image current is only a fraction of signal trace current.

(3) If the image or return current is an exact replica of the trace current and separation h is very small (Fig. 5), the radiated electric field at P will be zero. Because the ground current distribution is altered by the reactive and near fields of a signal trace, image current tends not to be an exact replica of the trace [8].

(4) While return current has a predictable source and load impedance and non-random flow, the image current tends to form a short circuit similar to the eddy current in a transformer and, therefore, its field pattern is difficult to predict.

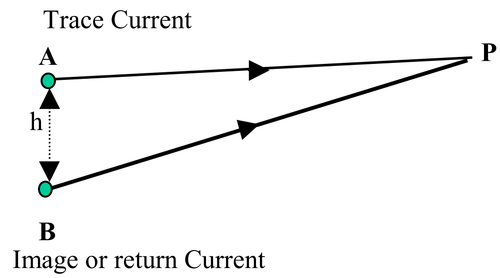

Figure 5. Signal Current Radiation and Image or Return Current Radiation at a Point P on the Antenna

The radiated field of a balanced or unbalanced trace with an adjacent ground plane changes with the field pattern of the trace and ground current. The field pattern of ground current is dependent upon current intensity and current spread width. The image current is an induced current, therefore, the magnitude is always much smaller than that of a trace or return current. The current spread for image current is not only non-uniform but also wider than that of trace current or return current. Therefore, a balanced trace over a ground plane does not reduce overall radiated emission, whereas an unbalanced trace over a ground plane is very effective in reducing overall radiated emissions (see section IV).

The variation in magnitude of image and return current for equal ground spread width was experimentally verified and the data are presented as graphs. The effectiveness of a ground plane for the control of radiated emissions was experimentally verified, and the data are presented in Cartesian and polar plots. Experimental set-up details are described in the next section. If the separation distance between two traces of a transmission line is very small, it will be very difficult to use a current probe to measure the image current of individual traces. Therefore, a square trace loop was used for the experimental verification.

VI. EXPERIMENTAL VERIFICATION

A 9"x 9" FR4 dielectric PCB having a 10 mil wide, 1.4 mil thick, 4"x4" square trace on one side, with or without ground plane on the opposite side, was tested. The separation distance between trace and ground plane was 10 mils. Testing was performed by connecting one end of the trace to the ground plane through a 50Ω resistor as an unbalanced trace and without a connection to the ground plane as a balanced trace (see Fig. 6). In order to get repeatable results for conducted emission tests, the signal-input coaxial cable was held tightly in position on a secondary ground plane. For radiated emission measurements, ferrite beads were added to the coaxial cable, so that radiation from the cable was below the spectrum analyzer noise level.

Conducted emission tests were performed using a current probe enclosing just the trace, and enclosing a trace and a ground segment (spread width) under the trace for the following configurations and the results are presented in Graph -1. The input to the trace loop was from a signal generator. A signal level of 0 dBm was used for all measurements.

1. Trace current is shown as Curve 1.
2. Differential current for 560 mils spread width for balanced and unbalanced trace is shown as Curves 3 and 5.
3. Differential current for 200 mils spread width for balanced and unbalanced trace is shown as Curves 2 and 4.

Radiated emissions testing was performed in a 3 m absorber lined shielded room in the frequency range 20 to 220 MHz. The field intensity measured for each frequency was plotted. The PCB was located 1 m above the chamber ground plane and plane of the its trace loop was parallel to the chamber ground plane. The input signal to the loop was from a pulse generator located outside the test chamber. A square pulse of 100 ns period, width of 50 ns, rise time (tr) of 1 ns and amplitude of 1 Volt was used. The data were taken for both horizontal and vertical antenna polarities. The results of horizontal and vertical data were similar; and, therefore horizontal polarity data only is presented for the following configurations:

1. Trace radiation without ground-plane in Graph 2A.
2. Radiated emissions levels for a balanced trace with ground plane in Graph 2B.
3. Radiated emissions levels for an unbalanced trace in Graph 2C.

Radiated emissions testing was performed in the same 3 m absorber lined shielded room as above at 100 MHz and 200 MHz. The field intensity measured with respect to the azimuth angle of the PCB was plotted in polar coordinates. The PCB was located 1 m above the chamber ground plane and the plane of its trace loop was parallel to the chamber ground plane. The input to the trace loop was from a signal generator located outside the test chamber. A signal level of –10 dBm was used for all measurements. The data were taken for both horizontal and vertical antenna polarities. Results of both 100 MHz and 200 MHz were similar and therefore, the result of 200 MHz only are presented for the following configurations.

1. Trace radiation without ground-plane in Graph 3A and 4A
2. Radiated emissions levels for a balanced trace with ground plane in Graph 3B and 4B.
3. Radiated emissions levels for an unbalanced trace in Graph 3C and 4C.

VII. RESULTS AND CONCLUSIONS

From Graph 1, the ground-spread current can be calculated by comparing the differential (trace and ground) current with the trace current.

1. For both balanced and unbalanced traces, 560 mils ground spread widths produced larger current than 200 mils ground spreads.
2. For the same ground-spread width, an unbalanced trace produced more ground current than a balanced trace.
3. Radiated emissions data presented in Graphs 2B, 3B, and 4B show that overall trace emissions are unaffected by the ground plane for a balanced trace except in some cases, where emissions are actually increased because of in-phase radiation due to image current.
4. Radiated emissions data presented in Graphs 2C, 3C, and 4C show that unbalanced trace emissions are much lower than trace loop or balanced trace loop emissions with ground plane, because the return current has a loop area similar to the trace loop (see Fig 6). Since the fields are oppositely directed, they cancel each other.

This paper concludes that an adjacent ground plane in a PCB is very effective for unbalanced traces but does not help to reduce overall radiated emission levels for balanced traces. The balanced traces are normally high impedance traces and, PCB designers tend to route them on outer layers, making use of air as dielectric to achieve the high impedance levels. Since adjacent ground planes do not reduce radiated emissions, high frequency balanced traces must be treated as transmission lines and must be properly matched to satisfy regulatory compliance requirements.

VIII. REFERENCES

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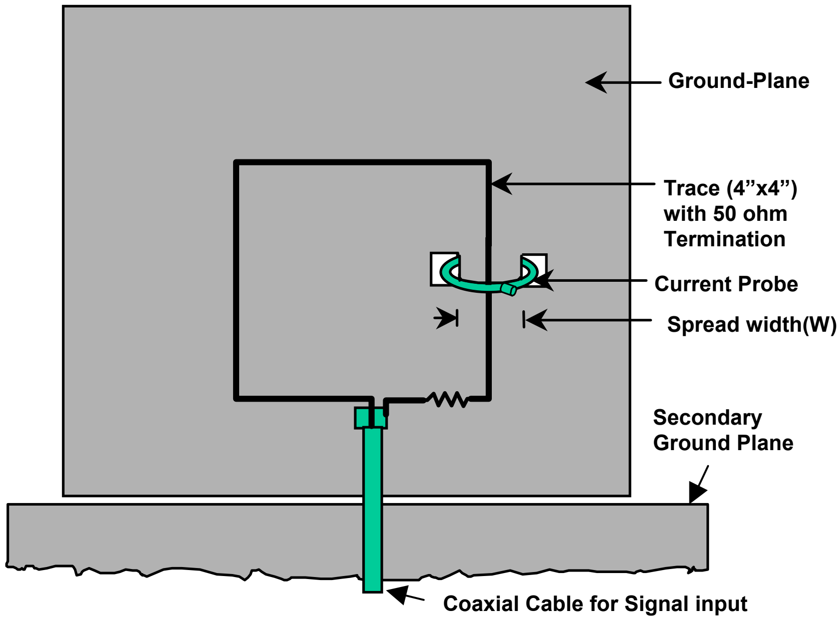
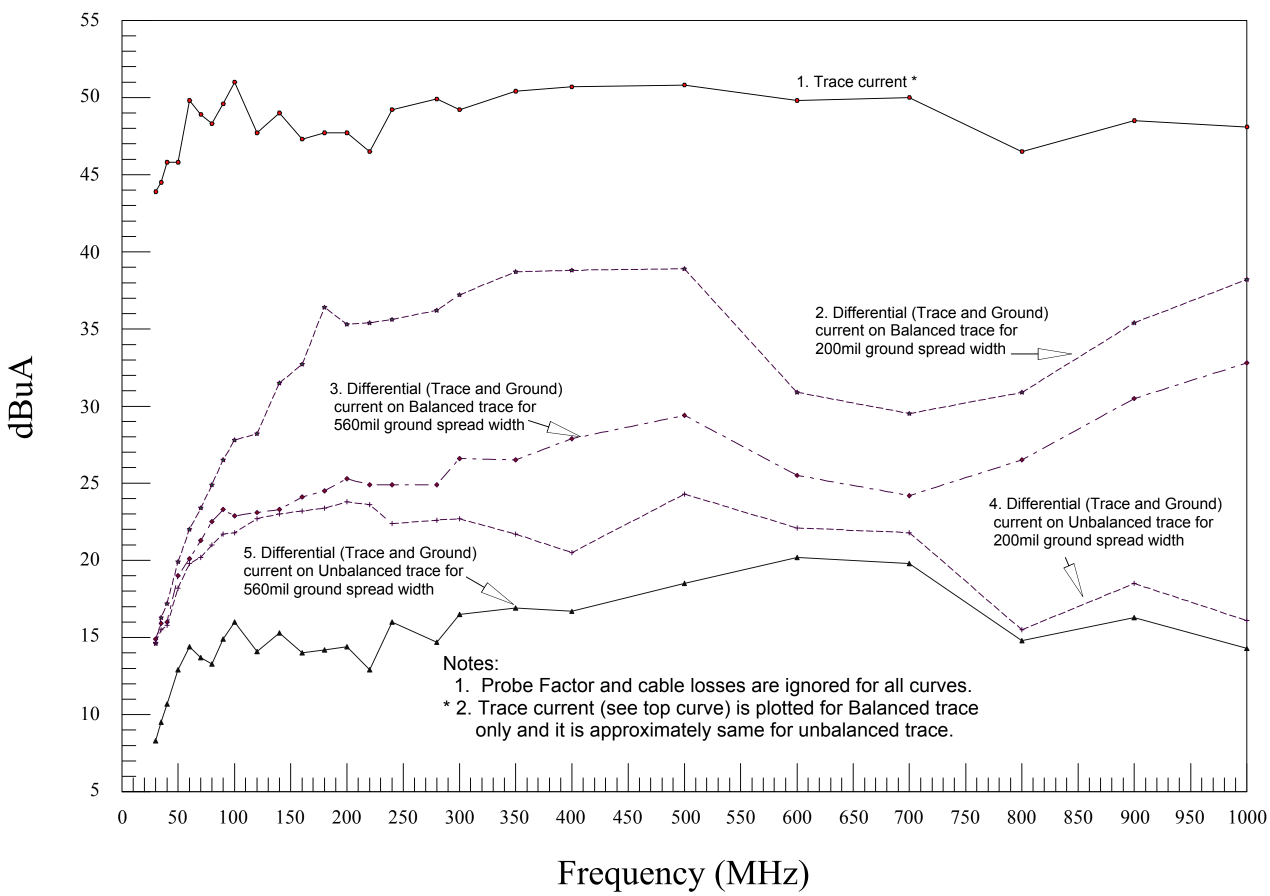
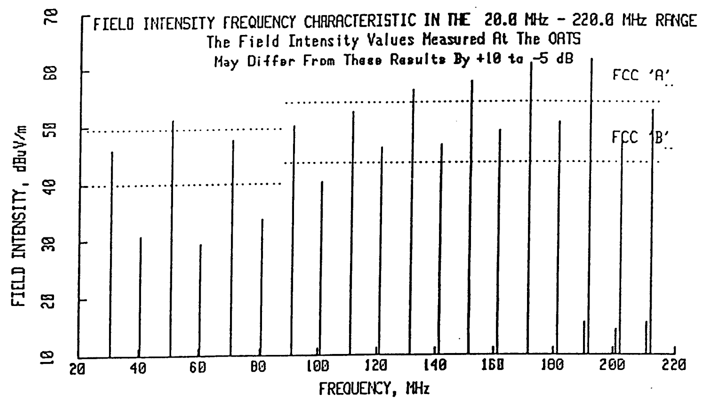


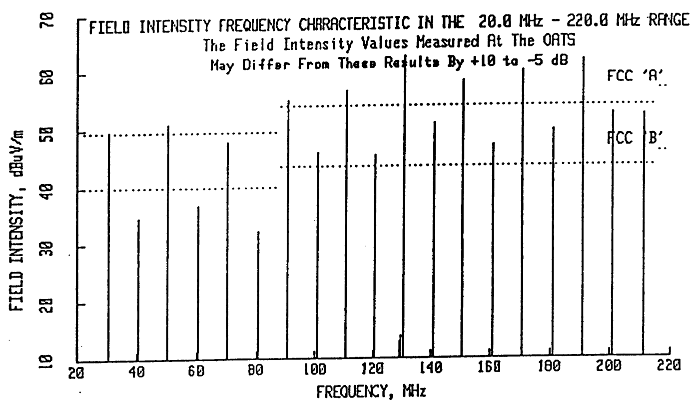
Figure 6. Current Spread Measurement set-up



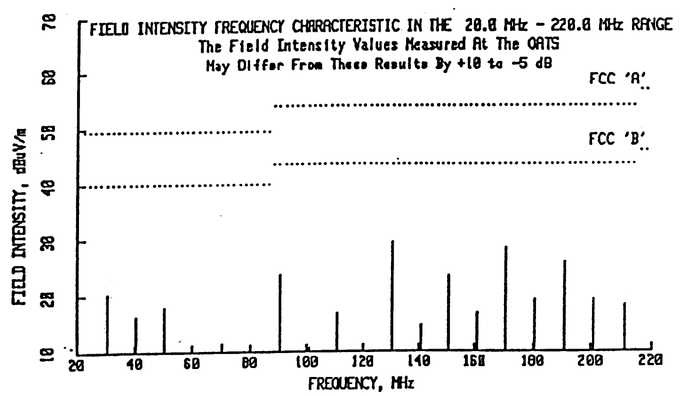
Graph 1. Current Spread Measurement Data



Graph 2A. Trace Radiation without Ground Plane.



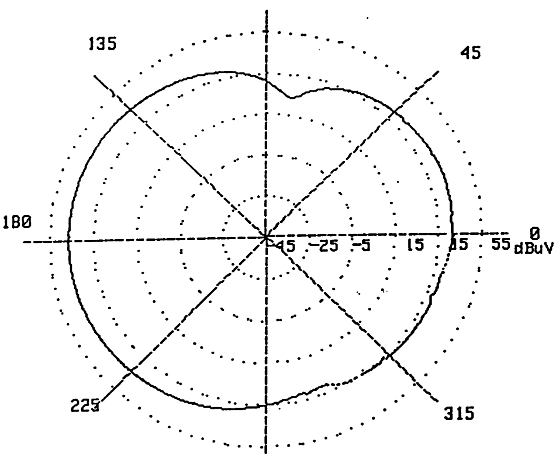
Graph 2B. Balanced Trace above Ground Plane Radiation.



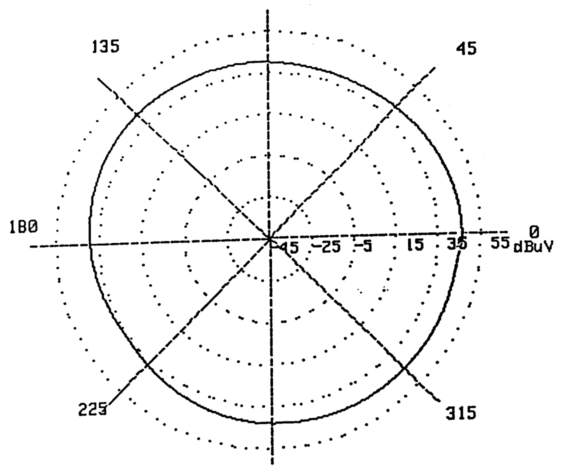
Graph 2C. Unbalanced Trace Radiation.

Loop Size: 4"x4" Signal input: Square Pulse Pulse Period: 100 ns Pulse width : 50ns Pulse Amplitude: 1V

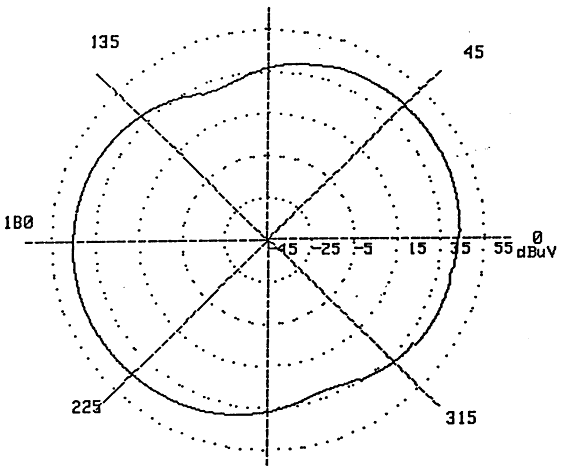
Graph 2: Field Intensity Measurement Data with Measuring Antenna Vertically Polarized



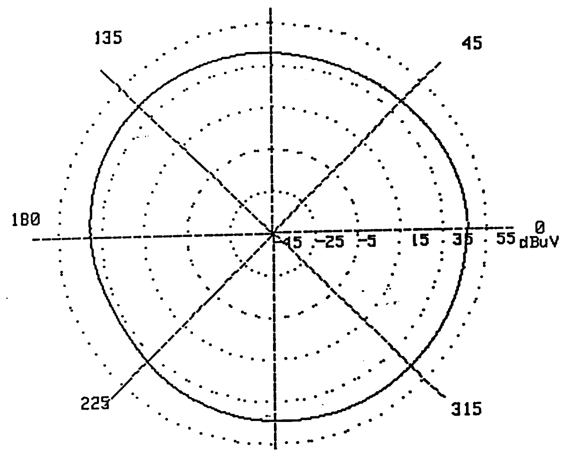
Graph 3A. Trace Radiation without Ground Plane



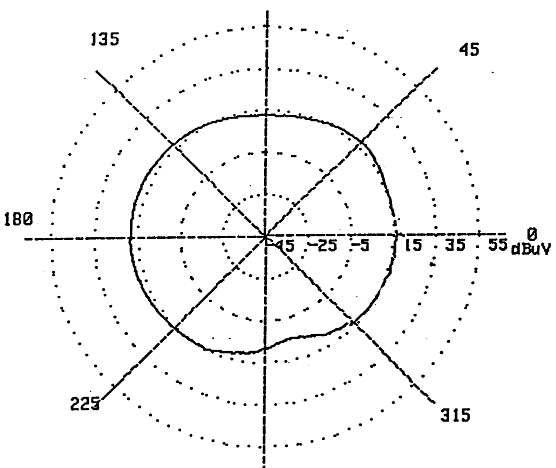
Graph 4A. Trace Radiation without Ground Plane



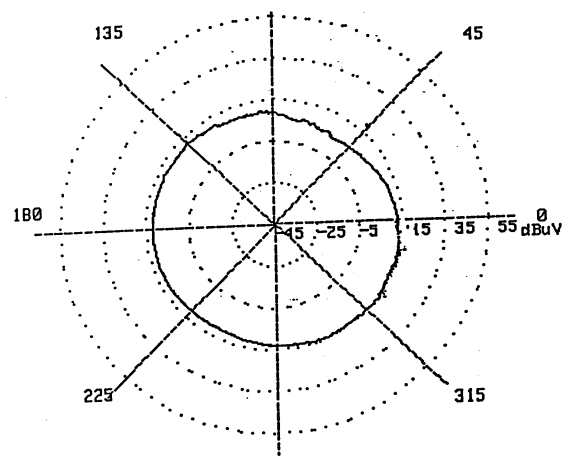
Graph 3B. Balanced Trace above Ground Plane Radiation



Graph 4B. Balanced Trace above Ground Plane Radiation



Graph 3C. Unbalanced Trace Radiation



Graph 4C. Unbalanced Trace Radiation

Loop Size: 4"x4" Signal input: 200 MHz CW Signal Level: -10 dBm

Graph 3: Polar Plot with Measuring Antenna Vertically Polarized.

Graph 4: Polar Plot with Measuring Antenna Horizontally Polarized.