for the wave to have propagated. This fact is obvious since it is a fundamental requirement determined by the Poynting vector.

Any measurement in this zone at $\theta = 0^\circ$ involves both of these components, thus the value of H_θ cannot be obtained independently of E_ϕ.

In order to be able to obtain values for the electrical characteristics of the medium it is necessary to measure both the attenuation constant α and phase constant β of that medium. Various techniques for doing this have been described in the literature, but are beyond the scope of this study.

4.8 Practical measurements

Numerous measurements have been performed underground, at various frequencies, in order to examine the effect of a typical mining environment on radio wave propagation.

Immediately evident from these tests has been the dispersion which occurs with frequency. In other words, different frequencies suffer different rates of attenuation. This result was expected. In addition though, it is evident that the fields encountered are considerably more complex at the low frequency end (i.e. 100 kHz to 1 MHz) than above 1 MHz. This is due to the fact that the measurements, at the lower frequencies, are being made within, or at least close to, the near field zone, and obviously one is encountering both far field and near field components.

It becomes particularly difficult to analyse the resulting measured signal strengths since these field components are not physically separable. At higher frequencies the influence of the radiation field is definitely more evident, and measurements of its characteristics are considerably easier to make. However, as the frequency is increased further the rate of attenuation increases very rapidly, resulting in propagation ranges which themselves do not extend far into the far field zone.

From the work done on the characteristics of typical rock samples, and particularly in the light of the findings of other workers in the field it is possible to select as fairly typical, a range of conductivity values likely to occur in practice underground. The range limits are selected bearing in mind two factors, namely that <u>in situ</u> conditions, at mining depths, bring about an increase in conductivity over that measured in the laboratory, and similarly that the upper limits of conductivity would not be expected to be as high as those found in surface layers, which have been measured by a variety of geophysical techniques. These considerations have led to the conductivity being considered to lie in the range

$$10^{-5} \leq \sigma \leq 10^{-3} \text{ S/m}.$$

Permittivity likewise has been discussed, and, as in the case of conductivity, it should be possible to assume a fairly typical value, which is determined by <u>in situ</u> conditions. Since this parameter has been shown not to vary drastically with frequency, a fixed value, $\epsilon_r = 10$, will be used.

Two basic conditions relating to loss tangent have been shown to effect propagation. The frequency range necessary to satisfy these will be examined.

For $p \le 0{,}6$ and $\sigma = 10^{-5}$ S/m the operating frequency necessary to satisfy this loss tangent restriction would be

$$f \ge 3 \times 10^4 \text{ Hz}$$

The wavelength λ in the rock is thus given by

$$\lambda \le \frac{\lambda_0}{\sqrt{\epsilon_r}}$$

$$\le \frac{10^4}{\sqrt{10}}$$

$$\le 3\,162 \text{ m.}$$

For $p \le 0{,}6$ and $\sigma = 10^{-3}$ S/m, we have

$$f \ge 3 \times 10^6 \text{ Hz}$$

and the wavelength, λ, in the rock is

$$\lambda \le 31{,}62 \text{ m.}$$

On the other hand, for loss tangent $p \ge 10$, and $\sigma = 10^{-5}$ S/m, the frequency range necessary would be

$$f \le 1\,800 \text{ Hz}$$

yielding $\lambda \ge 23{,}6 \times 10^3$ m

and, for $\sigma = 10^{-3}$ S/m, we have

$$f \le 18 \times 10^4 \text{ Hz}$$

and $\lambda \ge 236$ m.

Thus, bearing in mind that the propagation of electromagnetic energy via this lossy medium is dependent both on choice of operating frequency and on a suitable antenna system to effectively radiate and receive the energy, these frequency limits bear close scrutiny.

Examination of equation 4 - 2 illustrates that the effective transfer of energy is dependent on the product of gain G and efficiency η of the transmitting and receiving antennas. These characteristics were related to one another by the directivity, D, of the antenna, 4 - 9. Thus we may write

$$\eta G = \frac{G^2}{D} \qquad 4 - 39$$

and from 4 - 11,

$$G_{max} = \frac{3,7\ d}{\lambda} \qquad 4 - 40$$

is the maximum gain of a small loop of diameter d in a lossy medium, at a wavelength of operation, λ. As has been stressed many times before, portability of equipment is of prime importance in this application, thus the higher frequencies must be used to maximise the antenna gain, hence the loss tangent condition $p \leq 0,6$ would seem to apply.

4.9 The test site

Various factors influence the choice of test site, not least of which was its accessibility. In addition, the geology of the site had to be typical of gold mining areas, and obviously be completely devoid of any metal objects whatsoever, which could distort field patterns and also act as transmission lines and radiating elements.

Obviously, however, no single site would offer all the likely geological variations typical of a vast mine. From a practical point of view though, results obtained in an area selected for its basic suitablility, would be of immediate interest and would provide the guide lines for any engineering recommendations.

The site chosen was a section of 11 level at the Durban Deep Gold Mining Company, near Roodepoort, Figure 4.4. It was accessible via two shafts, namely 7 and 8, and consisted of a single haulage, with cross-sectional dimensions averaging about 3 m square. The haulage was basically horizontal, and is situated at a depth of approximately 500 m below surface. It should be borne in mind that gold mining depths well in excess of 2 km are now typical, thus this test site is somewhat shallow. However, it is sufficiently far below surface to be well below the sedimentary overburden, and thus to be within typical gold mining geological strata.

The geology actually consisted of quartzite interspersed with shaley bands, two sections of which are shown in Figure 4.5. In addition a dyke, rich in Ilmenite, intersects the haulage at one point, providing a useful geological discontinuity to the medium. The quartzitic rock surrounding the dyke is as homogeneous as is likely to be found in any gold mine, and the dyke, which is about 7 m in width at the point of intersection with the haulage, is physically very different from the surrounding rock, making its identification easy.

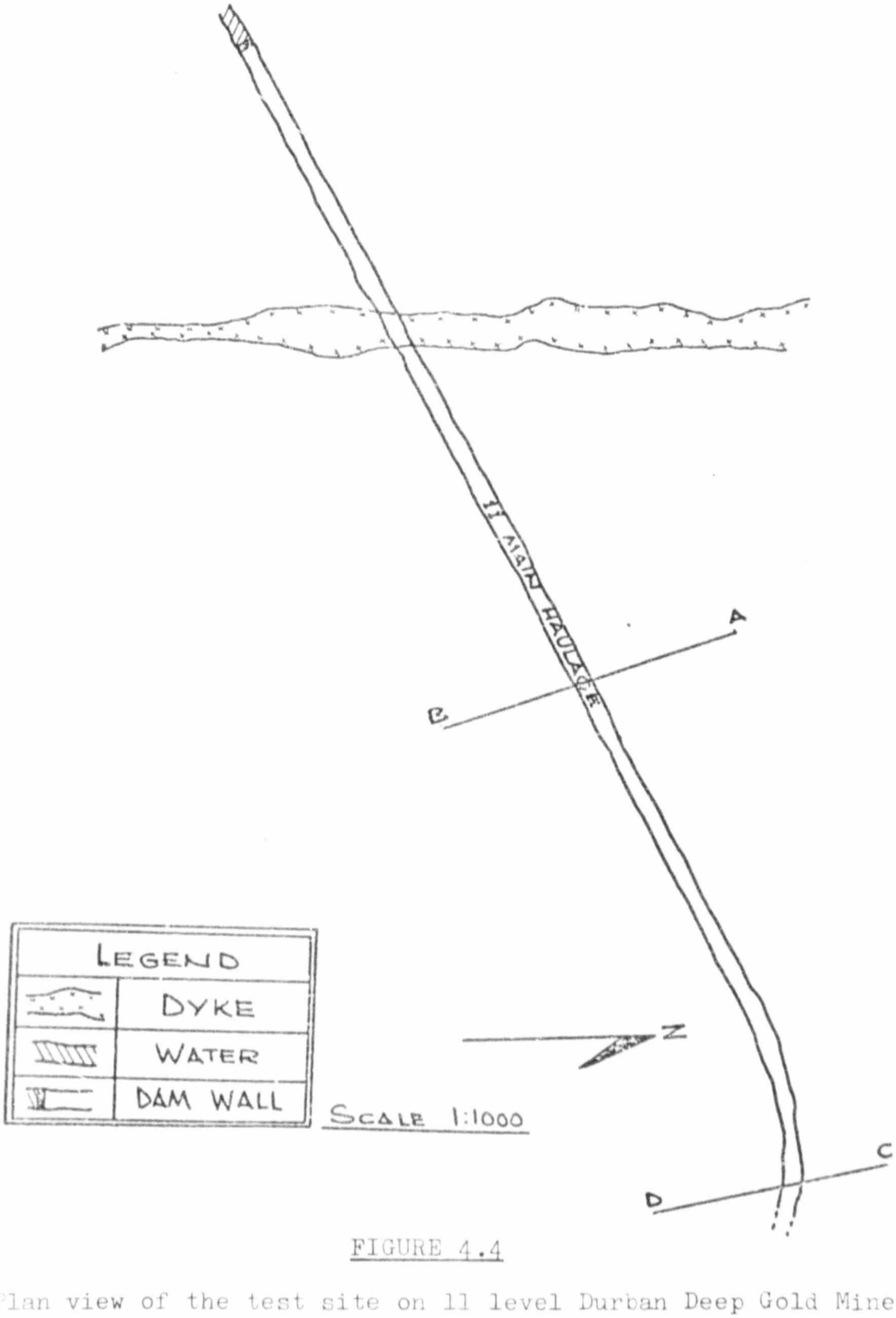

FIGURE 4.4

Plan view of the test site on 11 level Durban Deep Gold Mine.

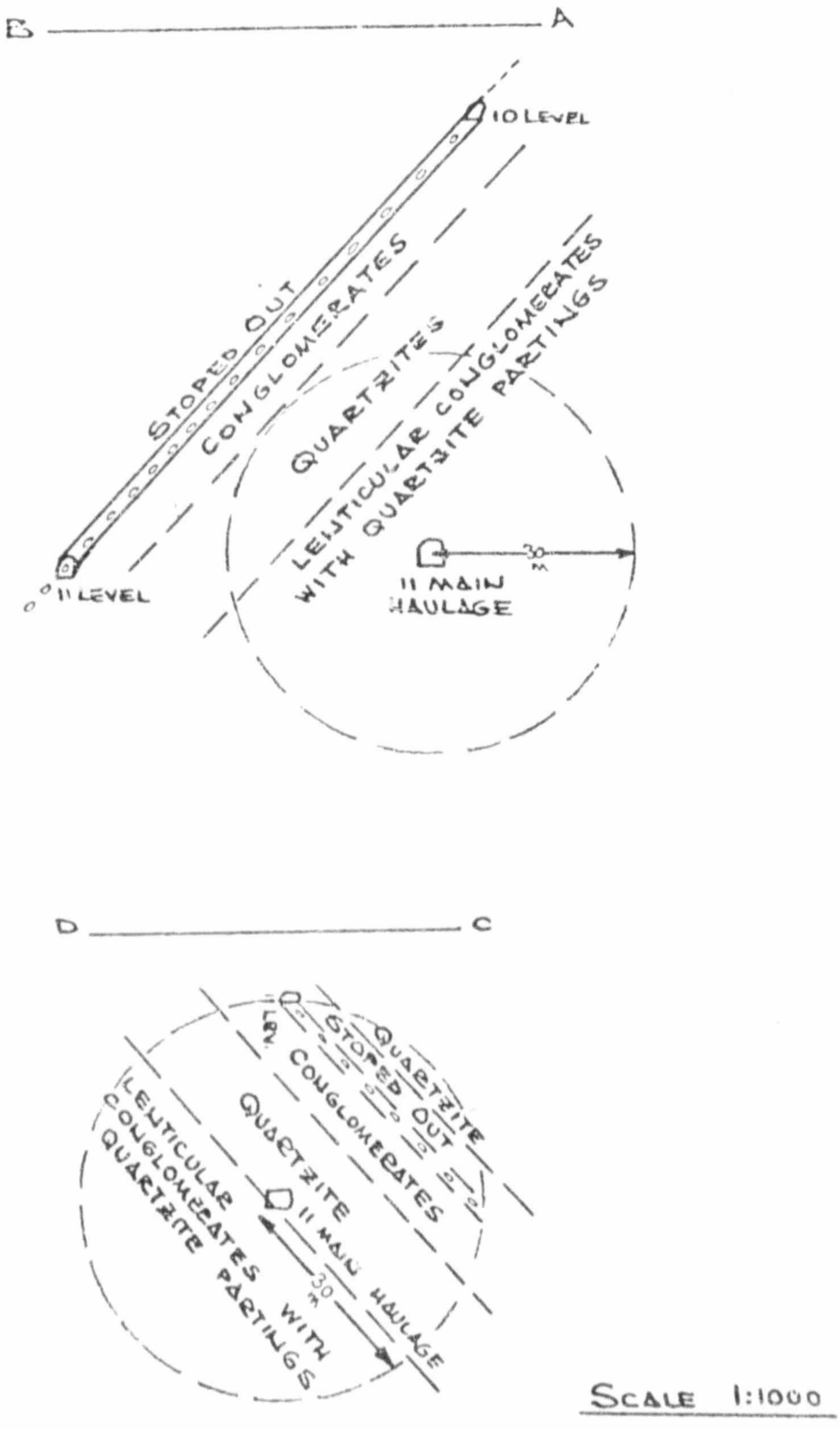

FIGURE 4.5

Sectional drawings showing the geology surrounding the test area.

All measurements of field strength were made over a distance of about 250 m, which, though appearing short by communication standards, has in the past been shown to be typical of the sort of range obtainable with completely portable equipment. As is evident from Figure 4.4 there is some curvature in the haulage and the majority of measurements were made between points which were not within line of sight. This situation was not chosen to preclude propagation via the airpath, as at first might seem to be the case, since at the frequencies of interest, the wavelengths are all in excess of the cross-sectional dimensions of the haulage, based on the loss tangent considerations discussed earlier.

The measurement area was moved to incluue the dyke within the transmission path in order to examine its effect, since many previous radio experiments in a variety of mines had indicated qualitatively that signal attenuation does increase when a dyke intervenes in the propagation path.

4.10 The equipment

In order to gain some insight into the propagation mechanism within this lossy dielectric medium, measured results of signal strength between transmitter and receiver would be required at various frequencies over the range from 100 kHz to about 10 MHz. These limits were determined by a variety of considerations as outlined previously. This range, of over six octaves, presented its own very real problems from the point of view of suitable equipment. Of prime importance was the portable aspect of all equipment used, since the mere logistics of mounting an operation of this type required ease of movement within the test area, and the utilization of a minimum number of personnel. No single, portable transmitter was available which would satisfy these requirements, thus it became necessary to use various pieces of apparatus which would cover portions of this spectrum, and by so doing, over a period of time, representative measurements over as much of the required band of frequencies as possible could be obtained.

4.11 Transmitting equipment

Three different transmitters were used in these tests. These are described below:

a) RACAL TR28 transceiver - 2, 4, 6 and 8 MHz channels at nominally 10 W output into 50 ohms.

b) Chamber of Mines hand-held transceiver - 903 kHz at nominally 1 W output into 50 ohms.

c) Chamber of Mines portable transceiver - 335 kHz at nominally 10 W output into 5 ohms.

All are standard single sideband voice transceivers, designed for two-way voice communication, and have the facility for tone transmission and it was this mode which was used to provide a constant level signal for measurement purposes.

4.12 Receiving equipment

In order to obtain quantitative readings of signal strength as distance and frequency are changed, it is necessary to be able to measure some voltage or current within a receiver and express signal strength at the input to that receiver in terms of this measured quantity. Obviously equipment designed to provide two-way communication does not normally provide this signal strength readout, thus it was necessary to include it as an "add-on" accessory to existing equipment.

Since items (a), (b) and (c) above are all transceivers, the receiving section was used in conjunction with the associated transmitter. The automatic gain control function of a receiver provides a readily accessible point from which to extract a voltage which varies in proportion to the input signal. This was duly done in the cases of the 2 to 8 MHz transceivers and the 903 kHz transceiver. The equipment was calibrated in the laboratory, and this calibration checked at various intervals throughout the duration of the tests to ensure accuracy and repeatability. Figures 4.6 and 4.7 show these calibration curves.

Tests at 335 kHz were only conducted at a later stage, and by that time a selective voltmeter made by Brüel and Kjaer was available. This B & K 2007 is a precision instrument covering the frequency range 100 kHz to 300 MHz and is capable of measuring input voltage levels from 2 μV to 100 V, at bandwidths of 2 kHz, and 200 kHz (above 3 MHz

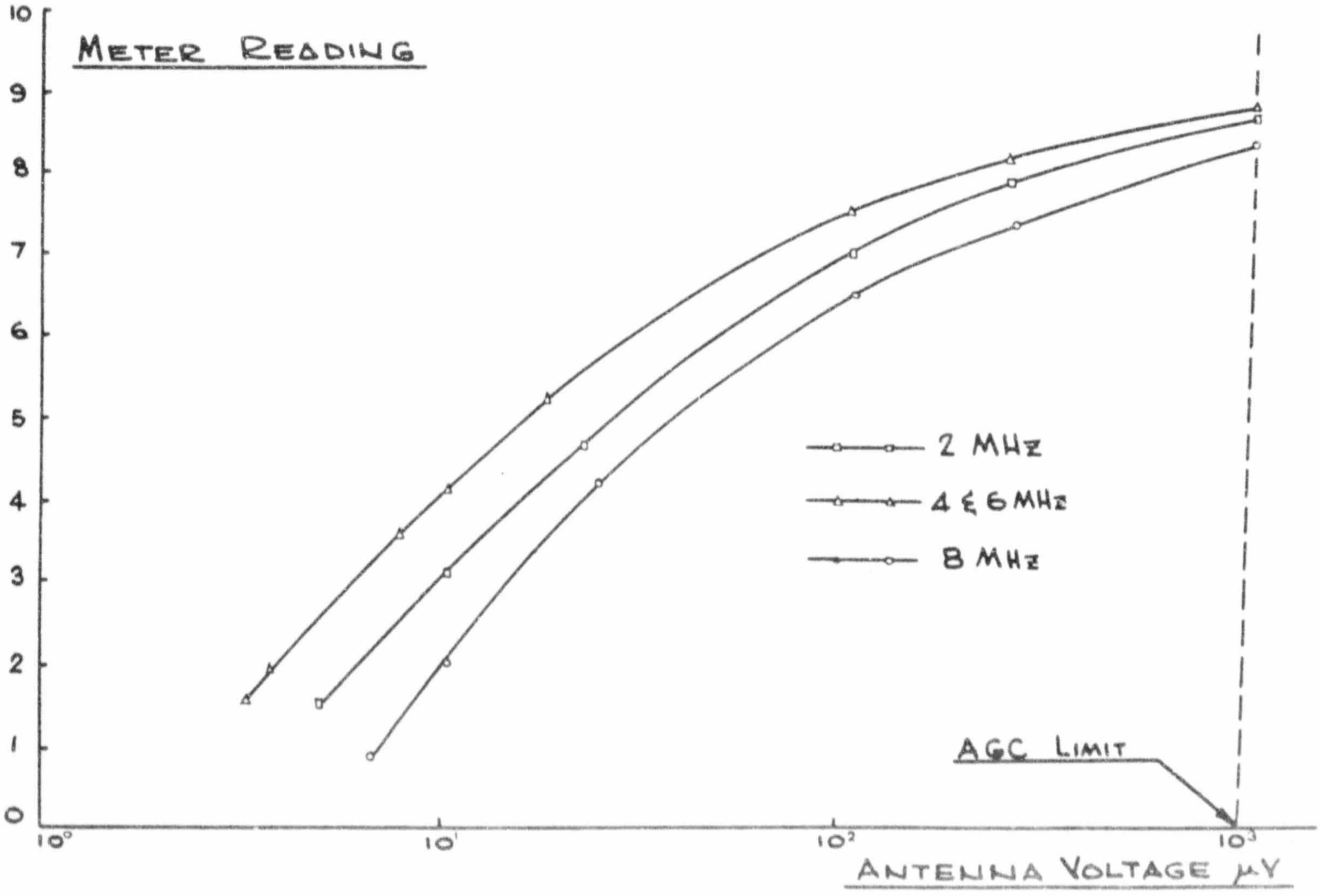

FIGURE 4.6

Calibration curve for signal strength measurements using the RACAL TR28, (□) 2 MHz, (Δ) 4,6 MHz, (o) 8 MHz.

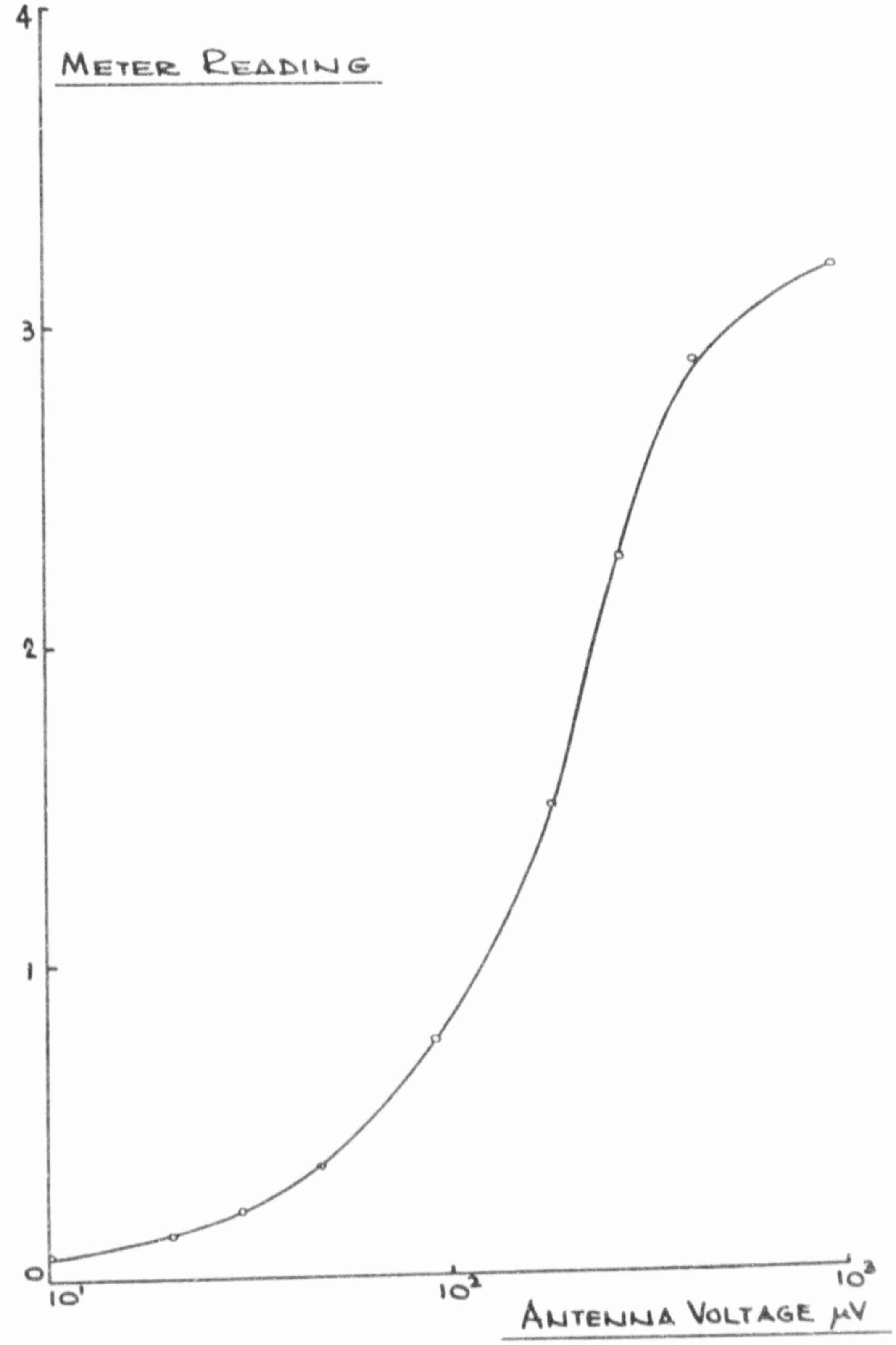

FIGURE 4.7

Calibration curve for signal strength measurements using C.O.M. 903 kHz transceivers.

operating frequency). Had it been available earlier the measurement problem would have been considerably simplified.

Examination of Figures 4.6 and 4.7 shows that in both cases signals above some specified level can cause the A.G.C. circuit to overload, in other words the response to changes in input becomes highly non-linear, resulting in invalid output readings. This fact did prove troublesome and precautions had to be taken to eliminate its effects. It was, however, particularly annoying when measurements were being taken within the vicinity of the dyke on 11 level, because what appeared to be anomalies in signal strength readings due to the effect of the dyke, were in some instances caused by this A.G.C. overload. However, various tests, with transmitter and receiver further apart, to reduce signal levels, indicated that the "dyke" effect was present, and bore closer investigation.

4.13 The antenna

For wideband measurements of signal strength characteristics with variation in distance between transmitter and receiver, the antenna system used provided by far the major problem area in the system. This fact is made clear by consulting the basic transmission equation (4 - 2), repeated here for clarity.

$$\frac{P_r}{P_t} = G^2 \eta^2 \left(\frac{\lambda}{4\pi R}\right)^2 e^{-2\alpha R} \qquad 4 - 41$$

Any measurement of α is made considerably easier if the number of variables in the above equation is kept to a minimum.

Of interest in this study are the variation in α with λ and R. Thus P_t and η, by being held constant would certainly facilitate this. Control over P_t is a simple matter, whereas G and η present problems since both are frequency dependent.

Using the relationship in (4 - 9), namely

$$G = \eta D$$

and the fact that small antennas should preferably be used in order to most accurately simulate the conditions of portability, D may be assumed equal to 1,5 as used before. In addition, the mere fact of measurements being made at frequencies as low as 100 kHz would indicate that any antenna erected within the confines of a mine tunnel would be considered "small" in terms of wavelengths, which is, after all, the criterion.

Thus we may write

$$(G\eta)^2 = (\eta^2 D)^2 \qquad 4 - 42$$

from which (4 - 41) may be solved for α yielding

$$\alpha = \frac{1}{2R}\left[\ln\frac{P_r}{P_t} - 2\ln\left(\frac{4\pi R}{\eta^2 D\lambda}\right)\right] \qquad 4 - 43$$

Now, at a fixed frequency, (in an area where the medium is <u>assumed</u> to be homogeneous, meaning fixed λ), then α may be determined by measuring P_r, if η is known.

Similarly, if R is fixed, α can be determined in like manner, but again only if the antenna efficiency η is known.

In the likely event of η being unknown it is possible to determine α by making two measurements of received power (or voltage) and calling these P_{r_1} and P_{r_2} respectively, at distance R_1 and R_2 respectively, from the source.

Thus we may write

$$P_{r_1} = P_t \; \eta^2 \; G^2 \left(\frac{\lambda}{4\pi R_1}\right) e^{-2\alpha R_1} \qquad 4 - 44$$

and $$P_{r_2} = P_t \; \eta^2 \; G^2 \left(\frac{\lambda}{4\pi R_2}\right) e^{-2\alpha R_2} \qquad 4 - 45$$

Therefore

$$\frac{P_{r_1}}{P_{r_2}} = \left(\frac{R_2}{R_2}\right)^2 e^{2\alpha(R_2 - R_1)} \qquad 4 - 46$$

from which we obtain

$$\alpha = \frac{1}{2(R_2 - R_1)} \ln \frac{P_{r_1}}{P_{r_2}} \left(\frac{R_1}{R_2}\right) \text{ nepers/m} \qquad 4 - 47$$

or, since measuring received voltage is more direct than power

$$\alpha = \frac{1}{R_2 - R_1} \ln \frac{V_{r_1}}{V_{r_2}} \frac{R_1}{R_2} \text{ nepers/m} \qquad 4 - 48$$

which follows because the receiver input impedance is common to both measurements.

In order that the methods discussed here may be used to obtain values for α, it is absolutely necessary that all measurements of field strength be conducted in the area of far field influence. At the lower end of the frequency range under discussion here, the wavelengths in the medium are considerable, and since the high loss tangent criterion may apply, this far field zone may only really dominate over the near field components many hundreds of metres from the source. Since an exponential decrease in signal strength occurs due to α, in addition to spreading losses, the signal level in this far field zone may be minimal and thus too small to enable accurate measurements of it to be made, in order that α may be calculated. It is thus necessary to employ more transmitter power or an antenna system exhibiting higher efficiency or both. Transmitter power and equipment size go hand in hand, hence an increase in this area is not practicable, particularly when one bears in mind that to effect an increase in range by a factor of two requires, in a typical case, where α might be 0,01 nepers/m, an increase in power by a factor of about 30 (Appendix C). The medium was considered to have $\epsilon_r = 10$, $p = 15$ and the frequency of operation to be 200 kHz.

4.14 Experimental results

Presented below are the results of the many measurements made at the Durban Deep test site. These measurements were made at six discrete frequencies, namely 335 kHz, 903 kHz, 2182 kHz, 4066 kHz, 6520 kHz and 8227 kHz. No special significance must be attached to the actual frequencies. These happened to be available in the equipment (4.1) used, and give a reasonable spread over the medium frequency - high frequency overlap region of interest here.

These measurements will be discussed by presenting the six discrete frequency results. Each frequency will be discussed separately, after which the overall variation in medium characteristics will be examined, from which the effect that the medium has on the propagation of electromagnetic energy can be obtained.

4.14.1 335 kHz

The variation in signal strength received (in µV) with distance from the transmitter which delivered a constant output of 10 W to a matched small loop antenna is presented in Figure 4.8. The signal strengths were expressed in decibels with respect to one microvolt (dBµV) and three orientations of the loops were used. In each case both loops were orientated as described, that is, both coaxial, or both coplanar and vertical to the footwall, etc. The receiver was fixed at approximately 240 m from the dam wall, and the transmitter was moved in steps of a few metres at a time.

It will be noted that at distances less than about 15 m from the source antenna, the coaxial antenna orientation yields the strongest signals, confirming that this is the H_r field, which contains no component which decays as $1/_R$. Of particular interest, however, is the fact that the two coplanar antenna orientations do not yield the same variation in signal strength with distance, as would surely be expected of them, since it is the coplanar aspect and not their orientation with respect to some arbitrary reference such as the footwall, which should determine

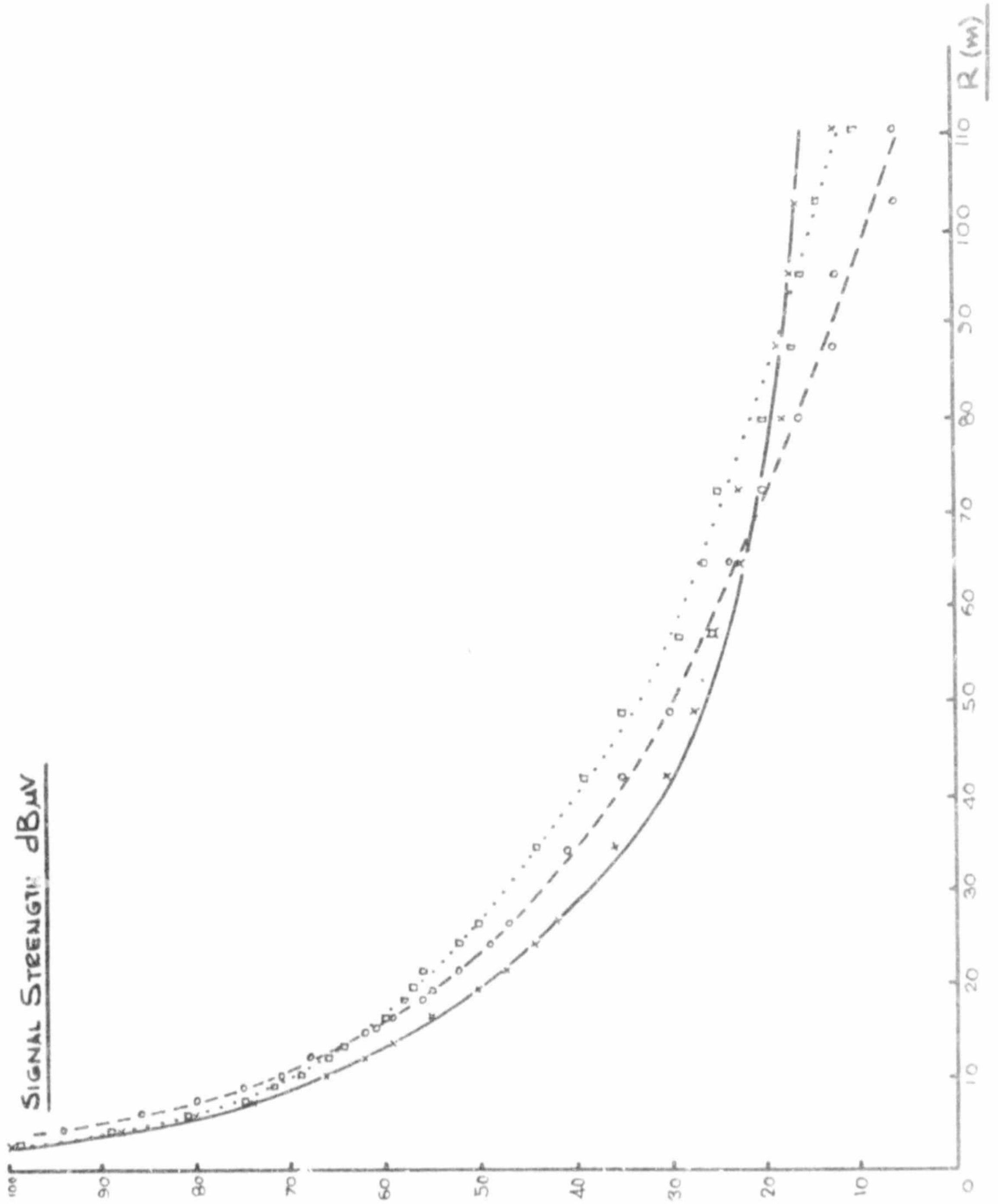

FIGURE 4.8

Signal strength with distance R, between transmitter and receiver for antennas orientated: (o) coaxially, (□) coplanar vertically, (x) coplanar horizontally.

their performance. This difference suggests that the surrounding medium is affecting propagation of signals launched with different angular orientations, in different ways. It is thus indicative of some geological discontinuity since the change in electrical characteristics of the medium has been shown to be due to changes in geological detail. The effect was also noted at 2 MHz, and would also possibly have occurred at all other frequencies had the various antenna combinations been employed there as well, but which, for reasons made clear later, were not. Three references in the literature will be cited, after discussion of these measurements, which confirm both theoretically and experimentally the existence of this propagation anomaly due to geological discontinuities.

Further examination of Figure 4.8 shows that, at about 60 m from the source, the slope of the curve due to the coplanar horizontal orientation of the antennas changes rather rapidly, indicating a definite decrease in attenuation compared with both the coaxial and coplanar vertical cases. That this is not an isolated result due, possibly, to experimental error, it was confirmed by many measurements of the various signals, taken in the same area.

In the far field zone the $^{1}/R$ rate of attenuation should dominate. No obvious dominance is evident from these figures, which is taken to indicate that the measurement area did not extend far enough, if at all, into this zone. Thus, as 335 kHz, with the transmitter, receiver and antenna characteristics as used here, the fields prevailing over these measured distances were complex, showing no real dominance of one component over another. From an operational point of view this means that antenna orientation, for optimum performance, will vary depending on the distance between transmitter and receiver.

This fact has been noted in many experimental exercises using this equipment in the past, and the results presented here confirm the complex nature of the fields at 335 kHz.

In order to determine the attenuation characteristics of the medium at this frequency, using the techniques discussed previously, it is essential that far field components be employed. If it is assumed that the coplanar horizontal component discussed above, is indeed that which decays as $1/_R$, then its slope will yield the attenuation "constant" α of that section of the medium in which the measurements were taken, when the variation of log VR is plotted against distance R. This is done in Figure 4.9, which shows the variation of all components, so modified, with distance.

A least squares fit of the data relating to that portion of the curve which exhibited minimum attenuation with distance yielded a value for α equal to 0,12 dB/m (see Appendix D).

The last discernible reading on the receiver selective voltmeter was 2 µV. The 335 kHz transceiver used as a signal source was designed, obviously, to provide voice communication and this function was in fact used, while making the signal

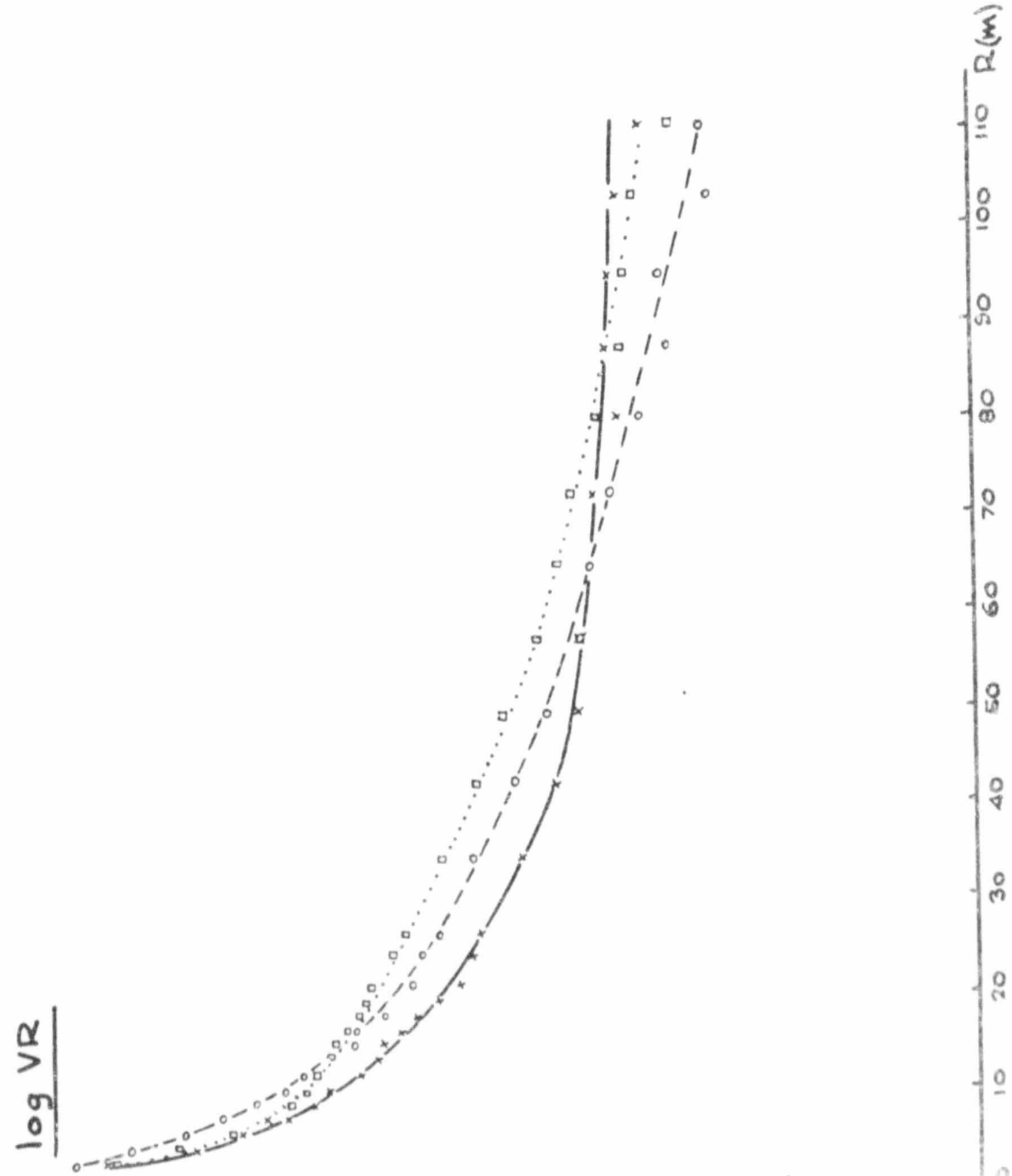

FIGURE 4.9

Log VR with distance R, between transmitter and receiver for antennas orientated as in Figure 4.8

strength measurements, to co-ordinate operations between transmitter and receiver. During the many measurement sessions no electrical noise was heard in this test area, thus communication was limited only by the noise generated internally by the equipment.

Perfect, but weak, voice communication was possible out to the maximum separation distance attainable in this site of approximately 235 m via the rock, and occurred with antennas orientated in the "coplanar horizontal" position. No signals were audible for the coaxial orientation at all, thereby indicating that the "radiation field" was being received.

The minimum speech signal, which was still understandable on the 335 kHz transceivers, was measured in the laboratory as 0,22 μV p.d. If this value of V_r is now used in the expression

$$\eta\ G\ \lambda = \frac{4\pi R V_r}{V_t e^{-\alpha R}} \qquad 4 - 59$$

with $R = 235$ m

$V_t = 7{,}1$ V

$\alpha = 0{,}12$ dB/m $= 0{,}014$ nepers/m

we obtain

$$\eta\ G\ \lambda = 2{,}46 \times 10^{-3} \qquad 4 - 60$$

Now, from 4 - 9, $G = \eta\ D$, thus

$$\eta^2\ D\ \lambda = 2{,}46 \times 10^{-3}$$

and since the antennas used were elemental dipoles, $D = 1{,}5$, therefore

$$\eta^2 \lambda = 1,64 \times 10^{-3} \qquad 4 - 61$$

If, using Figure 4.9, the signal level at R = 100 m is used, and η G λ is calculated, as above, we find:

At R = 100 m log VR = 2,8

thus VR - 631, giving

$V = V_r = 6,31\ \mu V$

therefore

$$\eta G \lambda = 4,5 \times 10^{-3} \qquad 4 - 62$$

which compares very favourably with 4 - 60, being only 1,83 times greater, and thus, bearing in mind that the signal level V_r, used to calculate 4 - 60 was not necessarily all that accurate since the observations made both underground and in the laboratory were subjective.

This result is heartening since it would indicate that the value of α obtained from the slope of the "coplanar horizontal" curve is representative of the area in question, and indicates also that this antenna orientation produces field components, so aligned with respect to the surrounding medium, such that they suffer the least attenuation of all components, with distance.

4.14.2 903 kHz

An output power of 1 W was fed into a small portable loop antenna, matched to 50 ohms and was received via a similar matched loop and hand-held transceiver. Actual signal strengths were determined by reading these off on the calibration curve shown previously in Figure 4.7.

Shown in Figure 4.10 is the variation in signal strength, presented as decibels with respect to one microvolt, with distance between transmitter and receiver, R, in metres. It was noticed, while making the measurements, that the orientation of the receiving antenna changed from basically "coaxial" to the "coplanar" positions described in the previous section, for all readings beyond 13,7 m from the transmitter. No definite coplanar horizontal or coplanar vertical position was employed, rather an orientation somewhere between the two, since the loops were worn across the operator's chest and one shoulder. The change in orientation, for maximum signal strength was most noticeable and in the light of the previous results, is felt to be significant.

Two basic slopes are evident, which coincide with the observed changes in antenna orientation necessary to maximise signal strengths. Those points lying further from the source than about 14 m were plotted in Figure 4.11, as ln VR with distance R. The slope of these points is 0,029 nepers/m or 0,25 dB/m.

Now, as for 335 kHz, using 4 - 59, with

$R = 29$ m

$V_t = 7,1$ V

$\alpha = 0,25$ dB/m

we obtain

$$\eta^2 \lambda = 0,67 \times 10^{-3} \qquad 4 - 63$$

and

$$\eta G \lambda = 1,01 \times 10^{-3} \qquad 4 - 64$$

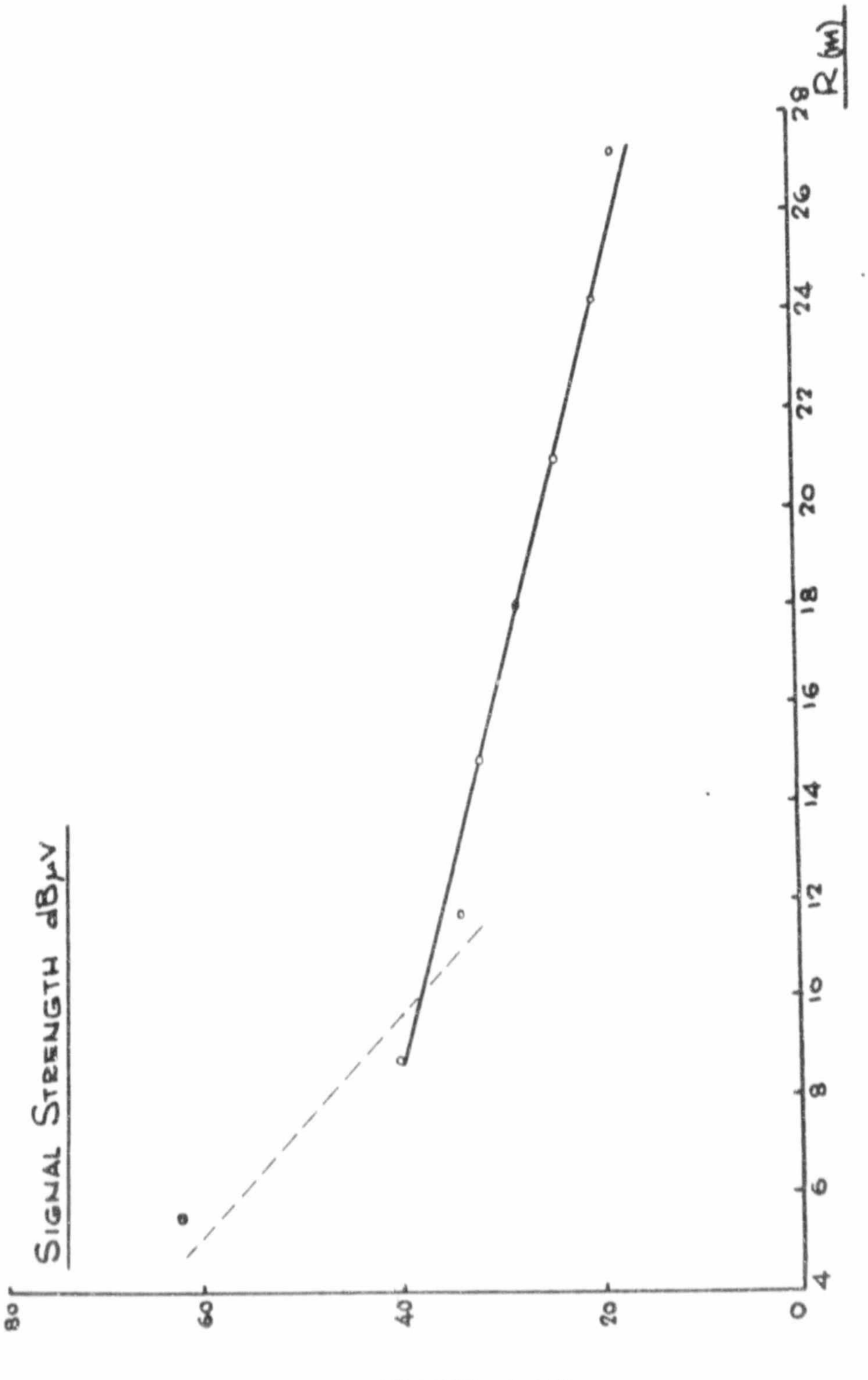

FIGURE 4.10

Signal strength with distance R, between transmitter and receiver at 903 kHz.

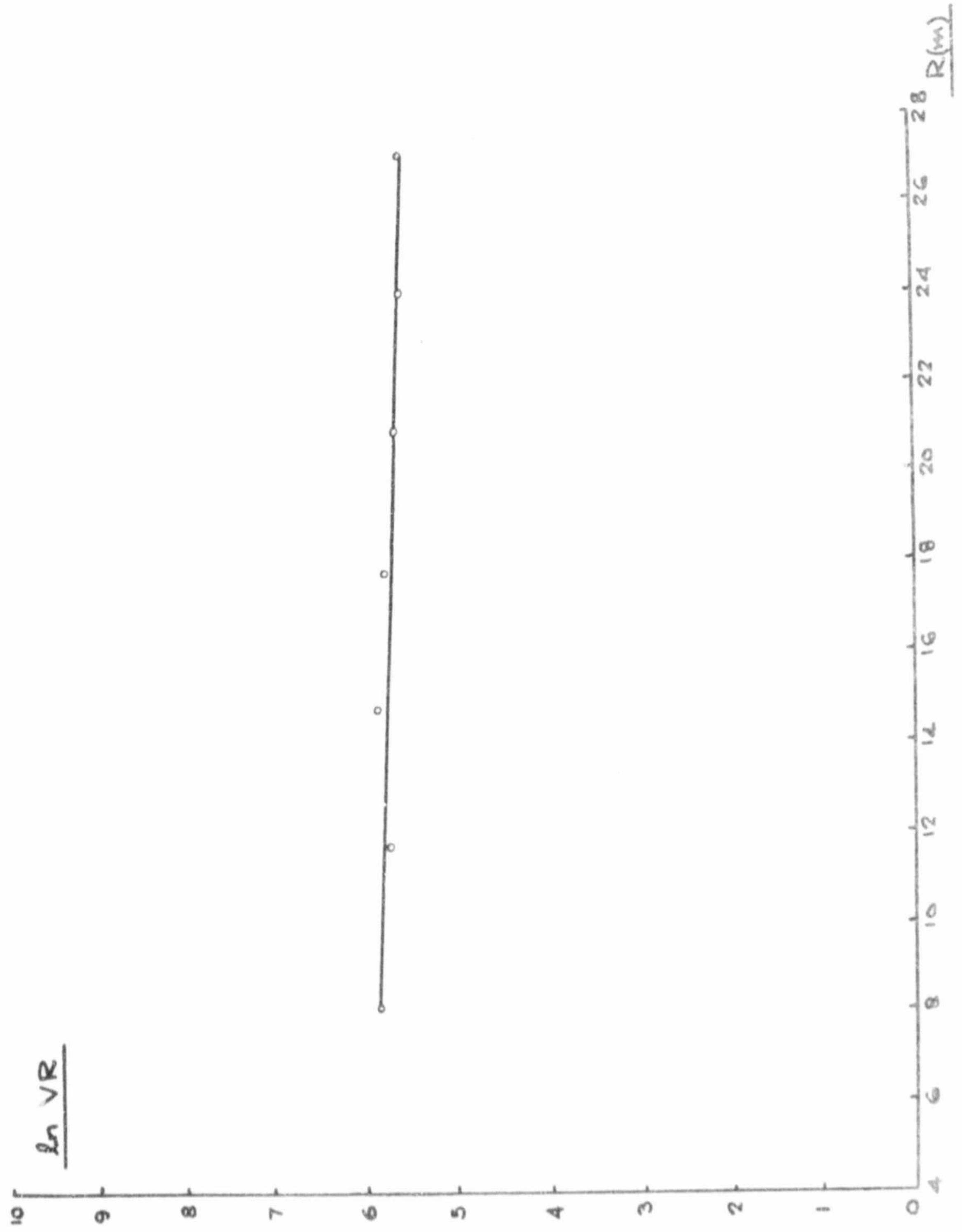

FIGURE 4.11

In VR with distance R, between transmitter and receiver at 903 kHz.

which again compare favourably with the equivalent values obtained at the lower frequency. It is interesting to compare 4 - 63 with 4 - 61, where we find

$$\frac{(\eta^2 \lambda)_{903}}{(\eta^2 \lambda)_{335}} = \frac{0,67 \times 10^{-3}}{1,64 \times 10^{-3}} = 0,41 \qquad 4 - 65$$

Now, if we consider ϵ_r to be constant over the range of frequencies being examined here, (see 3.1.4), then we may compare the wavelengths in the medium as follows:

$$\frac{\lambda_{903}}{\lambda_{335}} = \frac{335}{903} = 0,37 \qquad 4 - 66$$

Thus, substituting 4 - 66 into 4 - 65, we obtain

$$\frac{\eta_{903}}{\eta_{335}} = \sqrt{\frac{0,41}{0,37}} = 1,05 \qquad 4 - 67$$

This result is based on 2 - 15 where, if $p \leq 0,6$, then the wavelength in the medium λ, and that in free space λ_o, are related by

$$\lambda = \frac{\lambda_o}{\sqrt{\epsilon_r}} \qquad 4 - 68$$

Assuming a median value of 6 for ϵ_r, this condition would be satisfied if the medium conductivity, for each case, were

$$\sigma_{335} \leq 6,7 \times 10^{-5} \text{ S/m}$$

and $$\sigma_{903} \leq 18 \times 10^{-5} \text{ S/m}$$

Using the measured values of α, and the expressions 2 - 11 and 2 - 12, namely that if $p \leq 0,6$ then

$$\alpha = \frac{1,64 \times 10^{3}\, \sigma}{\sqrt{\epsilon_r}} \text{ dB/m}$$

and, if $p \geq 10$, then $\alpha = 0,545\sqrt{f\,(\text{kHz})\,\sigma}$ dB/m, we can calculate σ by assuming a value for ϵ_r, as above, for $p \leq 0,6$, and directly for $p \geq 10$.

Thus, for $p \leq 0,6$, the conductivity σ would be

$$\sigma \doteq \frac{\alpha \sqrt{\epsilon_r}}{1,64 \times 10^{3}} \qquad 4 - 69$$

yielding $\sigma \doteq \frac{0,12 \sqrt{6}}{1,64 \times 10^{3}} \doteq 1,79 \times 10^{-4}$ S/m

at 335 kHz, and

$$\sigma \doteq \frac{0,25 \sqrt{6}}{1,64 \times 10^{3}} \doteq 3,73 \times 10^{-4} \text{ S/m}$$

at 903 kHz.

Or, if $p \geq 10$,

then $\sigma \doteq \left(\frac{\alpha}{0,545}\right)^{2} \frac{1}{f\,(\text{kHz})} \qquad 4 - 70$

$$\doteq \left(\frac{0,12}{0,545}\right)^{2} \frac{1}{335} \doteq 1,45 \times 10^{-4} \text{ S/m}$$

at 335 kHz, and

$$\sigma \doteq \left(\frac{0,25}{0,545}\right)^{2} \frac{1}{903} \doteq 2,33 \times 10^{-4} \text{ S/m}$$

at 903 kHz.

If these results are examined, the first point which comes to mind is that the conductivities yielded for the two loss tangent conditions are very similar. However, an assumption was made as to the value of ϵ_r, and the validity of this assumed value should be examined. From the calculated value for σ it is possible to find what value of p obtains given these rock characteristics.

Thus $$p = \frac{\sigma}{\omega \epsilon_o \epsilon_r}$$

$$= \frac{1,79 \times 10^{-4}}{2\pi \times 335 \times 10^{3} \times 8,85 \times 10^{-12} \times 6}$$

$$= 1,6 \text{ at } 335 \text{ kHz}$$

and similarly,

$$p = 1,24 \text{ at } 903 \text{ kHz}.$$

Whereas, if p is assumed greater than or equal to 10, then to satisfy this would require the following values of ϵ_r.

$$\epsilon_r \leq 0,78 \text{ at } 335 \text{ kHz}$$

and $$\epsilon_r \leq 0,46 \text{ at } 903 \text{ kHz}.$$

These values of ϵ_r are particularly low, suggesting therefore, that at these frequencies, for the rates of attenuation as measured, the loss tangent condition $p \geq 10$ does not apply.

In order that $p \leq 0,6$ should apply, for the conductivities as calculated, would require values of ϵ_r of about 16 at 335 kHz and 12 at 903. Now these are not unrealistic values, but since it has been found, (2.6.3), that the *in situ* value of ϵ_r does not differ drastically from that measured in the laboratory, and is almost independent of frequency, the assumed value of $\epsilon_r = 6$ will be retained as being typical.

It, therefore, appears that the loss tangent applying *in situ* would be $p \leq 0,6$ if the respective conductivities were less than about $6,7 \times 10^{-5}$ S/m at 335 kHz, and $1,8 \times 10^{-4}$ S/m at 903 kHz. On the other hand the intermediate range of values of p apply for the values of σ obtained from 4 - 69.

It seems reasonable, therefore, to accept the value of 1,05 for the ratio of antenna efficiencies at 903 and 335 kHz as given by 4 - 67.

The antennas used at these two frequencies were elementary magnetic dipoles, but were not physically similar, since they differed both in the respective areas A, and number of turns, N.

4.14.3 2, 4, 6 and 8 KHz

Measurements made at these four higher frequencies will be examined as a group since the same apparatus was used in their generation and detection, namely, the TR28 transceivers as described in 4.11. Use was made of two types of antennas at 2 MHz, these being a 1,8 m vertical monopole, which, at this frequency particularly, may be regarded as an elemental antenna, and a circular loop of

0,5 m diameter of one turn, which is also elemental. At the higher frequencies only the monopole was used since the loop could not easily be resonated and matched. This subject will be discussed in Chapter 5.

Figure 4.12 shows the variation in received signal strength, in dBμV, with distance R, in m, between transmitter and receiver at the four frequencies. It will be noted that a marked discontinuity occurs at a distance midway between transmitter and receiver. What appeared initially to be due to the dyke, which intersects the travelling way at that point, was shown to be due more to the A.G.C. non-linearity brought about by the magnitude of the received signal at that separation distance. This is illustrated in Figure 4.13, where the 2 MHz case was examined in more detail using four antenna configurations. In all cases the rate of signal decay beyond the dyke is shown to be more regular than that evident from Figure 4.12. There is also no peak in signal strength within the dyke, as was the case in Figure 4.12, and the non-linearity in the system at close spacing is also evident due to the lack of correlation between the 2 MHz readings at distances less than 60 m.

The dispersion through the medium is evident from Figure 4.12, with the 8 MHz signal being strongest at minimum separation, but decidedly weakest at the limits of measurement. Similarly 6 MHz shows up well at short distances whereas the 2 MHz signal is stronger than that at 4 MHz at the same point. The reason for these variationsis due to the trade-off between

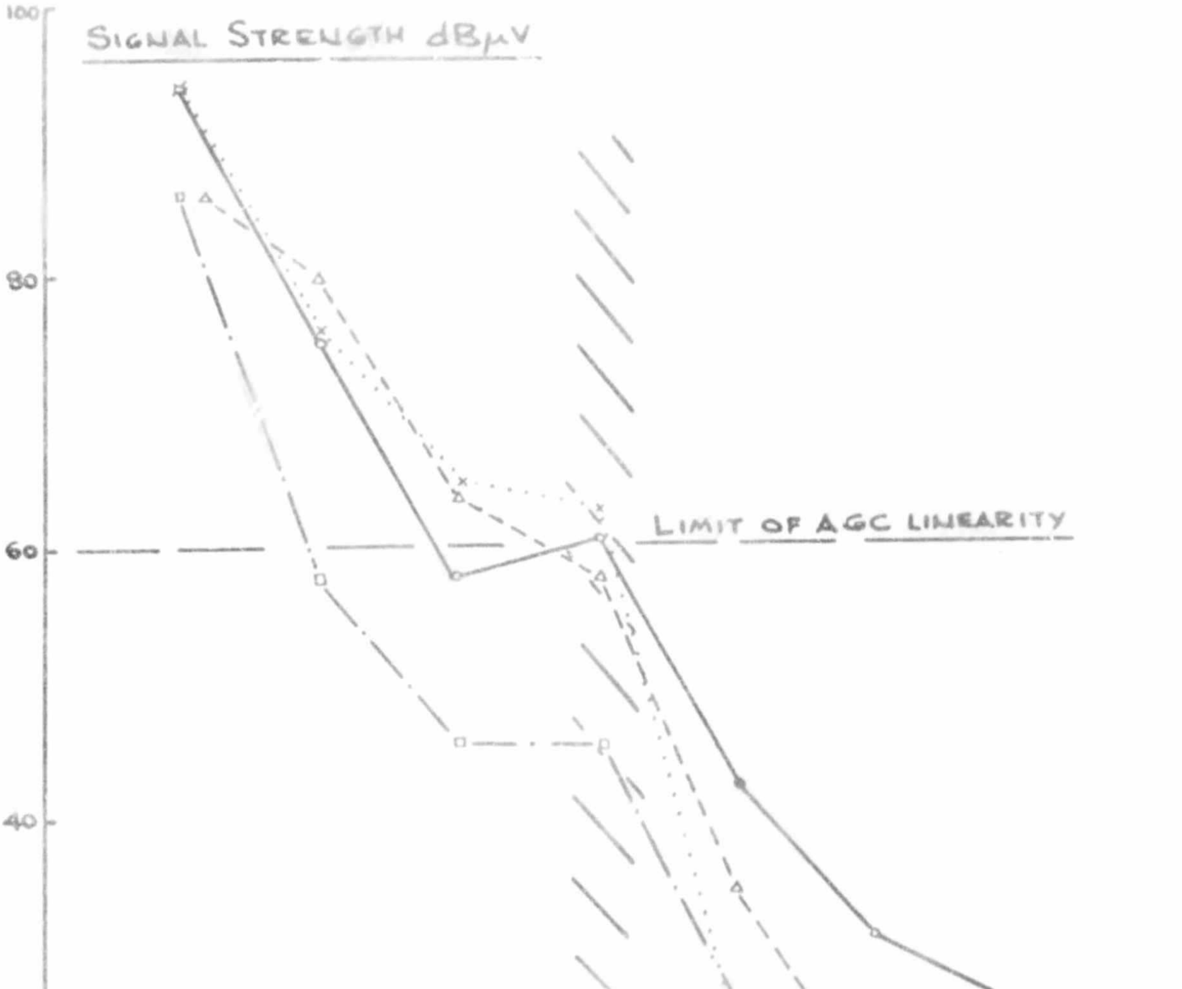

FIGURE 4.12

Signal strength with distance R, between transmitter and receiver at 2 MHz (o), 4 MHz (□), 6 MHz (Δ), and 8 MHz (x).

antenna efficiency and attenuation via the medium. The short monopole is considerably more efficient as a radiator at 8 MHz than it is at 2 MHz. With the transmitter and receiver less than 60 m apart this greater efficiency gives rise to a signal which, even though it is more severely attenuated by the medium, is stronger than that radiated with less efficiency and which suffers less attenuation at 2 MHz.

The rate of attenuation at 8 MHz was such that insufficient data was available to be statistically meaningful. The measured values of the attenuation constant α are shown in Table 4.1 for 2,4 and 6 MHz, and, according to the position in the travelling way where the measurement was made. The values shown are the confidence limits resulting from a number of measurements.

TABLE 4.1

Variation of the attenuation constant, α, with frequency and position in the travelling way

Frequency (MHz)	2	4	6	Position in travelling way
Attenuation Constant (α) (α in dB/m)	0,49 0,41	0,41 0,36	0,72 0,65	with dyke
	0,49 0,46	0,52 0,54	0,83 0,62	without dyke

It is interesting to note that the values of α at 2 and 4 MHz are very similar, and particularly, that with the dyke intervening in the path, α at 4 MHz is in fact less than that at 2 MHz, on average. In the area with no dyke in the signal path the increase in attenuation constant with frequency occurs, as expected.

From Figure 4.13 the effect of the antenna on the system is apparent. Again, as in the cases of 335 kHz and 903 kHz, the coaxial orientation shows a greater rate of attenuation than any of the others, once again confirming that the fields radiated, due to these different orientations, are different, and, therefore, that the far field, or radiation component is present.

The vertical rod and horizontal loop configurations produce virtually similar field strengths. It should be noted at this point that the vertical rod,.(plus its image) constitute a vertical electrical dipole and the horizontal loop is the equivalent, or vertical magnetic dipole, both of which are the elemental antennas as used in the previous field analysis.

With the transmitting and receiving loops orientated coplanar and vertically the signal strengths were slightly weaker than for the previous configurations. Since this result was surprising, for the same reasons as mentioned in 4.14.1, it was checked and found to be correct, with the general form of the curves in Figure 4.13. Orientating the loops vertically like this, results in the magnetic field component being horizontal and the electric field being vertical within the medium, as illustrated in Figure 4.14.

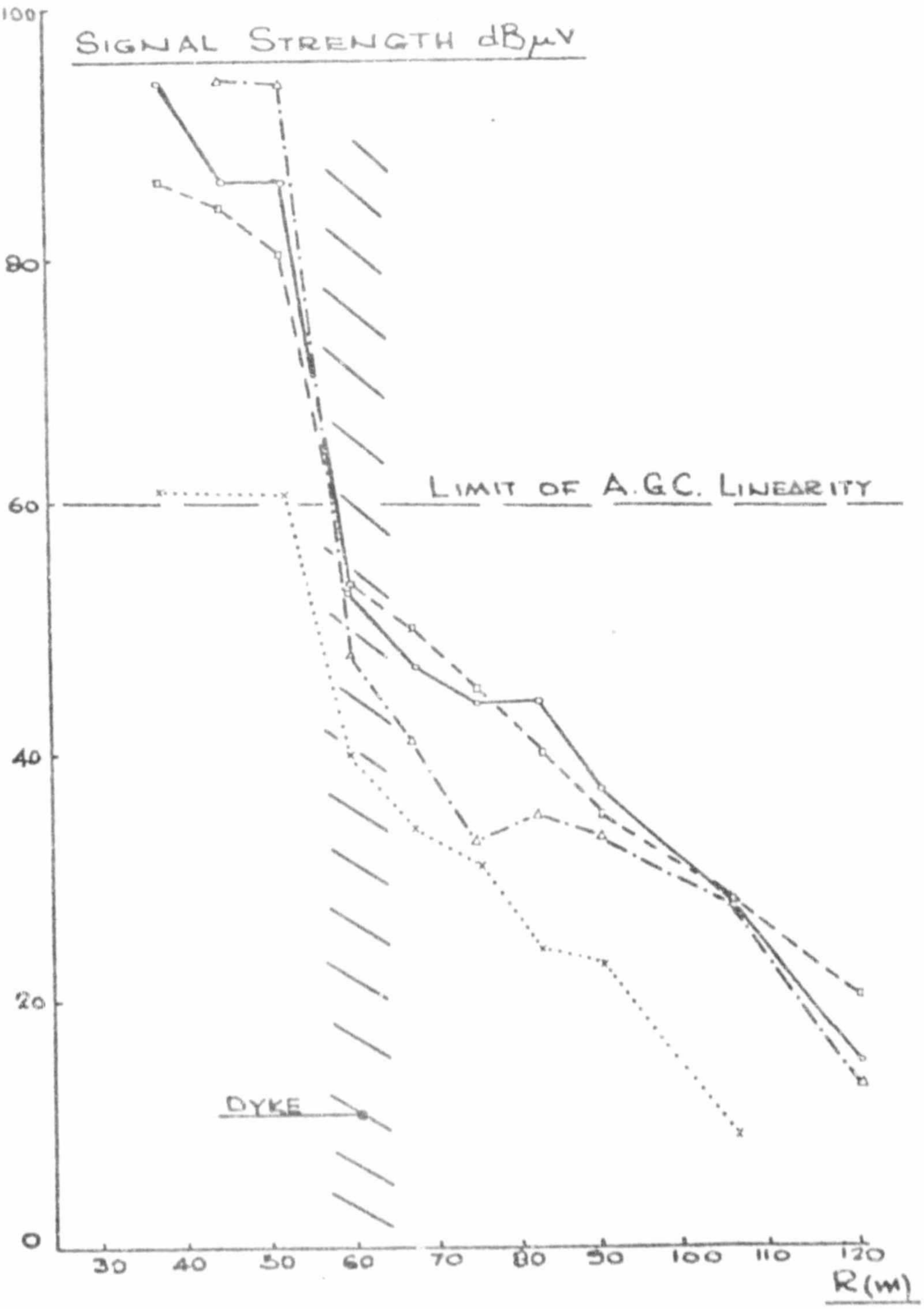

FIGURE 4.13

Signal strength with distance, R, between transmitter and receiver at 2 MHz, with vertical rod (o), coplanar horizontal (□), coplanar vertical (Δ), and coaxial (x), loops.

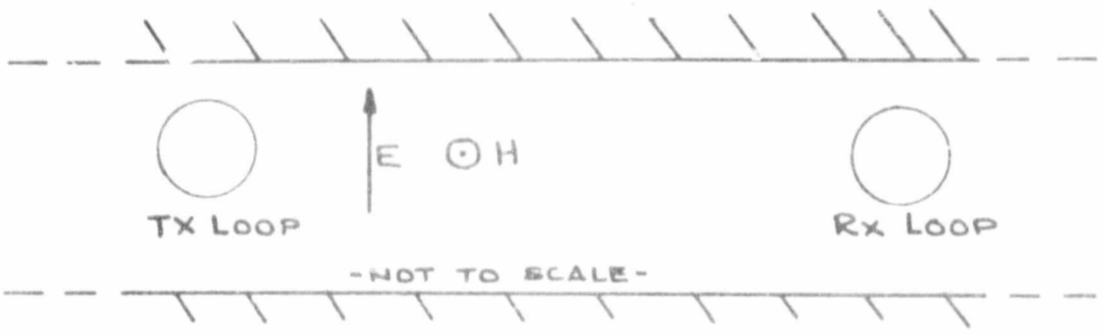

FIGURE 4.14

Field distribution for coplanar vertically orientated loop antennas

For differing field strengths to result merely by interchanging these E and H components (by vertical or horizontal alignment of the loops) must indicate that inhomogeneity exists within the medium which by a "wave-guiding" type action allows more effective propagation due to excitation by the one field component than the other.

Investigation of this phenomenon is beyond the scope of this study, but is well documented in the literature, and from practical results reported therein has been shown to play a definite role in sub-surface electromagnetic propagation.

Both Wait (1962) and Ziggh (1963) present theoretical analyses which confirm the existence of such modes in non-homogeneous media, and Emslie and Lagace (1976) offer both theoretical and experimental evidence which resulted from work done at frequencies similar to those used here, in United States coal mines.

4.14.4 The composite attenuation curve

Data is now available on the variation of the attenuation constant α, with frequency. This, being of fundamental importance in the design of a communication system is shown plotted graphically, and compared, on the same set of axes, with the curve derived by Wadley (1949), in his original work on the feasibility of radio communication underground.

As was pointed out in Chapters 2 and 3, the values of conductivity σ, and permittivity ε, as measured in the laboratory, are not indicative of the situation prevailing below the surface of the earth. Thus the variation in attenuation constant α, with frequency, as presented by Wadley in his paper, contrasts interestingly with that determined here, and to illustrate this, the two are shown in Figure 4.15.

The attenuation measured in situ is higher than that predicted from laboratory measurements, but the basic form of the curves is very similar. It is thus clear that the lower the frequency the less the signal is attenuated by the medium. The fact that the attenuation between about 2 and 4 MHz is roughly constant, in the vicinity of the dyke, raises an interesting point, and this is that a "high frequency window" might exist which would allow signals to propagate through an otherwise opaque medium.

This possibility was suggested by Gabillard, Degague, and Wait (1971) and was based on the assumption that the electrical characteristics σ, μ and ε of the medium were

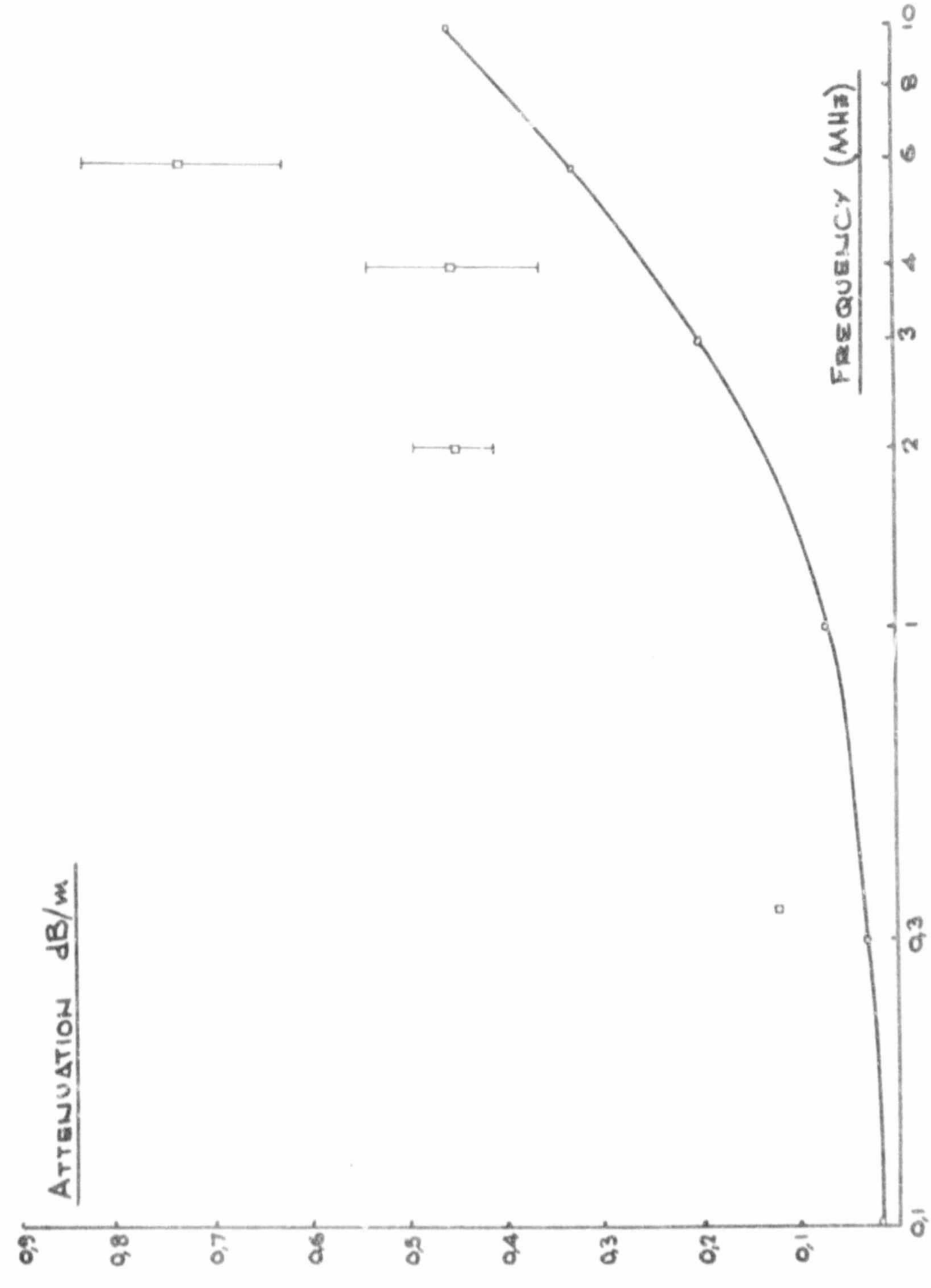

FIGURE 4.15

Attenuation with frequency showing the comparison between Wadley's theoretically determined values (○), with those measured at Durban Deep gold mine (□).

constant with frequency (i.e. over the frequency range of interest), and independent of frequency; that the length (dl), of the elemental antenna, was much less than the wavelength in the medium; and that the product Idl was constant over the frequency range.

Of these, only the restriction relating to σ, μ and ϵ might prove problematical. The others, by suitable choice of antenna and transmitter can be met. Considering the results in Figure 4.15 again, the question is raised whether the near constancy in α between 2 and 4 MHz as measured, was due to an anomalous effect of the dyke, and if so, whether this is an indication of the existence of this "high frequency window."

Viewed practically, however, even if this situation does exist, its usefulness in the day to day mining environment would seem to be rather limited since anomalies such as dykes make up only a small percentage of the basic strata and one is left more with the view that this propagation mode is an academic curiosity, since all other evidence suggests an increase in conductivity with frequency, even though permittivity may, and permeability certainly, be taken to be constant over the range of frequencies being examined here.

4.15 The conductivity of the medium

On the assumption that the permittivity of the medium is constant over the frequency range of interest here, the general expression for α, (2 - 3), may be solved for the loss tangent p, and from this, the value of σ obtained for the various frequencies.

Solving (2 - 3) for p we obtain

$$p = \left[\left\{ \frac{2}{\mu\epsilon} \left(\frac{\alpha}{\omega} \right)^2 + 1 \right\}^2 - 1 \right]^{\frac{1}{2}} \qquad 4 - 71$$

and, since $\sigma = \omega \epsilon_o \epsilon_r p$, the conductivity may be calculated. Table 4.2 presents these values.

TABLE 4.2

Values of loss tangent (p) and conductivity (σ) calculated from the measured values of attenuation constant (α) for $\epsilon_r = 6$ (assumed)

Frequency (kHz)	p min	 max	σ (S/m) min	 max
335	2,1		$3,35 \times 10^{-4}$	
903	1,48		$4,46 \times 10^{-4}$	
2 182	0,91	1,12	$6,6 \times 10^{-4}$	$8,2 \times 10^{-4}$
4 066	0,40	0,62	$5,4 \times 10^{-4}$	$8,4 \times 10^{-4}$
6 052	0,47	0,65	$9,5 \times 10^{-4}$	13×10^{-4}

If these measured values of conductivity are compared with those obtained from laboratory samples taken from the same Durban Deep area the results are interesting. Over a frequency range of about 18 : 1, the conductivity varies by about 5,5 : 1. The laboratory sample, over the range of frequency shows a conductivity variation of about 6, see Figure 3.2. However, it will be noted that there is about a two order of magnitude difference, confirming the statements made in Chapter 2.

CHAPTER 5

THE SMALL LOOP ANTENNA

5.1 Introduction

The type of antenna used in this underground communication environment is all important. This fact has emerged from the analysis of the basic propagation equation 4 - 1. As was discussed in chapter 2, the antenna characteristics of efficiency (η) and gain (G) play a vital role in influencing the total system loss between transmitter and receiver. It was seen there that these quantities were related by the directivity (D) of the antenna.

Since, in a mining environment, equipment portability is of utmost importance, the antenna would be limited in size. This fact, viewed in the light of low frequency operation being obligatory for effective penetration of the dissipative rock, means that the small antenna is an inefficient radiator, and since reciprocity holds, is likewise and inefficient receiver of electromagnetic energy. Thus, both η and G , are affected, due to their interdependence, by the propagation and equipment constraints.

It was also evident, from 2 - 19 and 2 - 20, that, of the two elemental antenna types which are candidates for this application, namely the electric and magnetic dipoles, the magnetic dipole or small loop antenna is to be favoured since power is dissipated in its immediate vicinity far less rapidly than is the case for the electric dipole, or "rod" antenna. In addition to this, must be added the further advantage in favour of the loop, that being its more suitable physical shape for use in a cramped environment.

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