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BOREHOLE RADAR FOR GEOTHERMAL APPLICATIONS

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INTRODUCTION

Locating fluid-filled fractures in a geothermal reservoir has been the objective of several instrumentation development programs. Electromagnetic techniques have seemed particularly promising because of the expected significant conductivity contrast between the fluid-filled fracture and the surrounding rock. High frequencies have also been preferred because of the narrow spatial extent of some fractures and the consequent need for good range resolution. This type of target may not be apparent to a seismic sensing technique. These considerations have led to the investigation of borehole radar for geothermal applications.

The type of borehole radar system which has been most extensively evaluated is pulsed radar. Measurement of distance with a pulsed radar requires the generation of a fast rise time pulse to be transmitted to the target and back to the receiver. The receiver must accurately measure the time of arrival of the leading edge of this return pulse. Although this technique is capable of giving good range resolution, a thorough evaluation reveals several limitations.

One limitation of the pulsed radar is its requirement for a wide bandwidth antenna. The wide bandwidth is required to preserve the pulse rise time and provide good range resolution. But wideband antennas are difficult to package in the small size needed for the borehole environment. Achieving the required bandwidth also forces trade-offs of other desired antenna properties, such as good coupling efficiency and directionality.

Another disadvantage of a pulsed borehole radar is a result of the nature of the geothermal medium. A typical geothermal reservoir has a high water content, leading to high attenuation of electromagnetic signals with frequencies above a few megahertz. This high attenuation could be avoided using a low operating frequency, but the low frequency will result in poor range resolution since the sharp rise time pulse required for good range resolution will necessarily have a high frequency content. The geothermal medium is also characterized by severe dispersion in the material's properties (i.e., the material properties vary with frequency, and the significant conductivity leads to a frequency dependent wave velocity). Because a pulse is composed of a broad frequency spectrum, the pulse will be highly distorted in propagating through the medium. The pulse will not retain its sharp rise time, and therefore range resolution will be lost.

The effects of dispersion are illustrated in Figure 1 for a square wave input pulse with a center frequency of 50MHz as shown in this figure. For the simulation, the earth is assumed to be a 0.6 percent porosity granite with 0.75 ohm-m pore water, which is representative of some geothermal reservoirs. Shown in the figure are the resultant wave forms after the square wave input pulse has propagated 5m (solid line) and 10m (dashed line) through the earth. The decrease in magnitude of the pulse between the 5m

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and 10m results is due to wave attenuation. The fast rise time of the input pulse, which contains significant frequency content, is lost due to dispersion (i.e., due to the frequency dependence of the phase velocity). The range resolution of the pulsed system in the dispersive medium will be very poor.

The effects of dispersion can be minimized or even eliminated by using a CW system. For a continuous wave (CW) radar system, the transmitting antenna transmits a single, continuous sinusoidal wave at a single frequency. Since the wave contains only a single frequency, the wave travels at a single velocity and dispersion does not exist. The CW wave is still attenuated in the same way as the pulse.

A CW radar has other advantages when the instrument must be packaged for the borehole application. The antenna for the CW system will be a narrowband antenna, which is more suited to a small volume package. For comparable range resolution between the CW and pulsed systems, the CW system can operate with a frequency about equal to the fundamental frequency of the pulsed system. The high frequency content of the pulse is not required for the CW system. This avoids the problem with high attenuation of these frequencies. It also alleviates the need for high frequency electronics which complicated the design of the pulsed system.

These considerations have led us to begin the evaluation of a CW borehole radar system. In particular, we are considering a CW system which uses directional, steerable antennas to provide another measure of distance to the target, in addition to the time-of-flight measurement. This system could lead to a less costly radar than existing instruments and a simpler data interpretation technique.

THE CW RADAR WITH BEAM STEERING

Whether considering pulsed or CW systems, the classical radar approach to distance measurement is based on measuring the time delay for the propagation of the electromagnetic energy to the target and back. Distance is computed from time-of-flight by dividing by the propagation velocity in the intervening medium. Unfortunately, the propagation velocity depends on the dielectric constant, which is not always a known parameter of the earth. To alleviate this concern with the time-of-flight systems, we conceived the concept of a narrow-band, CW radar, using simple antenna elements, which would augment the distance measurement by the use of geometry. Figure 2 shows the concept: Two antennas are separated by a vertical distance "S" within a borehole, and their antenna patterns make angles θ_1 and θ_2 with the vertical. The target is illuminated by the upper antenna, the source, and its reflection is detected by the lower antenna as a receiver. The horizontal range to the target, "D", is given by:

$$D = \frac{S}{\text{Cotangent } \theta_1 + \text{Cotangent } \theta_2} .$$

If either θ_1 or θ_2, or both, can be varied electrically, the reflecting feature can be examined in more detail.

While this measurement is conceptually simple, there are complications associated with its practical implementation. For example, the beam widths of even the most directional borehole antennas will still be wide, and their region of overlap will typically be larger than the desired range resolution. This difficulty can be mitigated by the CW system, which allows coherent detection and accurate phase measurement of the return. Since different ray paths within the total beam width will have different propagation distances, and hence, different phases at the receiver, they can still be discriminated at the receiver by "locking" the receiver to a particular phase angle. Scanning the antennas to produce a maximum return amplitude will then enable the triangulation formula given above to be applied with the angles θ_1 and θ_2 set equal to the angles corresponding to the maxima of the antenna patterns. The phase of the return still provides time-of-flight information, so two distance estimates are obtained with this system. Comparison of several measurements of this type could also provide an estimate of the dielectric constant of the media.

ANTENNA DESIGN

Feasibility of the steerable borehole radar concept is dependent on the availability of a suitable antenna. The direction and width of the beam pattern should be independent of the media properties. That this is difficult to achieve in a conducting media has been recognized for many years. This is because, in the words of R. K. Moore [1], "there is attenuation of the contribution of one end of the antenna relative to that from another end of the antenna closer to the point of observation". Since the ranges from the antenna that the fields can be expected to propagate in the geothermal media are only on the order of tens of meters, the beam pattern of antenna whose length is a very few meters or more would be strongly dependent on media properties.

We have modelled the vertical electric dipole antenna in a conducting media, following the work of Moore and others [1-7]. We have found that an array of short dipoles can produce a beam pattern which is independent of media properties provided it obeys a "size rule". This size rule requires that the maximum array dimension not exceed one-tenth of a wavelength in order for the pattern to be independent of media properties at distances greater than one wavelength from the antenna.

Polar patterns from a two element dipole array are shown in Figure 3. The overall length of the array is 0.1λ. The direction and width of the major lobe of the pattern changes very little from one to four wavelengths away from the antenna. This illustrates that the short dipole array can provide a stable, well-formed pattern in a conducting media.

The beam direction is varied by controlling the phase with which the dipole outputs are combined. Figure 4 shows this behavior for an array of 2 dipoles operated in-contact with a wet geothermal media. The combined angle can be varied about 34° with this arrangement.

If electric dipoles are used for both source and receiving antennas, there will be substantial direct coupling between them. However, if a small horizontal loop is used as source, its electric field cannot be detected by an array of vertical electric dipoles centered beneath it. Moreover, if two horizontal magnetic dipoles, at right angles to each other, are used as a source, and the phase of their currents adjusted, the source beam can be used to perform an azimuth-scan.

The patterns of a two-magnetic dipole array for various values of phase difference between the dipoles are shown in Figure 5. The figure illustrates that ten degrees of scan angle (which may be all that is required for many applications) can be obtained by varying the phase difference between the dipoles by only ten degrees.

CONCLUSION

An initial evaluation of a CW borehole radar system with steerable antennas has been completed. Candidate antennas have been identified which meet the size requirements for borehole applications. The patterns of these antennas are not dependent on the properties of the surrounding media when the antenna dimensions are less than one-tenth wavelength. The beam patterns can be steered adequately to allow the volume of earth within several meters of a borehole to be investigated.

ACKNOWLEDGEMENT

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Simulated Response of Geothermal Medium to Pulse Input Showing the Effect of Dispersion

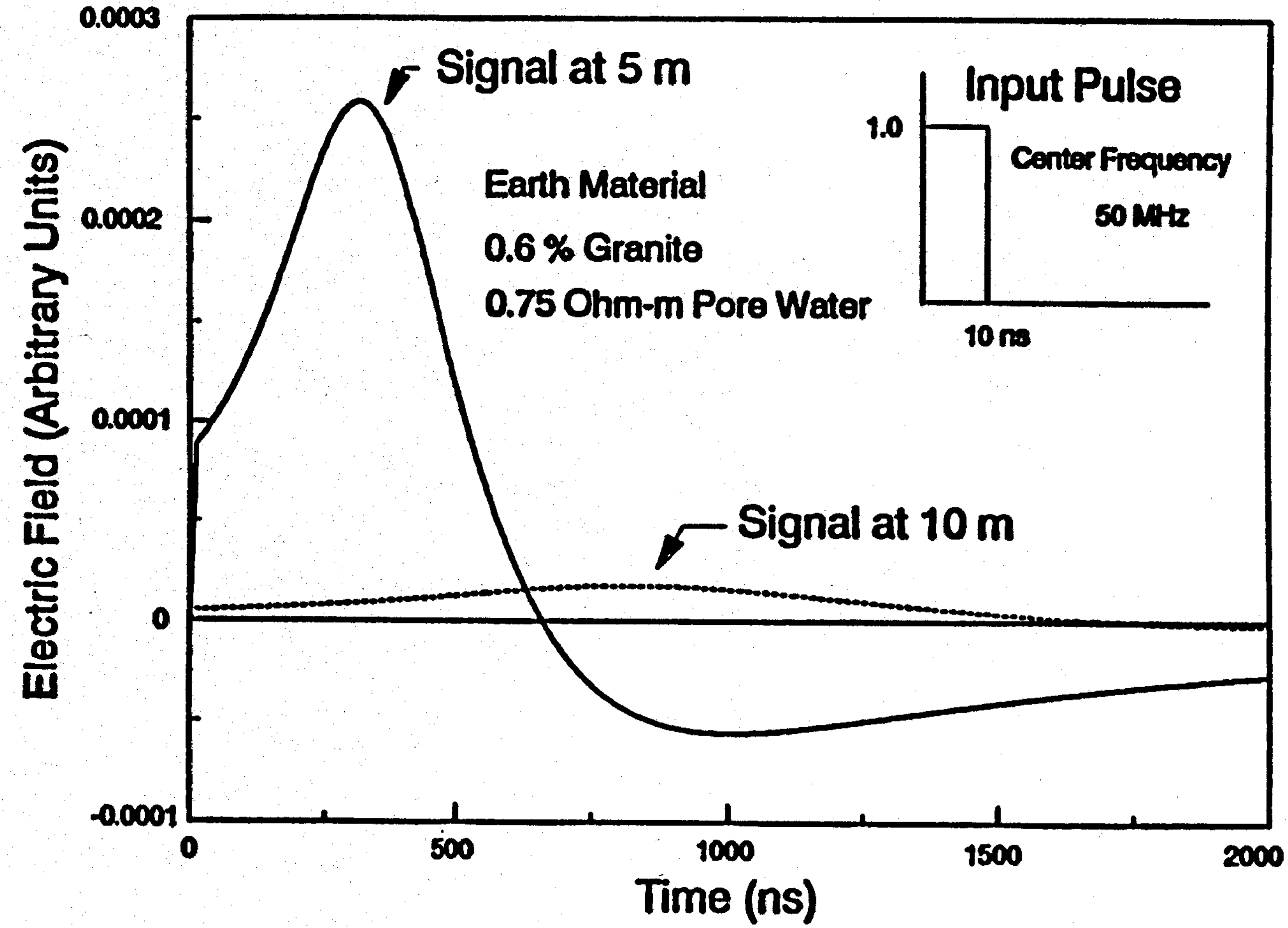

Figure 1

Measuring Distance by Triangulation Instead of Time-of-Flight

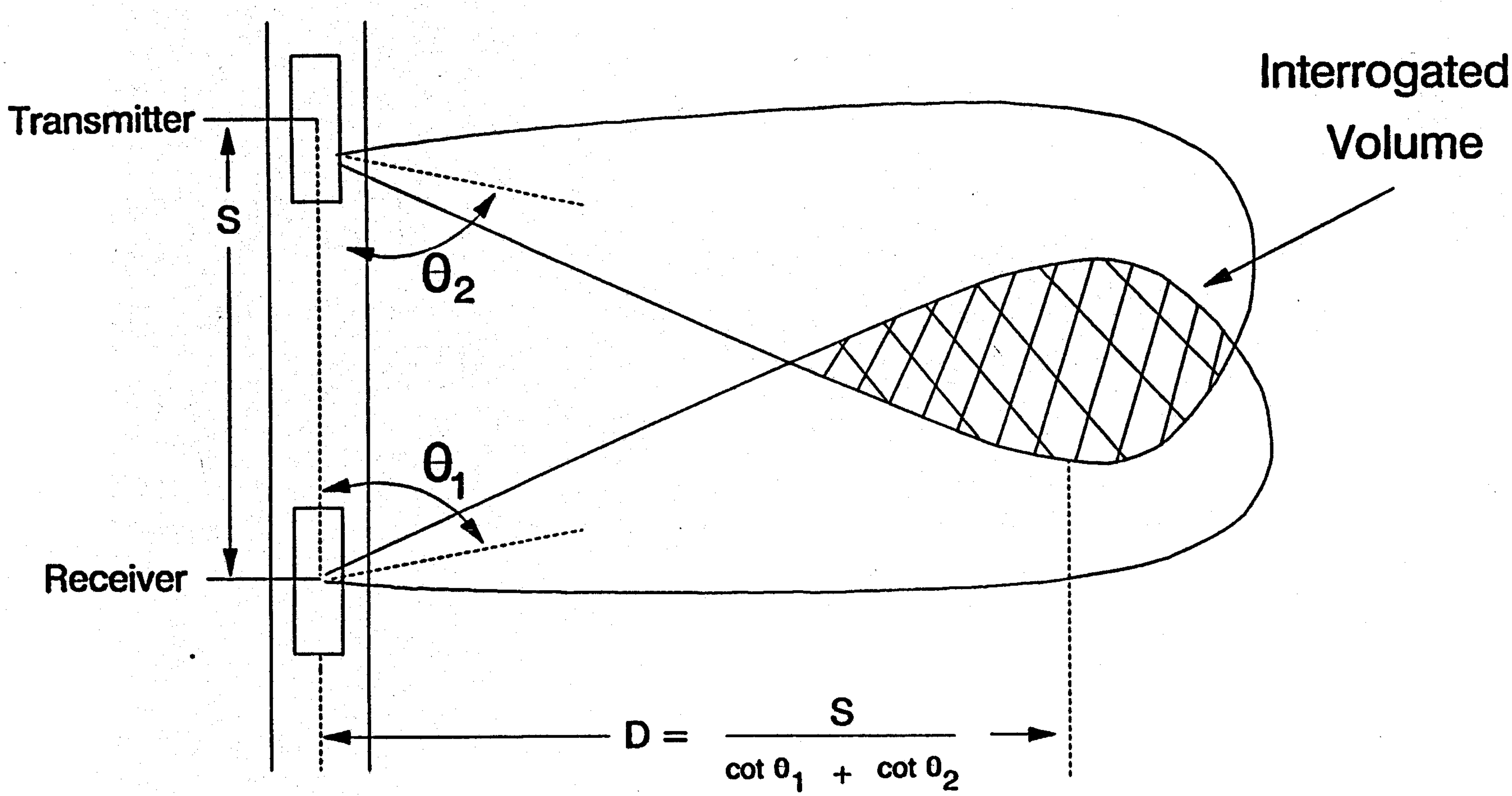

Figure 2

E_z-Power Patterns For 2 Colinear Dipoles

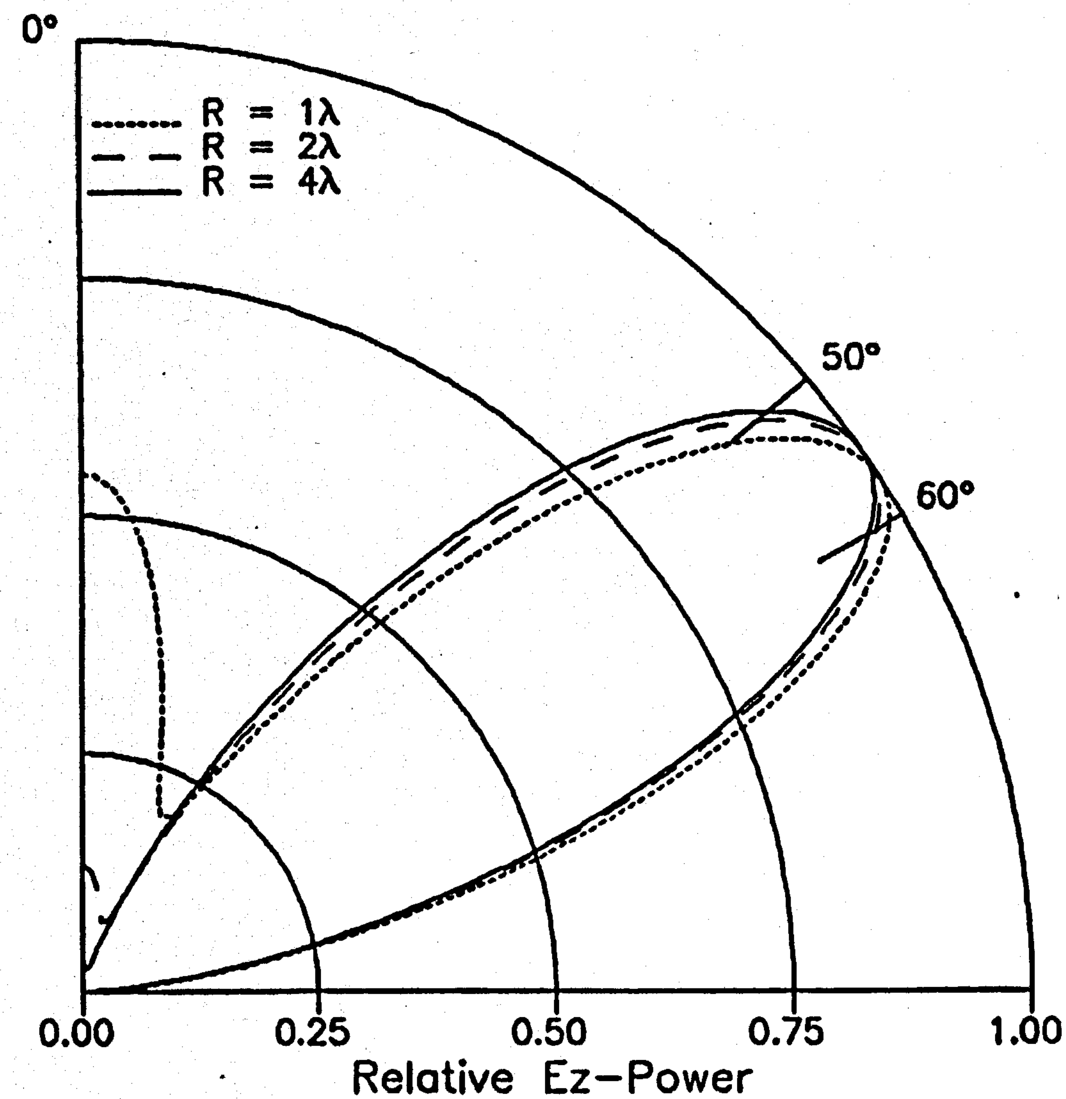

Figure 3

Polar Angle of Maximum Field vs Phase Angle
Two-Antenna Array

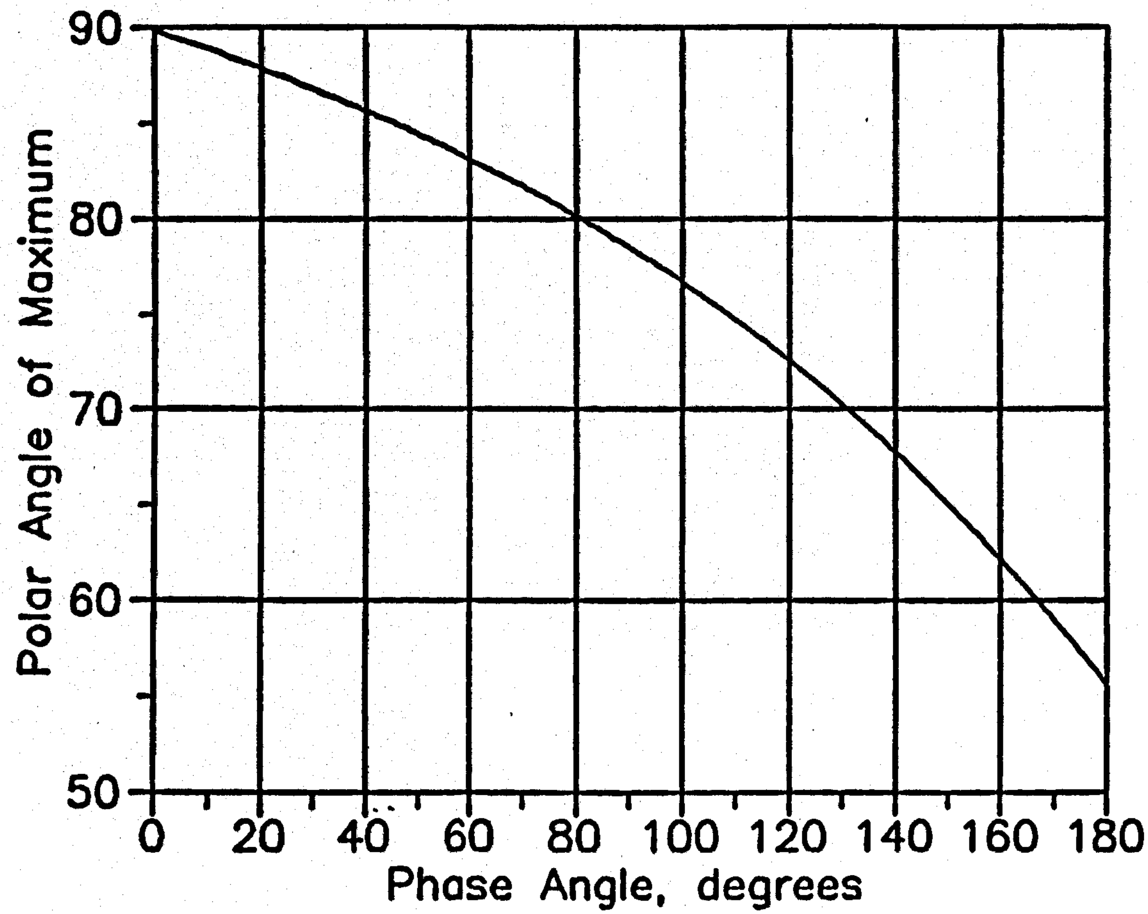

Figure 4

E_z-Power Patterns From an HMD 2-Array With Phase-Shift Angle as a Parameter

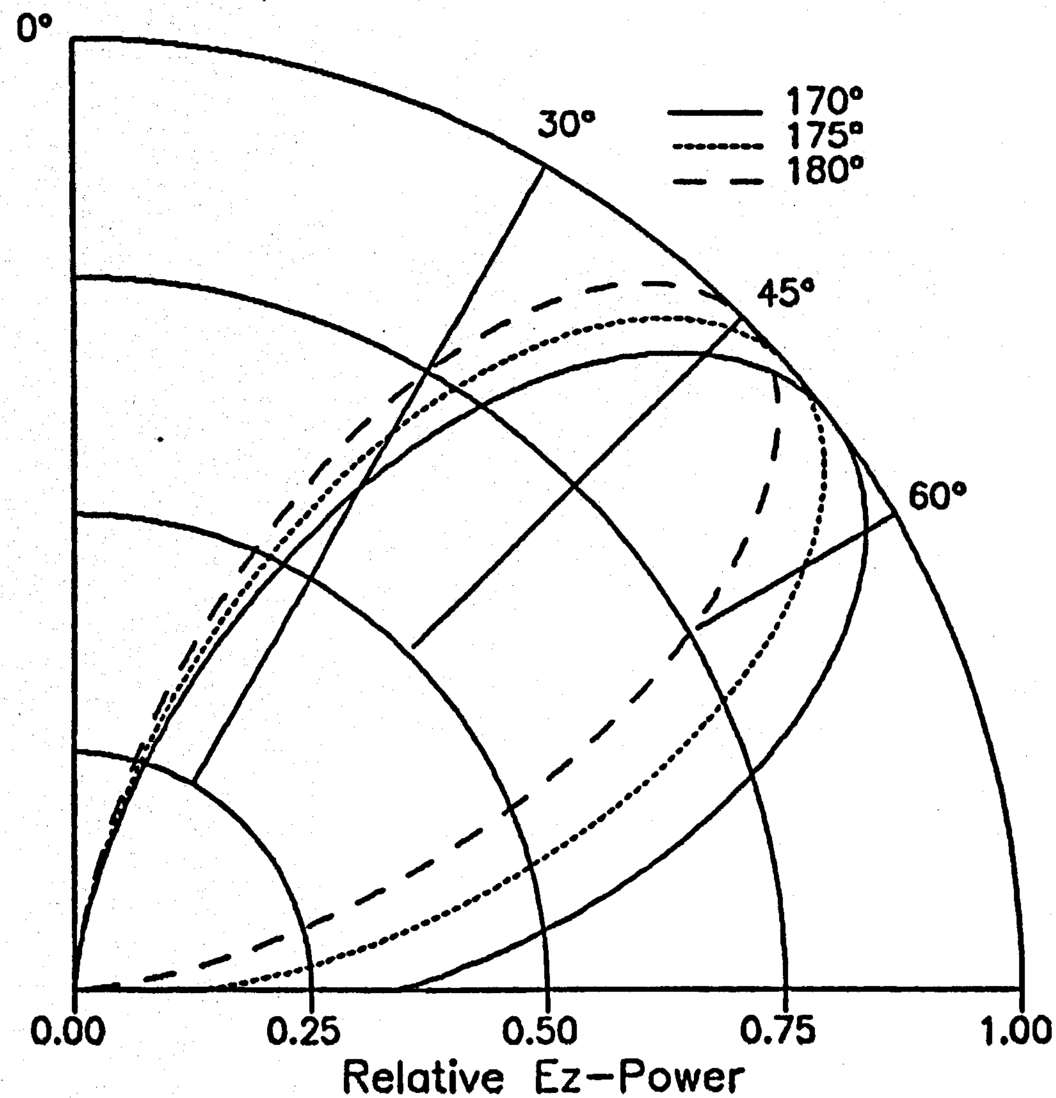

Figure 5