Scattering Error in a Radio Interferometer

Located on a Finite Length Conducting Cylinder

by

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Abstract

A modified general purpose plate/wire analysis computer program is used to predict the performance of a four-element interferometer mounted on the end cap of a finite length conducting cylinder. The analysis method includes effects of scattering from the cylinder and the antennas. Due to limitations of the computer program a square cylinder is modeled, and the antennas "float" above the end cap. Measurements made of a circular cylinder physical model generally confirm the computer results and show that good performance can be obtained with loop antennas provided that the cylinder exceeds a critical size.

Introduction

Accurate measurement of relative phase at radio frequencies using small and lightweight electronics has been made possible by recent advances in Surface Acoustic Wave discriminators. This, in turn, has made possible the use of very closely spaced (in terms of wavelengths) interferometer antennas. In some applications the antennas may be located on a structure which itself has a size of the same order of magnitude as the wavelength, and thus the currents excited on the supporting structure may cause severe errors in the bearing computed from the antenna current phases. This is in addition to the errors caused by reradiation from the antenna elements themselves, which was investigated by Harrison [1].

Harrison's work involved using numerical methods to evaluate the currents induced on four half-wave dipoles in free space due to both an incident plane wave and the currents on the other dipoles. He then compared the bearing angle computed from the relative phase of the induced currents with the actual bearing. Our approach is generally the same, in that numerical methods are be used. However, we consider the more practical problem of interferometer antennas located on the end cap of a finite length conducting cylinder and will include the effects of the currents induced on the cylinder as well as the reradiation from the antennas themselves.

Problem and Approach

The problem is to determine the performance of a four-element interferometer mounted on the end cap of a finite length circular conducting cylinder. Due to time limitations, rather than develop a special purpose computer model for analyzing a circular cylinder, an available general purpose wire-plate moment method code (known as ESP) was used.[2] Since this code was not capable of modeling curved surfaces, a square cylinder with sides equal in length to the circular cylinder geometry was made. The geometry considered by the computer model is shown in Fig. 1. This figure shows half-loop antennas, and dipole antennas were considered as well. Connected flat conducting plates were used to model the sides and end cap, and wire and lumped loads for the receiving antennas. Each antenna modeled included an impedance load, located for the antennas shown in Fig. 1 at the peak of the triangular loop and marked by a dot.

During the early phases of the computer analysis and design it was found that due to approximations made in computing the impedance matrix in ESP the currents in the interferometer antennas were not in phase even when the incident wave was on boresight, i.e., incident theta of zero degrees. These approximations involved an automatic reduction in the number of Simpson's rule integration intervals used to compute mutual impedances between current modes as a function of the distance between the modes. After modifying ESP so that the number of integration intervals remained constant for all mutual impedance calculations [3] this problem was removed, at the expense of increased running time. (This problem does not seem to be present in newer versions of ESP).

By using the computer model, the currents induced in the receiving interferometer antennas due to an incident plane wave, including reradiation from the cylinder and antenna currents, were calculated as a function of antenna type position (antennas arranged in a "cross" shape performed better than when arranged in a "square" shape with the dipoles parallel to the nearest edge of the square cylinder end), load resistance, and incidence angles of the plane wave (θ and ϕ). Variation in performance was investigated. The most important performance parameter was the relative phase of a pair of antennas as a function of the bearing angle of the incident plane wave. The goal was to have this variation be as close as possible to that which would ideally occur in free space without the disturbing effects of the currents induced on the cylinder and the other antennas.

The other performance parameter considered was antenna gain. It was desired to have the antenna gain be as high as possible subject to the constraint that higher gain would tend to increase errors due to mutual coupling effects between the antennas (since the antenna currents would be larger) and would require matching circuitry which would make the measurement of relative phase at the antenna terminals more difficult. For these reasons the load impedance was chosen to be 50 ohms.

The radially symmetric antenna configuration of Fig. 1 was obtained after investigation of several other configurations using the computer model. The computer results predicted higher gain for loop antennas then dipole, and to confirm these predictions it was decided to include both types of antennas in the experimental measurements. The square cylinder computer design, including the dimensions of the cylinder, are shown in Fig. 2 for both antenna types. The frequency range considered in the design was 200 to 800 MHz. Over this range of frequencies the cylinder length varies from 0.8 λ to 3.2 λ, the width (diameter) from 0.1 λ to 0.4 λ, and the antenna center-to-center spacing from 0.06 λ to 0.25 λ. Thus the cylinder is in the resonance region, and the induced currents on the cylinder will be relatively large. For the frequencies and cylinder size shown the computer model was not capable of including wires that were connected to the end cap since ESP requires an "attachment" current disk at least 0.1 wavelength in radius, so both types of antennas "float" above the end cap.

The corresponding physical model is shown in Fig. 3. There are two obvious and important limitations of the computer model. First, the square cylinder has been changed into a circular cylinder, since this was the actual shape of interest. Second, the physical antennas cannot actually "float" above the end cap but must be fed using transmission lines and physically connected to the end cap.

Results

The physical model was built, and extensive measurements were made. Both the dipole and half-loop antenna systems were measured for gain, amplitude versus bearing angle, and relative phase versus bearing using a commercial (Scientific Atlantic) receiver. Frequencies of 200, 300, 400, 500, 600, and 800 MHz were covered. Referring to Fig. 1 and considering the pair of antennas which lie along the y-axis to be under test (with all antennas terminated in 50 ohms), pattern cuts were made with ϕ equal to 0°, 45°, and 90° for both ϕ and θ polarizations as a function of θ. Gain measurements were made only for boresight ($\theta = 0$), but were repeated for both vertical and horizontal polarization (with the cylinder rotated by 90° to retain a polarization match) in order to check repeatability and range dependence.

Since relative phase is more important than amplitude in assessing DF antenna system performance, we will be primarily concerned with phase results. However, in general the agreement between calculated and measured received amplitude was as good or better than was the case for the phase measurements.

Regarding the half-loop antenna system, several conclusions can be drawn. First, the measured and computer results agreed well, especially at frequencies above 200 MHz. Even at 200 MHz, the computer results indicated the trend correctly even if they did not agree exactly with the measurements. Second, for frequencies above 200 MHz, both the computer and measured results indicated relative phase reception that was a reasonably good approximation to ideal free-space results for a field of view of approximately ±30°. Third, even for bearing angles not in the principal plane of the antennas, the performance was good for both polarizations.

Figures 4 through 7 contain data that illustrate and quantify the above points. Figure 4 is for a frequency of 200 MHz. Referring to Fig. 1, the active antennas are the pair along the y-axis, and the incident wave direction lies in the y-z plane, i.e., $\phi = 90°$. This is the principal incidence plane for this pair of antennas. The curves in Fig. 4 show the relative phase between the y-axis pair of antennas as calculated using the computer model for θ (principal) polarization (including effects of induced cylinder currents and mutual antenna coupling), the measured relative phase, and the relative phase for the "ideal" free-space situation with the cylinder absent. The computer predicts less phase variation with incidence angle than ideal, and the measured results show even less. Judging by the measured results, there is not enough phase variation over a ±30° field of view for an interferometer-type direction-finder (DF) processor to function.

The results for the loops for a frequency of 400 MHz contained in Figs. 5 through 7 are much improved. Both the computer predictions and the measured data indicate very nearly ideal performance over a ±30° field of view in the principal plane (Fig. 5). The computer results do not exactly match the measured results, probably due to the previously discussed differences in the physical and computer antenna models. However, the agreement is quite good for the boresight region, which is the area of most interest.

Figures 6 and 7 show the same set of predicted, measured, and ideal relative phase curves, but this time for the 45° plane of incidence and for both polarizations. The computer results agree fairly well with the measurements but not as well as in the principal plane. This is probably due to the square cylinder computer model versus the round cylinder physical model, since in the 45° plane, the computer model corners lie in the plane of incidence. Even so, the computer predictions which indicate a greater deviation from ideal behavior for ϕ-polarized waves as opposed to θ-polarized waves are confirmed by the measurements. The difference between the θ-polarized and ϕ-polarized results as shown in Figs. 6 and 7 is due to the excitation of different currents on the cylinder. At 400 MHz the cylinder is just over one-half wavelength in circumference, and thus the near-resonance circumferential currents excited by the ϕ-polarized incident wave will be stronger than the off-resonance longitudinal currents excited by the θ-polarized wave. For accurate DF performance, both polarizations must give good results in the $\phi = 45°$ incidence plane, since the antennas will receive both equally, and an arbitrarily-polarized incident wave will contain both. Results for higher frequencies are similar to these 400-MHz results.

Before considering the dipole case, let us relate the phase information of the preceding figures to bearing information. An ideal interferometer, given ideal relative phase information, will compute the incident bearing angle θ_b in the principal plane as

$$\theta_b = \sin^{-1}\left(\frac{\lambda \cdot \psi_e}{d \cdot 360}\right) \qquad (1)$$

where ψ_e is the relative antenna current phase, λ is the wavelength, and d is the antenna spacing. Considering, for example, the results of Fig. 5, at an incident θ of 30° the measured result differs from the ideal by about 1° of phase. This value of relative phase would result in an interferometer bearing of approximately 28.5°, which is in error by 1.5°. This error could be reduced by calibration if necessary.

Now let us consider the representative dipole results of Figs. 8 through 10. First, note that the relative phase scale maximum value had to be increased to accommodate the greater variation in dipole phase. Both the measured and calculated results indicate much greater departure from ideal free-space behavior for the dipole antennas than for the loops. However, the computer results do not accurately follow the phase measurements. Even so, the computer model does predict the trends in the measurements, including the reduced phase change with θ incidence angle evident for the ϕ-polarized case of Fig. 10. Dipole results for other frequencies were either similar or showed even more rapid variations near boresight.

Figure 11 shows a comparison of calculated and measured gain results. For these measurements the gain figure includes the mismatch loss due to terminating the (small, highly reactive) antennas in a 50 ohm load. The gain figures therefore indicate the power these antennas would deliver to a receiver with a 50 ohm input impedance without any impedance matching to compensate for the antenna reactance. The figure contains calculated and measured values of boresight (θ = 0) gain for both antenna types. The measurements were made for both vertical and horizontal polarization with the model rotated 90° to maintain polarization match to the antenna being measured. Thus, for an ideal range both measurements should yield the same result. Unfortunately, this is not the case, especially for the dipole antennas. This is due in part to range reflections and in part, for the dipole case, to the fact that at some frequencies the dipole amplitude pattern had a relative minimum on boresight. This tended to make the gain results for the dipoles more dependent on the precise position of the model. Nevertheless, the measurements do confirm the computer model prediction of higher gain for the half-loop antennas when terminated in 50 ohms. While the gain of both could be improved by impedance matching, the phase measurement would be complicated by the matching network.

Summary and Conclusions

A general purpose moment method computer analysis program capable of modeling wires and plates was modified and used to find the currents induced in four interferometer antennas located on the end cap of a finite length conducting square cylinder. Using this analysis tool, two different antenna configurations were chosen, one utilizing loop antennas and the other dipoles. A physical model based on the computer design was built, but with a circular cylinder and physically realizable antennas. Measurements made of current phase and antenna gain indicated general agreement with the computer predictions. Better agreement was obtained for the loops. Both measured and computer model results indicate that the loop system is capable of providing a good approximation to ideal interferometer performance within ±30° of boresight for a cylinder with length and radius greater than about 1.2 and 0.15 wavelengths, respectively. For a smaller cylinder the relative current phase did not change with bearing angle enough to allow a bearing to be reliably determined.

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2. Newman, E. H., "A User's Manual for Electromagnetic Surface Patch Code (ESP)," The Ohio State University Electro Science Laboratory Report 713402-1, July 1981.

3. Newman, E. H., private communication.

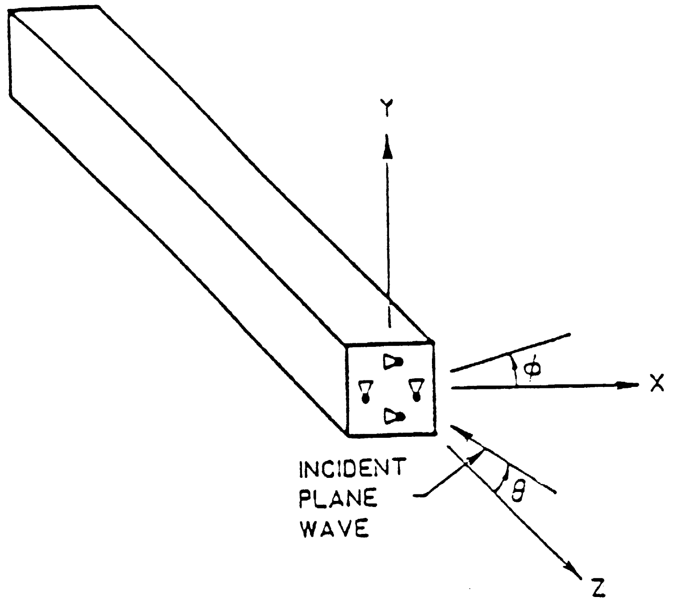

Figure 1 Geometry and coordinate system for computer model of square cylinder with two pairs of interferometer antennas.

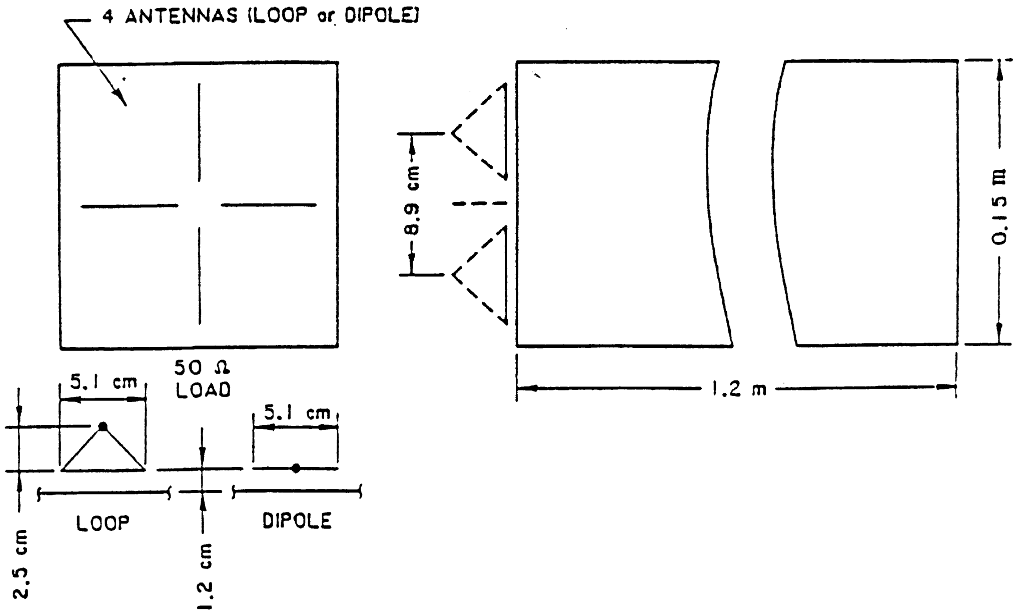

Figure 2 Dimensions of computer model square cylinder and antenna system.

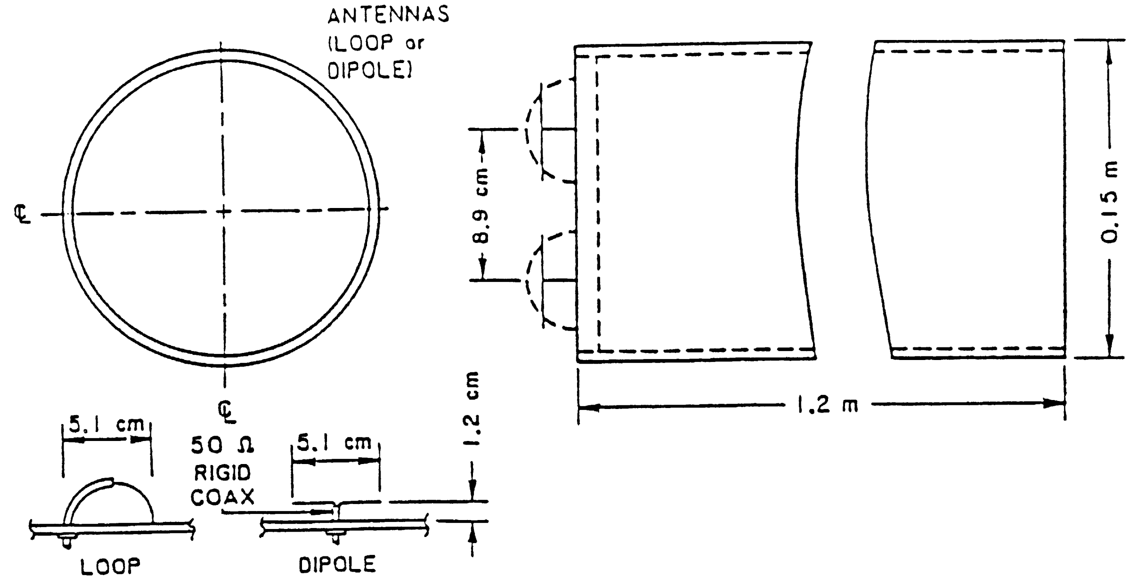

Figure 3 Dimensions of cylinder model actually built and tested, showing details of both the loop and dipole antennas.

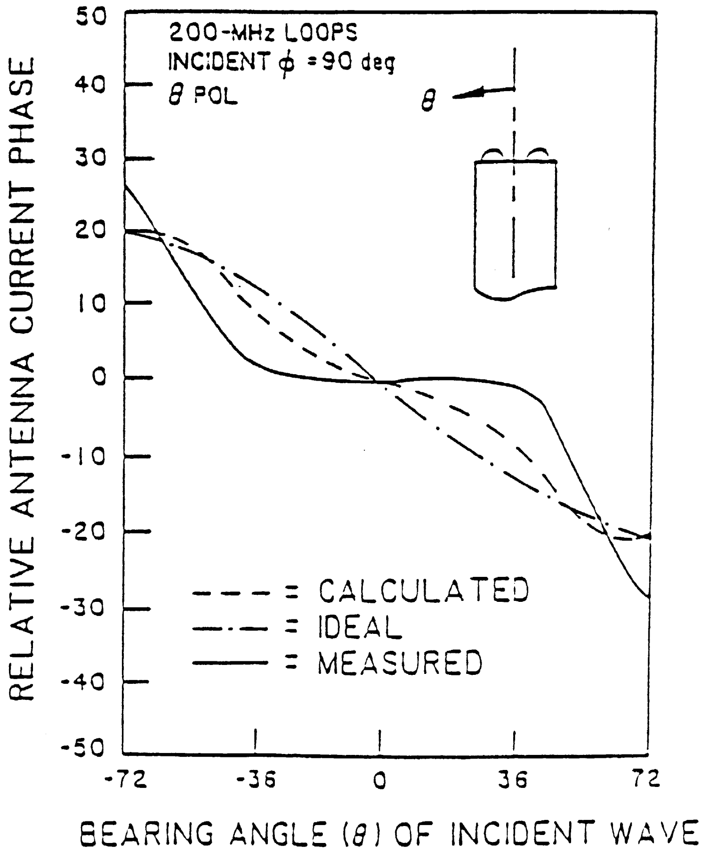

Figure 4 Calculated, measured, and ideal relative phase versus bearing angle for the loop antenna system in the principal plane (ϕ = 90 deg) at 200 MHz.

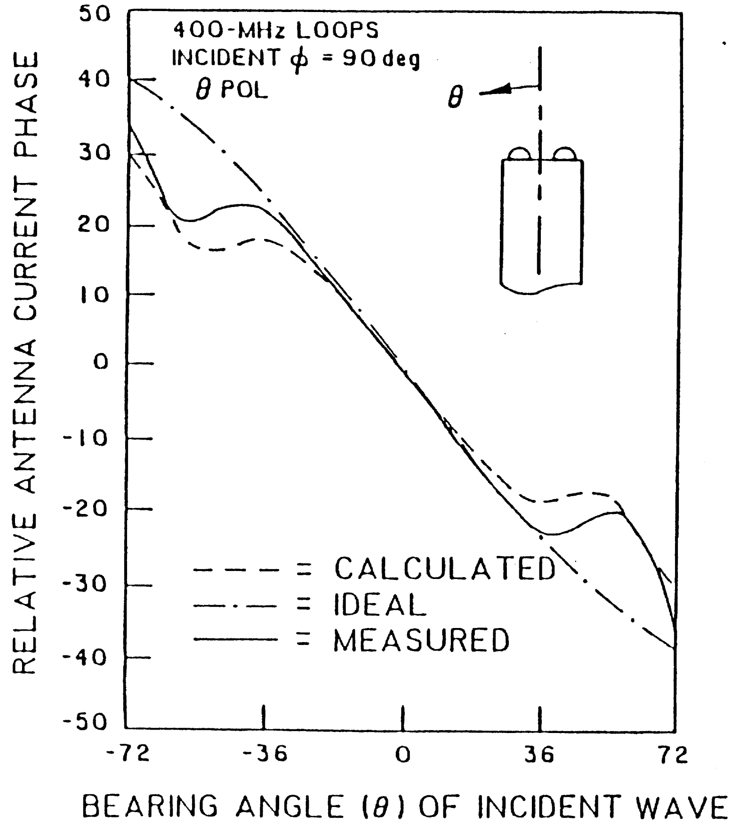

Figure 5 Calculated, measured and ideal relative phase versus bearing angle for the loop antenna system in the principal plane (ϕ = 90 deg) at 400 MHz.

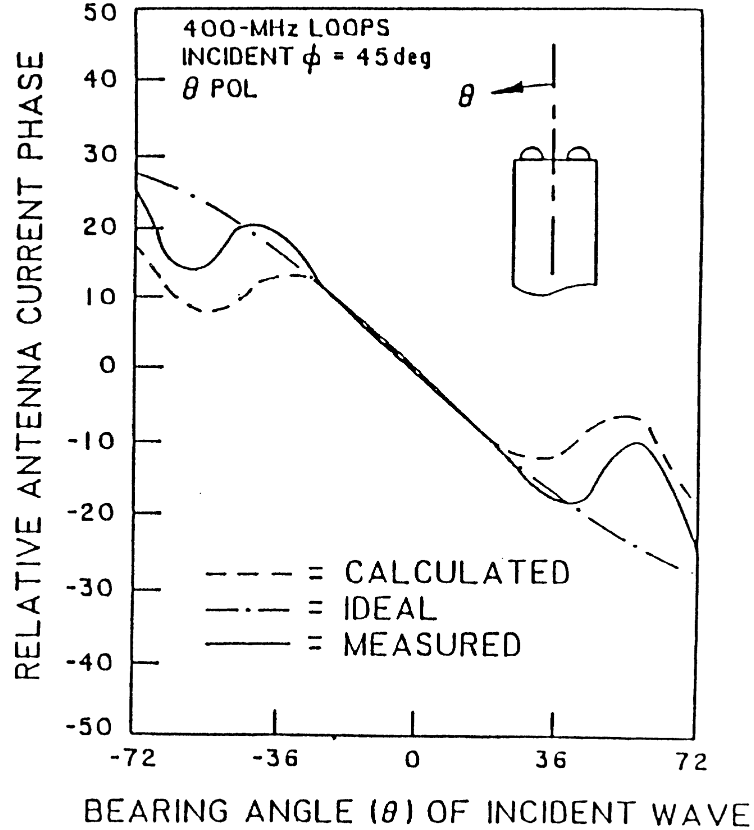

Figure 6 Calculated, measured and ideal relative phase versus bearing angle for the loop antenna system in the ϕ=45 deg plane for θ polarized incident wave at 400 MHz.

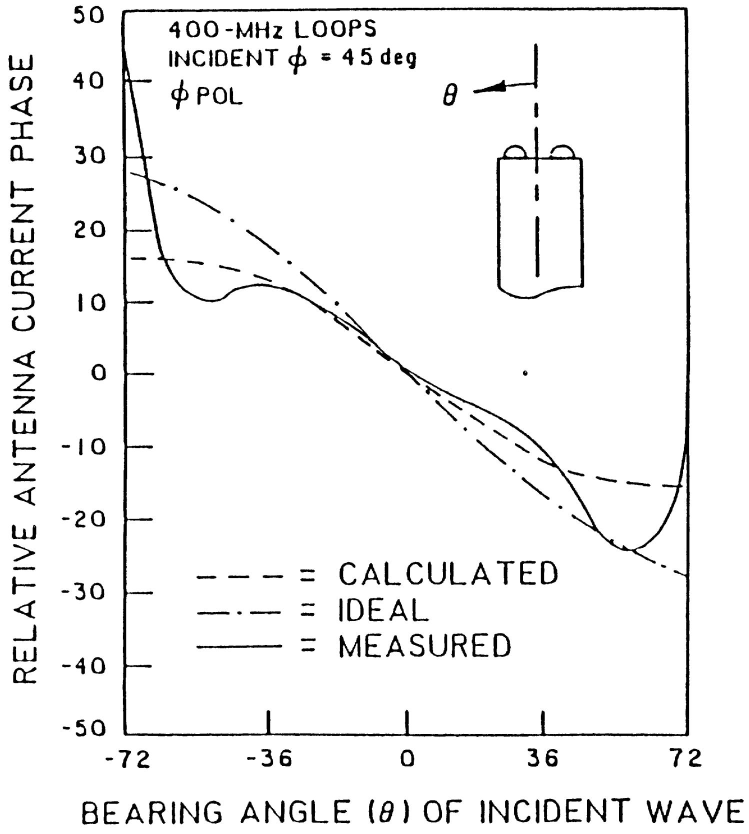

Figure 7 Calculated, measured, and ideal relative phase versus bearing angle for the loop antenna system in the ϕ=45 deg plane for ϕ polarized incident wave at 400 MHz.

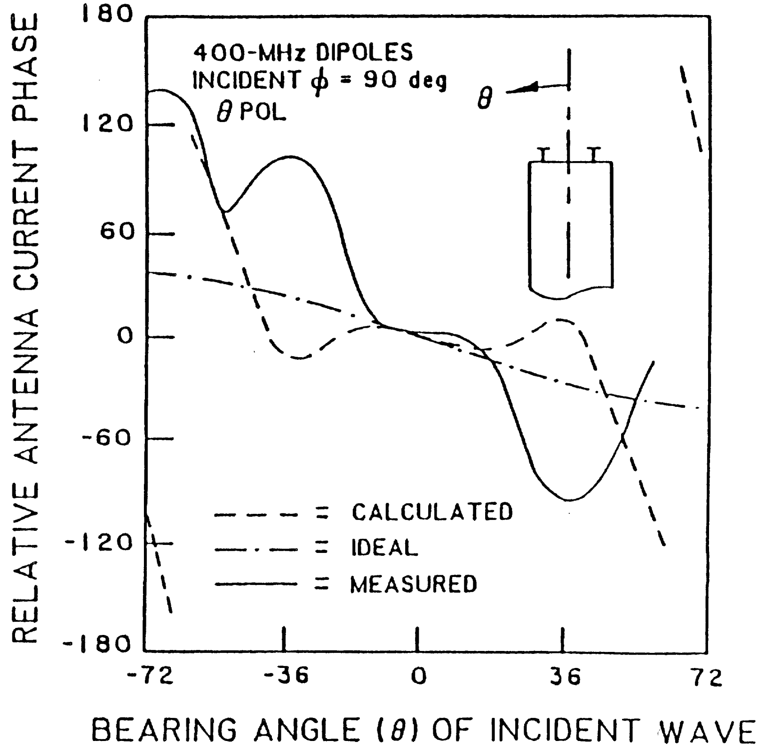

Figure 8 Calculated, measured, and ideal relative phase versus bearing angle for the dipole antenna system in the principal plane (ϕ=90 deg) at 400 MHz.

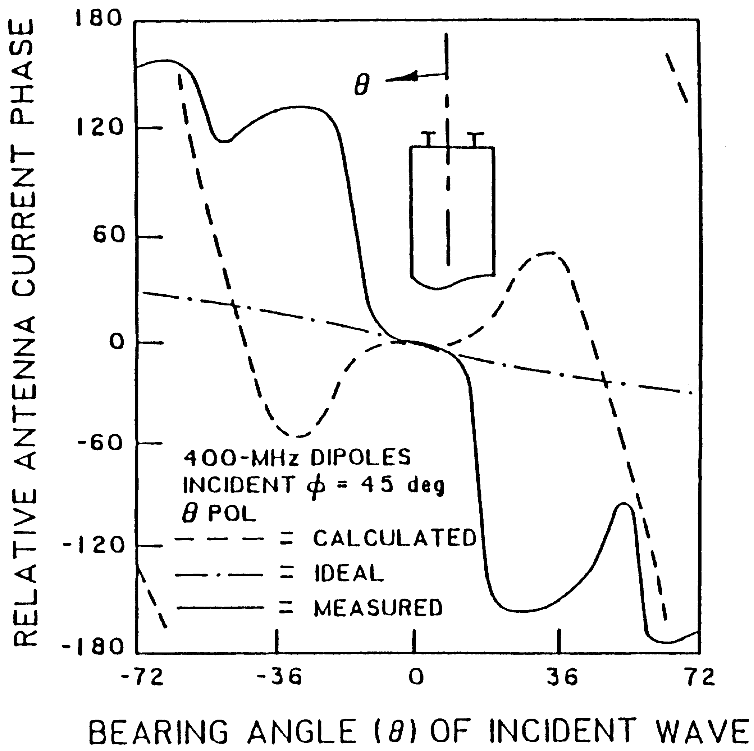

Figure 9 Calculated, measured, and ideal relative phase versus bearing angle for the dipole antenna system in the ϕ=45 deg plane for the Θ polarized incident wave at 400 MHz.

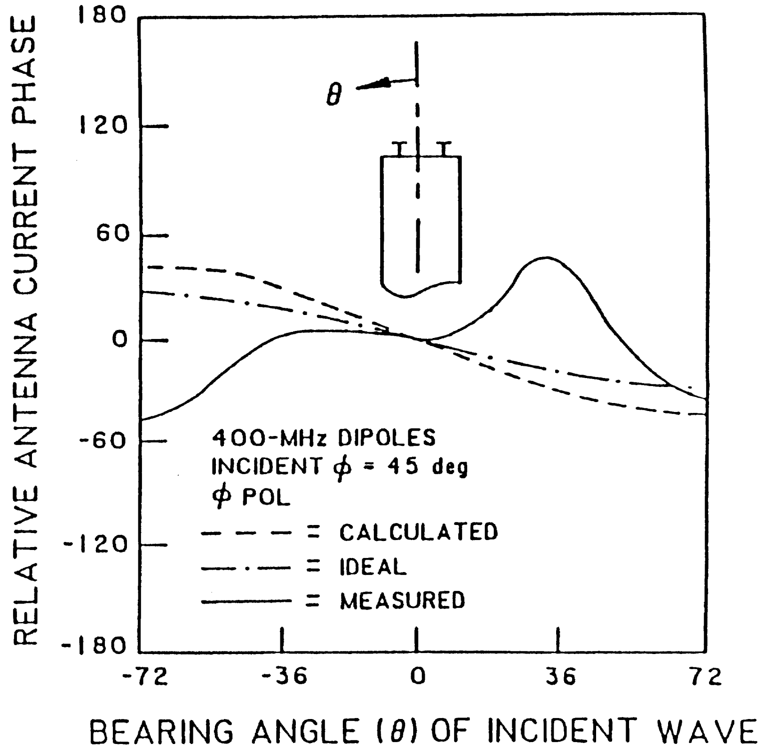

Figure 10 Calculated, measured, and ideal relative phase versus bearing angle for the dipole antenna system in the ϕ=45 deg plane for ϕ polarized incident wave at 400 MHz.

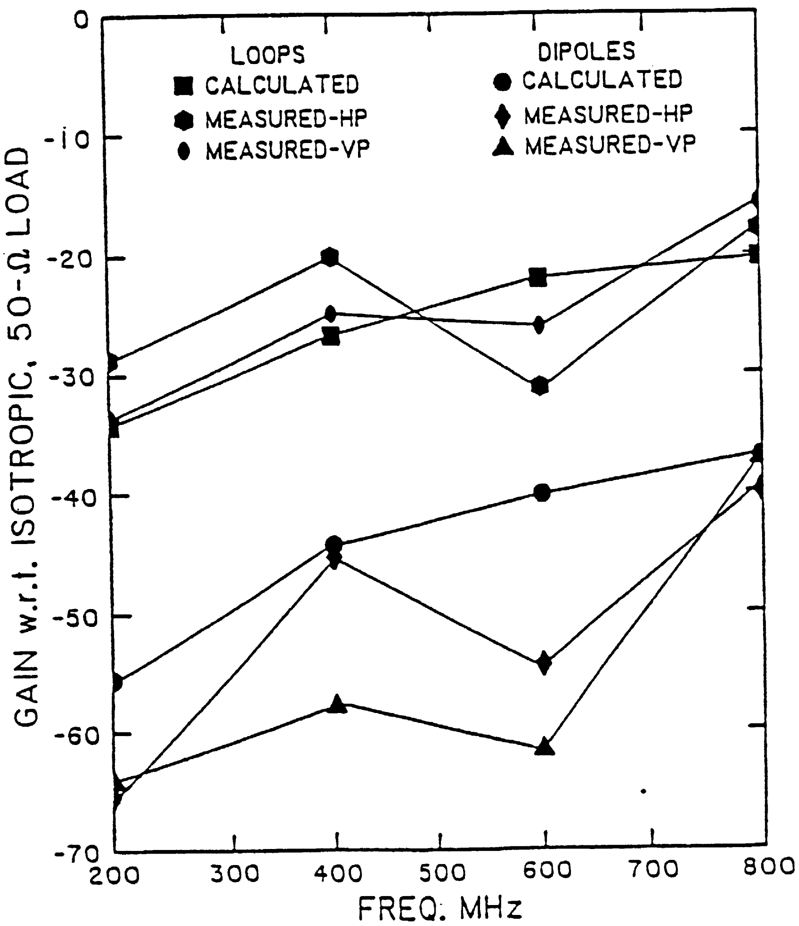

Figure 11 Calculated and measured values of boresight (θ=0 deg) gain versus frequency for both the loop and dipole antennas.