CANADA

DEPARTMENT OF ENERGY, MINES AND RESOURCES

Geological Survey of Canada

DEVELOPMENT AND CONSTRUCTION OF PROTOTYPE MULTI-SPECTRAL E.M. SYSTEM

by

GEOPROBE LIMITED

OPEN FILE 546

Ottawa
August 1978

GEOPROBE LIMITED

PROJECT

DEVELOPMENT AND CONSTRUCTION OF
PROTOTYPE MULTI-SPECTRAL E.M. SYSTEM (GEOPROBE)

DSS CONTRACT NO. SQ15.23233-5-0957
SERIAL NO. ISQ5-0069

CONTRACTOR: GEOPROBE LIMITED,
TORONTO, ONTARIO.

GEOPROBE LIMITED

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PREFACE

This project work has been carried out according to DSS Contract SQ15.23233-5-0957, Serial No. ISQ5-0069, title "Development and Construction of Prototype Multi-spectral E.M. System (Geoprobe)". This developed equipment is hereby called MAXI-PROBE (EMR 16) System. The development of this equipment is going to benefit the resource energy industry in Canada and all over the world.

We convey our sincere appreciation to the Department of Energy, Mines and Resources, (Resource Geophysics and Geochemistry Branch) and Department of Supply and Services for issuing the contract to Geoprobe Limited. Geoprobe Limited takes the opportunity of thanking everyone who has been involved in this project. Especial thanks are to Mr. L.S. Collett, Dr. W. Scott, Dr. A.K. Sinha and Dr. R.G. Agarwal for their immense interest in the execution of this contract.

DESCRIPTION OF GEOPROBE TECHNIQUE

Geoprobe technique is a new multi-frequency E.M. technique to determine different layers present in the ground by making inductive electromagnetic measurements on the ground surface. This system is called MAXI-PROBE EMR 16. This system consists of a transmitting unit and a receiving unit, separated by a finite distance away from each other. The separation between the transmitter and receiver is determined according to the desired depth of penetration. Usually in normal ground conditions, the separation is kept between one to two times the desired depth of penetration. The transmitting unit creates a large magnetic dipolar field by sending a sinusoidal current in a loop or a number of loops of ten turns, placed on the ground surface. The transmitter is powered by a 2.5KW gasoline driven motor generator.

The frequency range of the transmitter is from 1Hz to 40Hz approximately. Table 1 in appendix shows the exact frequencies available. A maximum of 123 frequencies are available. Normally, the transmitter is operated on approximately 10 frequencies to perform depth-sounding at a place. A detail description of the transmitter is given later in this report.

At the receiving station, vertical and horizontal magnetic fields are measured. It has been found that ratio of the amplitudes of the vertical and horizontal magnetic fields, also the phase difference between the vertical and horizontal magnetic fields are characteristics of the layered media. Amplitude ratio of the magnetic fields is the best parameter to measure. Measurements of all the frequencies are made at a fixed separation of the transmitter and receiver. Depth-penetration is achieved with the help of energy at different frequencies. From the concept of 'skin-depth' it is known that very high frequencies penetrate only small depths in the ground, whereas very low frequencies penetrate very large depths. The entire depth of interest is scanned by frequencies from very high to very low. Thus any discontinuities in electrical resistivities in the ground are reflected at different frequencies.

The receiver consists of a receiving antenna unit and receiver electronics unit. The antenna system is in the shape of a frame made of four ferrite rods and coils are wound on each of these rods. Two parallel identical pairs of vertical and horizontal coils measure the vertical and horizontal magnetic fields. The antenna system has a low noise preamplifier optimised for a frequency range of 1/2Hz to 50 KHz at present. This antenna is a wide band system. The whole antenna system is housed inside a fibreglass ball to eliminate noise due to wind vibrations. The ball is placed on a fibreglass ring having three legs and can be oriented towards the direction of the transmitter with the help of a metal pointer. The vertical orientation of the antenna is done using a preset bubble on the ball.

The receiver is a two channel system, so that the measurements of the vertical and horizontal magnetic fields may be made simultaneously. There is no cable connection between the transmitter and receiver. The reference is derived from an internal crystal clock at the receiver. A detailed description of the receiver is given at a later section in this report.

The advantages of measuring the amplitudes of the magnetic field and using their ratio to determine the ground structure are many fold. They are:

1) No knowledge of the transmitter dipole moment is required.
2) Transmitting loop may be laid out in any geometry in the ground. In the field conditions, it is not always possible to have the same geometry for the transmitting loop.
3) It is not required to note down the current at the transmitting loop.
4) It is not necessary to know the pick-up factors of the receiving coils.
5) Calculation procedures of field measurements are made very simple.
6) The ratio of the vertical to the horizontal magnetic fields is a function which varies monotonically with the E.M. response parameter. This feature itself is responsible for less ambiguity in interpretation compared to in-phase and quadrature methods.

THEORETICAL BASIS AND INTERPRETATION

Introduction:

The problem of E.M. response for a multi-layer earth model has been solved for a long time. Theoretical investigations of a multi-layer earth model have been carried out for the purpose of depth-sounding during the last ten years. The theory is now very well established. The problems of numerical calculations have been solved by quite a number of people in ingeneous ways. Well circulated literatures cover these developments. Especial reference may be made to FRISCHKNECHT (1967), Ward, et all (1969), Mining Geophysics - vol. 2 (1967), Ghosh (1969).

Tremendous amount of computations are known for various types of sources and various forms of measurements. The types of sources that have been used are: Vertical magnetic dipole, horizontal magnetic dipole, short grounded cable (electric field), long grounded cable (electric field),etc.

The types of measurement parameters that have been computed for such sources are: In-phase and quadrature components (with respect to transmitter current) of vertical or horizontal magnetic fields and electric fields, tilt-angle and ellipticity responses, amplitude and phase responses.

Though tremendous amount of computations have been carried out using the above mentioned quantities, there is no commercial equipment existing in geophysical industry to perform regular production geophysical surveys for the purpose of doing depth-sounding. There are also questions of what kind of source to use and what kind of measurements to make in depth-sounding problems. It is interesting to know that one group experimented using a horizontal axis transmitter by hanging a 30 foot diameter coil (150 lbs.) in a circle with the help of a T.V. tower-frame. But, logistics in the field-conditions prevent use of such source fields.

With this background, we have tried to come up with a multi-frequency E.M. technique to do depth-sounding to achieve the following goals:

1) Easiest operations in the field.
2) Simplest form of instrumentation minimising chances of errors in measurements.
3) To acquire the best possible field-data.
4) To be able to interprete field-data in the simplest way.
5) To be able to determine multiple layers in the ground.
6) To be able to achieve high accuracy in interpretation of field data.
7) To do everything mentioned above with the minimum of cost so that this could be a viable technique in production surveys.

Choice of Parameters:

We have chosen a vertical axis magnetic dipole as a source. This is the easiest one to use in the field. No ground contact is necessary. So survey could be done at a faster rate.

The reasons for choosing the ratio of the amplitudes of the vertical and horizontal magnetic fields have been described in the previous section.

We did not want to make measurements of the inphase and quadrature components with respect to the transmitting current and also the amplitude and phases because of the following reasons:

1) Usually a cable connection between the transmitter and receiver is necessary to transmit the phase information from the transmitter. This poses a serious problem in the field.
2) Transmission of the phase information by a radio link would be better; however, sufficient accuracy may not be achieved.
3) The inphase and quadrature responses do not vary monotonically with respect to the response parameter. This will cause ambiguity in the interpretation of field data.

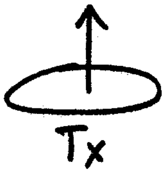
4) It is a requirement that the moment of the transmitting dipole be known very accurately. This is not always possible in the field.
5) More calculations are involved from field measurements.

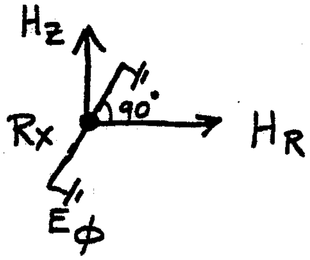
Measurement of the ratio of the orthogonal electric field to the magnetic field seems to be quite good from theoretical stand point. We did consider, at one time, to measure this quantity. However, we finally did not settle on measuring this parameter because of the following reasons:

1) Problem with ground contact of E-field probes.
2) Survey time is longer to spread the E-field cable at the receiving station.
3) It is difficult to design the E-field probe to give high accuracy in very high frequencies.

Theoretical Basis:

Let us consider a horizontal loop source as the transmitter (Tx). Let the receiving station (Rx) be at the same elevation.





Assume:

R : to be the distance between Tx and Rx.
H_R : to be the horizontal magnetic field at Rx.
H_Z : to be the vertical magnetic field at Rx.
E_ϕ : to be the orthogonal electric field at Rx.

Then, the responses for a homogeneous ground may be written as follows (FRISCHKNECHT, 1967):

(We shall use notations same as FRISCHKNECHT'S in this development)

$$E_{\phi} = \frac{M}{4\pi R^2}(i\omega\mu)\underbrace{\left[\frac{2}{\gamma^2 R^2}\left\{(3+3\gamma R+\gamma^2R^2)e^{-\gamma R}-3\right\}\right]}_{A_1}$$

$$H_R = -\frac{M}{4\pi R^3}\underbrace{\left[\left\{\gamma^2R^2(I_1K_1-I_0K_0)+4\gamma R(I_1K_0-I_0K_1)+16\,I_1K_1\right\}\right]}_{B_1}$$

$$H_Z = \frac{M}{4\pi R^3}\underbrace{\left[\frac{2}{\gamma^2R^2}\left\{(9+9\gamma R+4\gamma^2R^2+\gamma^3R^3)-e^{-\gamma R}-9\right\}\right]}_{C_1}$$

γ = Propagation Constant

$= (i\omega\mu\sigma_1)^{1/2}$

$\gamma^2R^2 = 2iB^2$

B = Distance in units of "skin-depth"

$= R/\delta$

δ = Skin-Depth $= \left(\frac{2}{\omega\mu\sigma_1}\right)^{1/2}$

Now, let us calculate the ratio of the electric field to the horizontal magnetic field:

$$\frac{E_\phi}{H_R} = \frac{\frac{M}{4\pi R^2}(i\omega\mu)\ A_1}{-\frac{M}{4\pi R^3}\ B_1} = -i\omega\mu R\left(\frac{A_1}{B_1}\right)$$

$$= -i\omega\mu R\left[X_1 + iY_1\right] \quad \text{(Say)}$$

$$\therefore \left|\frac{E_\phi}{H_R}\right| = \omega\mu R\left(X_1^2 + Y_1^2\right)^{1/2} = \text{Amplitude Ratio}$$

Phase Difference is:

$$\left(E_\phi - H_R\right) = \omega\mu R\left|-iX_1 + Y_1\right|$$

$$= \tan^{-1}\left|\frac{-X_1}{Y_1}\right|$$

The fields H_R and E_ϕ are near source fields. However, using the ratio of these fields, it is possible for us to calculate the impedance of the ground. So, we use the concept in magnetotellurics, given by Cagniard. Let us define our resistivity as Cagniard resistivity,

$$\rho_{CAG.} = \frac{1}{\omega\mu} \left| \frac{E_\phi}{H_R} \right|^2$$

$$= \frac{1}{\omega\mu} \omega^2 \mu^2 R^2 \left| X_1^2 + Y_1^2 \right|$$

$$= \omega\mu R^2 \left| X_1^2 + Y_1^2 \right|$$

We know,

$$B^2 = \frac{R^2 \omega\mu\sigma_1}{2}$$

$$\text{or, } \frac{2B^2}{\sigma_1} = \omega\mu R^2$$

$$\therefore \rho_{CAG.} = \frac{2B^2}{\sigma_1} \left| X_1^2 + Y_1^2 \right|$$

$$\text{or, } \frac{\rho_{CAG.}}{\rho_1} = 2B^2 \left| X_1^2 + Y_1^2 \right|$$

This equation shows that, the impedance ratio varies as B^2 i.e. $\omega\mu\sigma_1 R^2$

Considering, 'L' to be the separation between Tx and Rx,

$$\frac{\rho_{CAG}}{\rho_1} = f_n \left\{ L\sqrt{f\sigma_1} \right\}^2$$ for Homogeneous Ground

Now, we shall calculate Cagniard resistivity for a layer medium. Referring to the following equations (FRISCHKNECHT, 1967) eq. 1, 3, 11, 13 and 14 in pages 2, 4, 6 and 7:

$$E_{\phi,P} = -\frac{i\omega\mu M}{4\pi R^2}$$

$$E_{\phi,S} = \frac{i\omega\mu M}{4\pi\delta^2} T_2$$

Now, the mutual coupling is:

$$\left(Z/Z_0\right) = \frac{E_{\phi,T}}{E_{\phi,P}} = \left(Z/Z_0\right)'_V - B^2 T_2'$$

$$E_{\phi,T} = -\frac{i\omega\mu M}{4\pi R^2}\left[\left(Z/Z_0\right)'_V - B^2 T_2'\right]$$

$$\left(Z/Z_0\right)_{\underline{II}} = \frac{H_{R,T}}{H_{Z,P}} = \left(Z/Z_0\right)'_{\underline{II}} + B^3 T_1'$$

$$H_{R,T} = -\frac{M}{4\pi R^3}\left[\left(Z/Z_0\right)'_{\underline{II}} + B^3 T_1'\right]$$

$$\frac{E_{\phi,T}}{H_{R,T}} = \frac{-\frac{i\omega\mu M}{4\pi R^2}\left[(Z/Z_0)'_{V} - B^2 T_2'\right]}{-\frac{M}{4\pi R^3}\left[(Z/Z_0)'_{\underline{II}} + B^3 T_1'\right]}$$

$$= i\omega\mu R \, \frac{\left[(Z/Z_0)'_{V} - B^2 T_2'\right]}{\left[(Z/Z_0)'_{\underline{II}} + B^3 T_1'\right]}$$

Now,

$$\frac{\rho_{CAG.}}{\rho_1} = \frac{1}{\omega\mu}\left|\frac{E_{\phi,T}}{H_{R,T}}\right|^2$$

$$= 2B^2 \, \frac{\left|(Z/Z_0)'_{V} - B^2 T_2'\right|^2}{\left|(Z/Z_0)'_{\underline{II}} + B^3 T_1'\right|^2}$$

$$= f_n\left\{L^2 f \sigma_1\right\}$$

Therefore, we can conclude that the ratio of Cagniard resistivity to the resistivity of the top layer is a function of $L^2 f \sigma_1$. Now, we can compute the curves of $\rho_{CAG.}/\rho_1$ Vs. $L^2 f \sigma_1$.

Now, we shall use the ratio of the vertical magnetic field to the horizontal magnetic field.

$$H_{z,T} = H_{z,P} \times \left[\left(z/z_0 \right)_I' + B^3 T_0' \right]$$

$$H_{R,T} = H_{z,P} \times \left[\left(z/z_0 \right)_{\underline{II}}' + B^3 T_1' \right]$$

$$\frac{H_{z,T}}{H_{R,T}} = \left| \frac{\left(z/z_0 \right)_I' + B^3 T_0'}{\left(z/z_0 \right)_{\underline{II}}' + B^3 T_1'} \right|$$

This function will be plotted against $L\sqrt{f\sigma_1}$.

RESPONSE CURVES

Introduction:

Response curves have been computed for the amplitude ratio of the vertical (H_Z) and horizontal (H_R) magnetic fields for different values of the response parameter ($L\sqrt{f\sigma_1}$).

Curves have been computed for ONE LAYER EARTH-MODEL, i.e. one layer resting on a half-space. Computations have been done for the following cases:

L = separation between Tx and Rx

H = thickness of the top layer

L/H = 0, 2, 4, 5.5, 8, 16.

$\rho_1/\rho_2 = \sigma_2/\sigma_1$ = 100, 30, 10, 3, 1.5.

The response parameter has been covered in the range 150 - 6000. This is the range of interest for our depth-sounding problems. The ratio of H_Z/H_R cannot be measured accurately beyond this range of $L\sqrt{f\sigma_1}$. Amplitude ratio and phase-difference curves have been plotted by a calcomp plotter. Curves for each of these two responses have been stacked according to:

1) Constant ρ_1/ρ_2 value.
2) Constant L/H value.

The first set shows the effect of variation of thickness of a layer when resistivities are constant. The second set shows the effect of variation of resistivity of the second layer when the thickness of the top layer remains constant. Between these set of curves, it is possible to interprete a field curve of one layer over a half-space.

The curves have been plotted in double log scales for convenience of matching. The scales of the curves are compatible with the scales of a standard double-log graph paper number 46-7402 of Keuffel & Esser Co. The X-axis in the plot has twice the modulus, so that when the above mentioned graph paper is used, the X-axis is to be considered to be the variable $L^2 f \sigma_1$. The modules of the graph is 2.5 inches/cycle.

Analysis of Curves:

Important features of these response curves have been described here. Let us concentrate on the curve for constant $\rho_1/\rho_2 = 100$. In this set, the top most curve is the curve for the half-space of conductivity σ_1 . This curve is monotonic and theoretically, it varies from infinity at the lowest frequency close to zero to zero at the very highest frequency. It varies quite smoothly, excepting between $L\sqrt{f\sigma_1} = 2700 - 5000$. This is the zone where the field is changing from induction to radiation.

In this set of curves, we note that responses of high frequencies of all the one layer models almost coincide with the half-space curve. Then, the curves branch off from one frequency away from the half-space curve towards left hand side. In this set of curves, the bottom layer is more conductive. If the bottom layer would have been resistive, the one layer curve will branch off towards right hand side. However, as it is well known in all problems dealing with electrical resistivity, more resolution is obtained (i.e. more divergence of the one layer curve from the half-space curve occurs) when the bottom layer is more conductive.

If the top layer becomes thinner, the curve breaks off away from the half-space curve at a progressively higher value of $L^2 f \sigma_1$, i.e. at a progressively higher frequency. This is in accordance with the concept of "skin-depth", less penetration in high frequency and more penetration in low frequency. It is quite obvious from these curves that the curve for a thin layer is very divergent from the half-space curve. Again, if the top layer is extremely thin, then the curve will almost represent another half-space curve having a conductivity that of the bottom layer.

In fact, in this situation, the half-space curve in this set just shifts along the X-axis to indicate a half-space of the resistivity of the bottom layer. This shows the limitation of detecting a very thin layer in this technique. A curve for L/H = 16 can be recognised with sufficient confidence.

It is possible to detect a layer whose thickness is even two times the separation between the Tx and Rx. However, the limitation for thick layer comes when the ratio of amplitudes becomes so large that it cannot be measured with confidence. In proper ground conditions, it is quite possible to detect a thickness which is two times the separation (L) between Tx and Rx.

From this set of curve, we get a feeling for depth-penetration being affected by Tx-Rx separation and frequencies. The penetration also is affected by σ_1 , which also appears in the parameter for the X-axis ($L\sqrt{f\sigma_1}$).

If we look at the curves for the sets of decreasing contrast (ρ_1/ρ_2), we note that the divergence of the layer curves becomes progressively less from the half-space curve. This shows how resolution may decrease with decrease in resistivity contrast. It is interesting to note that the curves for the set of ρ_1/ρ_2 = 3 has still sufficient resolution to be identified.

Now, let us investigate the curves for contrast L/H (i.e. distance/depth) ratio. The individual curves represent a particular ρ_1/ρ_2 ratio. We note that curves for larger ρ_1/ρ_2 ratios diverge more from the half-space curve than small ρ_1/ρ_2 ratios. This indicates that resolution of a model is better for large resistivity contrast. It is interesting to note that for L/H = 8, the curve of ρ_1/ρ_2 = 1.5 is quite distinct from the half-space curve. Even such a small contrast in resistivities may be detected in this situation. One of the most important features of the curves for constant L/H ratio is that the curves for different resistivity contrast break off from the half-space curve at one point.

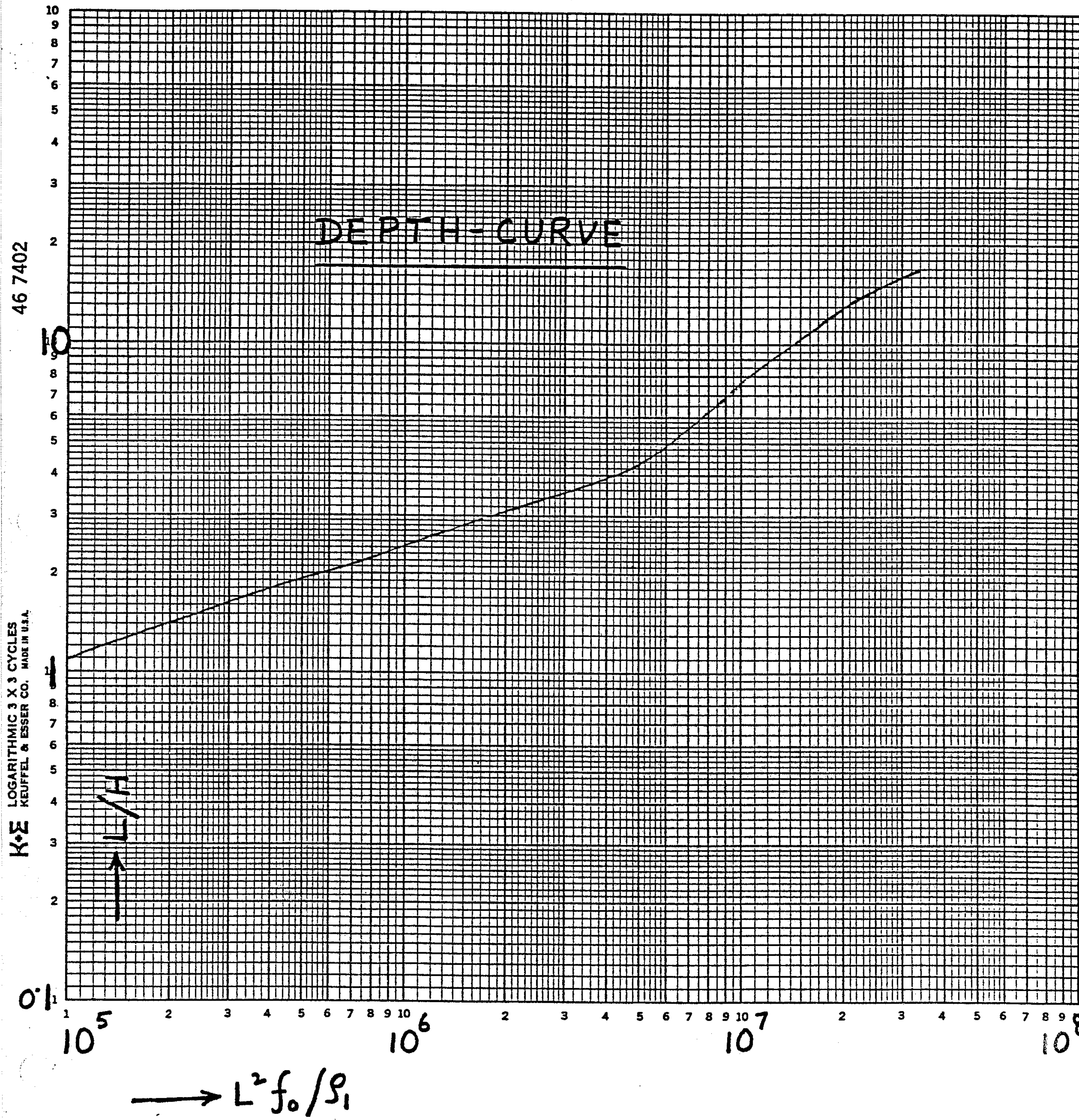

DEPTH-CURVE
L/H
$L^2 f_0/\rho_1$
10^5
10^6
10^7
0·1
1
10
K+E LOGARITHMIC 3 X 3 CYCLES
KEUFFEL & ESSER CO. MADE IN U.S.A.
46 7402

FIG. 1

For different sets of L/H values, these break-off points are different. The break-off points are at lower frequencies for smaller values of L/H ratio. We still note that the curves for a fixed set of L/H ratio breaks off away from the half-space curve at one point.

Let us concentrate on the fact that the curve for a model of a fixed L/H ratio breaks off away from the half-space curve at one point does not matter what the contrast of ρ_1/ρ_2 is. This may be a situation in the field, when Tx and Rx are fixed and the thickness (H) and electrical resistivity of the layer are constants for a particular place. Now, if we imagine ρ_1/ρ_2 to change by changing the resistivity of the bottom layer only, we should see the break in the response curve at the same point on the X-axis. The X-axis is a function of 'L^2','f' and 'ρ_1'. In this situation, since 'L' and 'ρ_1', are fixed, the break must occur at a fixed frequency when 'L', 'H', and 'ρ_1', are fixed. From this discussion we can conclude that for a particular layer situation in the field, there will be a particular frequency at which the response H_Z/H_R breaks away from the half-space response. This frequency will effectively indicate the depth of the first layer. In fact, this phenomenon indicates that little current is penetrated in the second medium at frequencies higher than this. Similar breaks are also obtained in cases where there are more than one layer on top of a half-space medium. In this context, we must note that in multi-layer cases all breaks will occur at different frequencies; however, the resistivity of the top layer must be taken into consideration when calculating depth of a layer using break points.

Fig. 1 shows a curve that has been plotted using break points to determine thickness of layers in ratios of the separation between Tx and Rx.

X-axis represents the BREAK PARAMETER $L^2 f_0/\rho_1$ where, 'f_0' is the frequency at which the break occurs in the response curve. The Y-axis represents the ratio L/H. This curve has been plotted from the set of response curves described earlier. It is very appropriate to call this the DEPTH-CURVE. This curve has been plotted in the same modulii as the response curves.

INTERPRETATION PROCEDURES

Introduction:

The theory of this Geoprobe depth-sounding technique is based on theoretical models of horizontally stratified earth. In practice in actual field conditions, the ground is usually much more complex than that. It is difficult to assume a particular theoretical model for a field situation without knowing the structure in the ground. We are essentially trying to map the ground structure. Therefore, any biased assumption of the ground structure may not be realistic. Again, even if a more complex model of the ground is known beforehand, it is extremely difficult to apply the exact model to compute theoretical responses to match with field results. In fact, even if sophisticated computer inverse programs are available these days, it is very difficult to computer-match the field data because of the more complex nature of the ground. The inverse programs are expensive. A lot of computer money may be wasted trying to interprete data this way. Keeping this in mind, we have been using simpler horizontally stratified model of the ground. In interpreting the data, we have convinced ourselves that simple procedure based on the discussions in the previous chapter works out the best. This impirical approach is quite inexpensive and gives very good results in more or less horizontally stratified ground. This approach also gives reasonably good results in cases where the ground is of more complex nature.

Procedure:

This subsection will outline the procedure of field operation and procedure of interpretation of field-data.

Let us assume that we are performing depth-sounding at a location without any prior knowledge of the ground. The only information we should have is the desired maximum depth of penetration. The steps are as follows:

1) The first step is to use a Tx-Rx separation which is in the range of 1 - 2 times the desired depth of penetration.

2) Determine the range of frequencies that are useful in this area. This will depend on the electrical resistivity of the top layer.

3) Determine the signal to noise ratio considering the different frequencies and the separation that is being used.

4) Depending on the output of step 3, choose Tx-Rx separation and the frequency range.

5) It is best to perform a few soundings at the beginning using approximately three Tx-Rx separations. Then choose the proper separation from the results.

6) Continue survey until the ground changes sufficiently to necessitate use of different Tx-Rx separation and frequency range.

Data Interpretation:

1) Compute ratios of the amplitudes of the vertical and horizontal magnetic fields. (Phase difference between the magnetic fields is difficult to use in interpretation).

2) Plot these ratios against corresponding frequencies on a tracing graph paper (K & E #46-7402). The points should fall in a pattern. Join the points by a smooth curve.

3) Lay this tracing paper on top of one set of response curves for a fixed ρ_1/ρ_2 ratio (say $\rho_1/\rho_2 = 30$), so that amplitude ratios in the field curve coincides with those on the response curve.

4) Displace the field-curve parallel to the X-axis until the high frequency data matches with the high frequency asymptote of the half-space curve.

5) Find out ρ_1 (or σ_1 ,) value from the intersection of the X-axis of the field curve with that of the response curves. Use M.K.S. units.

6) If the field curve is a model of one layer over a half-space, there will be a break point on the field curve from which point it separates out away from the half-space curve. Note this frequency (fo).

7) Compute '$L^2 f_o/\rho_1$'.

8) Now, use the 'Depth-Curve' to estimate 'Ho' using '$L^2 f_o/\rho_1$'.

9) The resistivity of the bottom layer may be estimated by approximately matching the field curve with the set of curves for the particular ratio of'L/H' which is closer to 'L/Ho' ratio. The estimate of the resistivity may not be exact.

10) If there are other layers present, we shall find other breaks towards lower frequencies. These break points must be transferred to the half-space curve of ρ_1 to find the other break frequencies. Follow the similar procedure as before to find depths of other layers.

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MAXI-PROBE EMR 16 TECHNICAL DESCRIPTION

General Principle - Ref: Fig.2, Fig.3

The system comprises a magnetic dipole transmitter and a receiver capable of resolving the magnetic field components at a finite distance from the transmitter.

The transmitted field is nominally vertically polarised at the transmitter, and is created by passing an alternating current through a multiturn loop, or loops, laid on the ground. The frequency of the transmitter field may be set in the range 1 Hz to approximately 42 KHz.

The receiver is set to receive the fundamental frequency of the transmitter field and simultaneously measures the vertical and radial horizontal magnetic field components at the receiver site. The two received field components are recorded in relative amplitude and phase to each other, at each chosen frequency.

The receiver employs a stable internal frequency source to avoid the requirement for phase locking, (and possibility of locking to a noise source in error).

To obviate the requirement for a bank of tracking filters, one per frequency, and to provide superior harmonic suppression, the receiver uses the heterodyne principal, whereby all input frequencies are converted to a common frequency for amplifing, filtering, and amplitude adjustment and detection.

System Functions - Receiver Ref: Fig.2

Antennae & Preamp

The magnetic fields are detected by a pair of orthogonal ferrite cored coils mounted in a spherical housing which simultaneously minimizes motional disturbance due to wind, and provides convenient multiaxis orientation with respect to gravitational vertical and the direction to the transmitter.

MAXI-PROBE EMR16 BLOCK DIAGRAM, RECEIVER

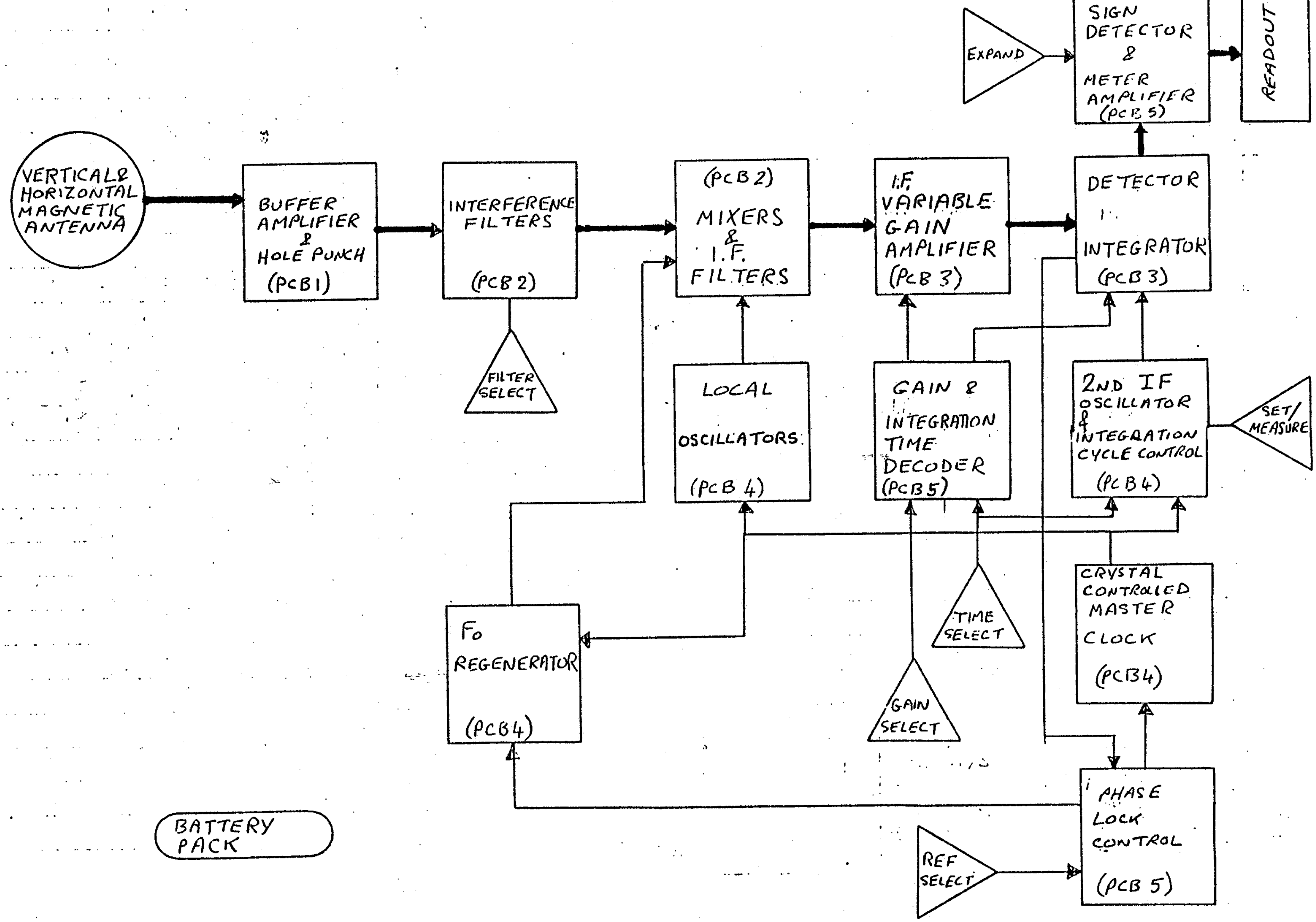


FIG. 2

Within the spherical antenna housing is a preamplifier which adjusts the signals to a level and impedance suitable for transmittal via approximately 5 meters of cable to the receiver console. The response is essentially flat in units of volts/amp/meter across the spectrum of interest.

Input Buffers

The receiver input stage provides some common mode isolation of possible unwanted signals picked up by the cable, and further bandpass limiting.

The input board provided three further functions:

1) It selects which magnetic field input is processed by which of the two internal channels.
2) It contains an amplifier for electric field signals, for use when probe preamplifiers are fitted.
3) It contains an impulse detector circuit whose function is to gate the signals off for a short period whenever a fast rising transient such as a lightning sferic is received.

Interference Filters

The two signals next pass through a filter array whose function is to suppress known interfering noise frequencies which might otherwise cause overloading of the processing channels. Notches are provided at 60 Hz, 180 Hz, and at selected VLF station frequencies. A low pass or high pass function centred on 1000 Hz is also provided. All filters track in amplitude and phase between channels. All filtering to improve dynamic range further gain is provided.

Mixers

The two broadband channel signals are next mixed with a high frequency of the order of Fo + 260 KHz. (Fo is the frequency of the signal for one measurement).

The lower sideband mixer product, approximately 260 KHz is then passed through a bandpass filter. This first intermediate frequency is then mixed with a frequency around 244 KHz, and the lower sideband of 16 KHz is extracted with a lowpass filter. Further gain is provided in these mixing stages.

IF Amplifier

This variable gain section permits normalization of the signal amplitude against output variation as a function of frequency, and change of transmitter receiver separation.

Detector Integrator

The normalized signals are synchronously detected at the 2nd intermediate frequency. The coherent detection product is integrated for a period of time from .25 seconds to 64 seconds.

Display

At the end of this interval, the output is displayed on meters. Each channel is resolved into inphase and quadrature components with respect to the internal clock, which is stable in frequency relative to a similar clock in the transmitter. Sign is indicated by LED, to permit full use of the meter scale.

Local Oscillators and Timers

A frequency synthesizer provides the various drive frequencies and time out functions. This contains a crystal oscillator. The synthesizer's primary function is to generate the first local oscillator drive which must be incremented in frequency from approximately 260 KHz to 320 KHz, in steps as small as 1/8 Hz.

The main timing function is that of the integration cycle. At low frequencies the upper sideband of the first mixer is not removed by bandpass filtering. In addition a significant proportion of carrier breakthrough is likely.

Both of these unwanted components are effectively removed by the integration cycle time control by ensuring that the cycle always includes a whole number of cycles of 'Fo'. At very low frequencies, e.g. 1 Hz, this also permits valid measurements with only a few cycles of signal.

Reference Selection

Facility is provided for obtaining phase and frequency locking between transmitter and receiver by means of a radio link, one of the actual signal channels, or by internal clock which is set once a day. The latter is the most convenient and is the only one currently fitted.

Operating Procedure for Receiver EMR-16:

Basic Procedure:

Place the ball antenna in its cradle as far from the receiver console as the cable will allow. Orient the arrow on the ball towards the transmitter, and centre the bubble level.

Assuming initialisation has been completed, the receiver is ready for measurement when switched on. Operate controls as follows:

- FREQUENCY COARSE	FREQUENCY FINE
- GAIN	"0"
- TIME	4 seconds
- SET CONTROLS	
- POWER ON	All meters should read near centre scale.
- GAIN	Increase until no meter reads off scale.
- MEASURE	Meter reading will increase and hold a valve after 4 second. If reading is less than 25 on top scale, expand reading by pressing meter switch X4.

- SET CONTROLS	To repeat measurement cycle from start.
- MEASURE	And the meter cycle will repeat.

Between frequency 1 and 4, at high gain, pulsation of the needles will be evident, even with no signal. This is normal and will not cause a reading error after the cycle time in MEASURE is complete.

Control and Display Functions for Normal Operation:

FREQUENCY COARSE AND FINE are set equal on transmitter and receiver

AVERAGING TIME

Select 4 seconds normally. Increase to 16 or 64 if the signal is noisy (non repeatable) at large distances, or at very low frequencies, or if the CHANGE SETTING lamp comes on when increasing gain. Decrease from 64 or 16 seconds if CHANGE SETTING lamp comes on when decreasing gain.

Set time to 1 second or 0.25 seconds for large signals (above frequence 4) to save measurement time.

GAIN

Gain increases in steps of X4 from position 0 to 16. It is necessary to change AVERAGING TIME as indicated by the CHANGE SETTING lamp to obtain certain gains. The instrument will give entirely false levels, although it will still operate correctly, if this lamp is on.

If an E-field or auxiliary measurement system is fitted, the gain of the upper pair of meters will be under control of the EY GAIN switch. Otherwise this is left 'off' and both channels are controlled by Hz Hx GAIN.

REFERENCE

Permanently internal (generated by a crystal clock) - the others are not connected on this model.

HOLE PUNCH

Switch on only when local sferics activity is suspected of causing noise, and the NOISE lamp is flashing on.

VLF1/VLF2

VLF1 is 17.8 KHz and will normally be switched on. VLF2 is 18.6 KHz, and will be used nearer the west coast.

LINE

This notches out 60 and 180 Hz, and will normally be on, unless working at short range, well away from urban areas.

HIGH PASS/LOW PASS

HP should be switched on for frequencies 11:3 and above, at gains greater than 8 or if the overload lamp comes on due to residual power line interference when operating at the higher frequencies.

LP should be switched on for frequencies below 11:3 at gains above 8 or if the overload lamp comes on due to residual VLF stations interference when operating at low frequencies.

ZY - X REVERSED/NORMAL

Repeating a measurement with this switch at REVERSED provides a second set of data, where the gain and phase errors are interchanged. This data can be used to remove instrument errors (if any) due to magnitude by taking the geometric mean of the two measurements, and by taking the arithmetic mean for any phase errors.

X4 EXPAND

This switch increases the reading of each meter by a factor of four. Read the lower, red, scale.

BATTERY TEST

Operate ZERO and SET CONTROLS . Operate +BATT switch. All LEDS should light. Voltage of the positive battery will be indicated on first meter, lower scale. It should not be allowed to fall below 17V. Operate -BATT switch. Voltage of the negative battery will be displayed on second meter, lower scale. It should not be allowed to fall below 17V.

Initialisation Controls

ZERO/OPERATE ZY I, ZYQ, XI, XQ, ZERO

Switch to ZERO with SET CONTROLS, GAIN 4, TIME 64, FREQUENCY 11. Adjust each ZERO knob until the appropriate meter reads zero. Its -VE lamp will just be on the point of extinction. Zero should be checked every hour, unless temperatures are stable.

CAL/OPERATE PHASE I MAG Q MAG

After zeroing, with the antenna connected but with no transmission, set FREQUENCY to 14:3, TIME to 4 seconds and HP/LP at 'OUT'. Set GAIN at 8. CAL/OPR at 'CAL'. Switch from SET CONTROLS to MEASURE After four seconds a reading will be steady on the meters. Repeat the MEASURE cycle, adjusting PHASE controls slightly between cycles until the two pairs of meters read the same. If it is not possible to make both 'I' meters and 'Q' meters read the same by adjustment of the PHASE control, equalise the pair of meters with the lowest reading by use of the I MAG or Q MAG control.

FREQ

With the transmitter at a range of less than 200 meters, set FREQ to 16:3, TIME to 4 seconds and increase gain for a significant meter deflection. The meter readings will slowly alternate from side to side, due to slight difference between transmitter and receiver frequency. Adjust FREQ trimmer until the needle passes through zero at a rate of less than 0.5% of the peak deflection, per second.

SPECIFICATIONS:

Frequency Range -	1 Hz to 64 KHz
Sensitivity -	Full scale $2.5\times10^{-8}\ \frac{A}{M}$ to $1.6\times10^{-3}\ \frac{A}{M}$
Measured Parameters -	Vertical magnetic field and horizontal (radial) magnetic field
Displayed Parameters -	Vertical and horizontal magnetic field each resolved into inphase and quadrature components relative to an internal phase reference.
Display Resolution -	Meter resolution better than 1% of larger of two channels, using X4 expansion if required. Reading is held steady at time of reading.
Noise Bandwidth -	Selectable at 1 Hz, 1/4 Hz, 1/16 Hz, 1/64 Hz, or 1/256 Hz.
Dynamic Range -	Operating below 1000 Hz, system will tolerate line frequency components with a fundamental amplitude up to 80 db above the signal. Operating above 1000 Hz the system will tolerate VLF stations 80 db above the signal. This range depends on frequency and bandwidth, and in most cases will be better than the above.
Harmonic Rejection -	The instrument does not respond to harmonics of the signal frequency.

MAXI-PROBE EMR-16 TRANSMITTER

1. Introduction:

The Geoprobe Transmitter is basically a driven power oscillator designed for inductive loads in the frequency region from 1 Hz to 40 KHz.

The transmitter consists of 3 main circuits:

1) Low-frequency power circuit for frequencies less than 1.5 KHz.
2) High-frequency power circuit for frequencies from 1.5 KHz to up to 40 KHz.
3) Low power driving circuit which is controlled by a variable frequency source, for generating necessary driving waveforms for the power circuits.

2. Low Frequency Power Circuit:

This is a bridge-type SCR square wave inverter which inverts the DC input power source to square wave output. The basic circuit is shown in fig.4.

It consists of 6 SCR's, 6 diodes, two inductors and two capacitors.

SCR2, SCR3, SCR5, SCR6 form a full-wave bridge, SCR2, SCR4, L1, L2, C1 and C2 are the cummutating circuit for the bridge. The diodes are necessary for returning the inductive currents back to the DC source so that dangerous high voltage transients are suppressed. The characteristic waveforms are also shown in fig.4.

3. High Frequency Power Circuit:

This consists of two SCR series inverters coupled together by the inductive load as shown in fig.5.

The load consists of 4 identical windings L1, L2, L3 and L4 closely coupled with each other with polarity as shown in fig.5.

This is a series tuned circuit. The current through the load are shared equally by 4 SCR's, so that the time available for each SCR to turn off may be as long as 1.5 the period of the output waveform.

MAXI-PROBE EMR 16 BLOCK DIAGRAM, TRANSMITTER

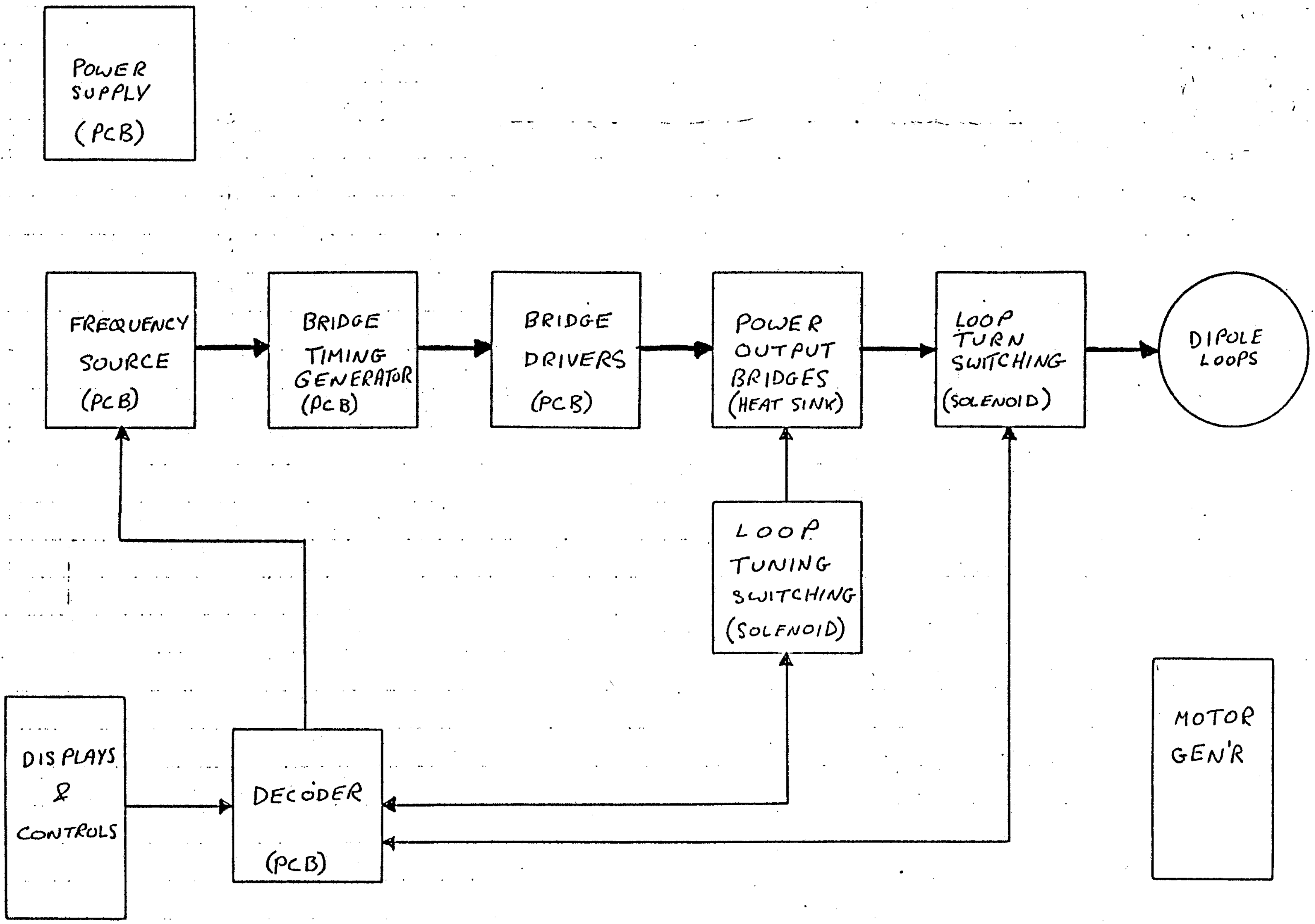


FIG. 3

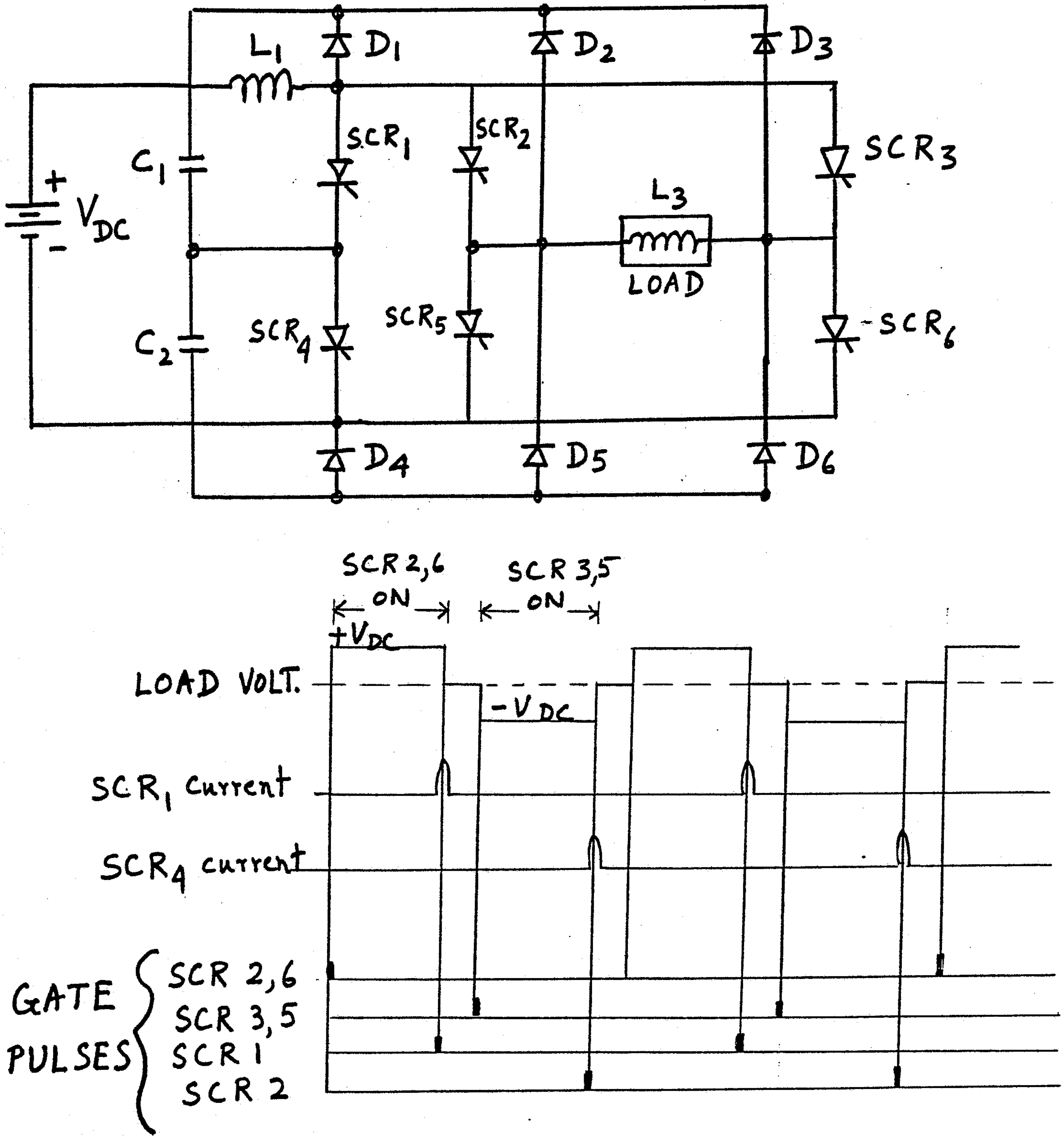


FIG. 4. LOW FREQ. POWER CIRCUIT

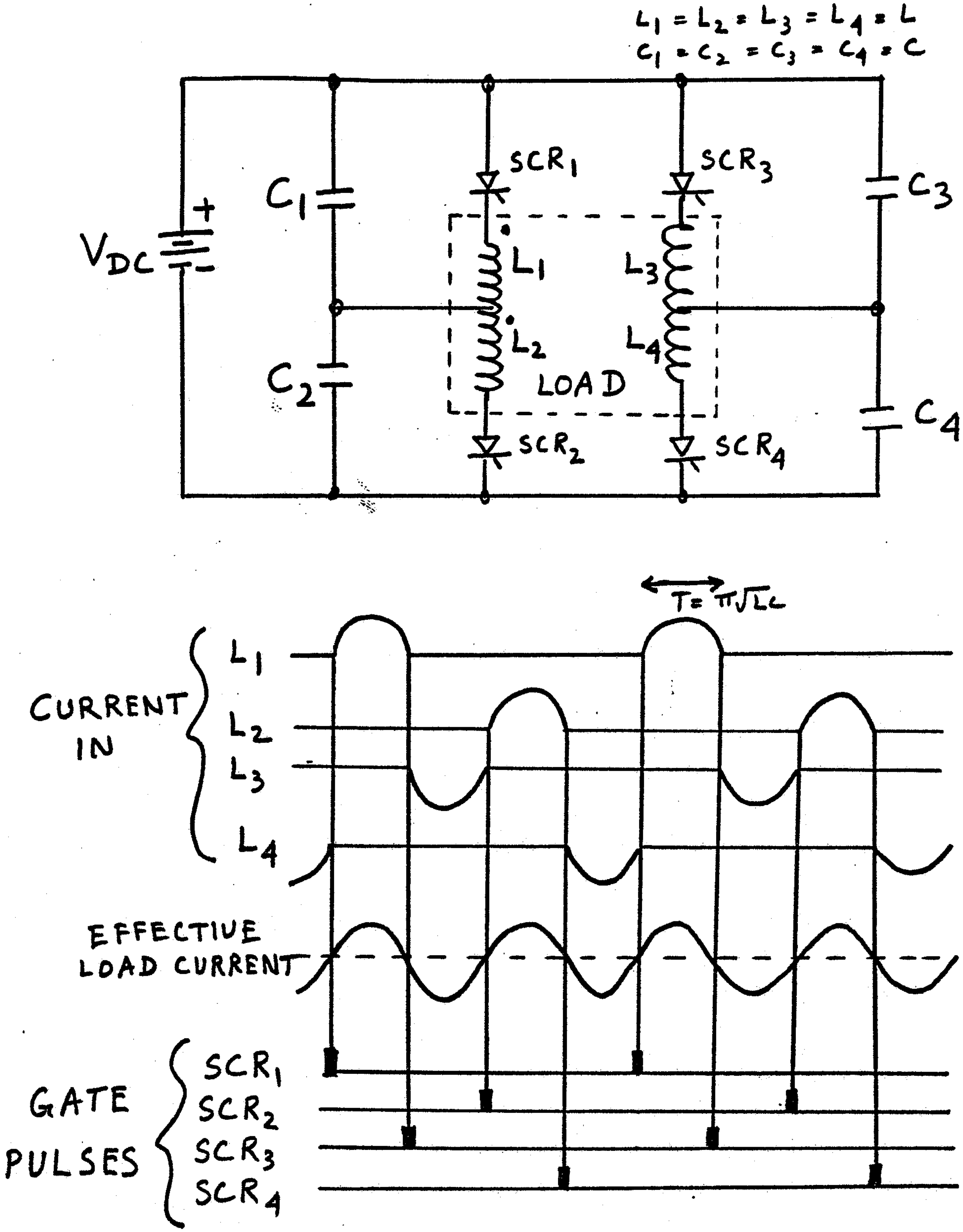


FIG.5. HIGH FREQUENCY POWER CIRCUI

For 40 KHz this turn-off period is 1.5 X 25 μs = 37.5 μs which is quite adequate for present day standard inverter SCR's.

When the driving frequency is different from the L-C tune frequency, power is still delivered to the load because the energy stored in the capacitors is prevented from flowing back to the DC source by the blocking SCR.

The output waveforms are sinewave as shown in fig. 5.

4. Driving Circuit:

The driving circuit supplies the SCR gate pulses of fig. and . The logic is built from standard C-MOS integrated circuits. Output drives are provided by transistors and pulse transformers.

5. Conclusion:

The wide frequency range necessitates the use of two forms of power oscillator circuits. The flexibility of these circuits may render them useful for many purposes and for different kind of geophysical instruments such as E.M. transmitter, time-domain I.P., frequency domain I.P., air-born EM transmitter.

6. Tx Loop Configuration:

The Geoprobe Tx is a very wide band transmitting system. Generally speaking, transmitted power in these systems would be limited ultimately by the maximum loop impedance which can be driven by the power circuitry.

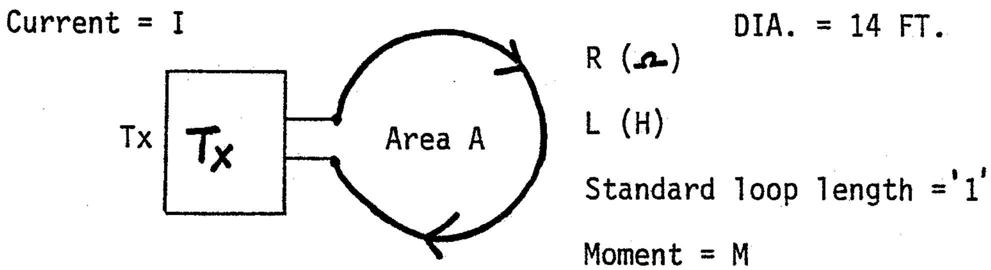
We have arrived at a very simple solution to this problem using the basic fact that the inductance of non-coupled inductors in parallel varies inversly with the number paralleled. Regardless of this reduction in inductance, the loops may be oriented so that the dipole moment is increased directly. This fact applies equally to receiver coils where the current delivered to the preamplifier could be increased without increasing the impedance of the receiver coils.

The dipole moment may be increased and the impedance held the same by the following method:

The moment of a loop can be most effectively increased by increasing the loop area. However, this method changes the loop impedance and the power source may have to be adjusted for re-matching.

The following method increases the loop area without changing either the loop resistance or the loop inductance so that a fixed standard power source can be employed to drive different loop configurations over a wide frequency range.

Consider a transmitter which is designed to drive a standard loop of resistance R, inductance L, area A, and length 'l'.



Basic Configuration

If we use two standard loop lengths to form a bigger loop of area 4A, the new loop resistance and inductance becomes 2R and 2L respectively. To reduce these values to the original ones, two such loops are connected in parallel to form a figure 8 configuration as shown below.

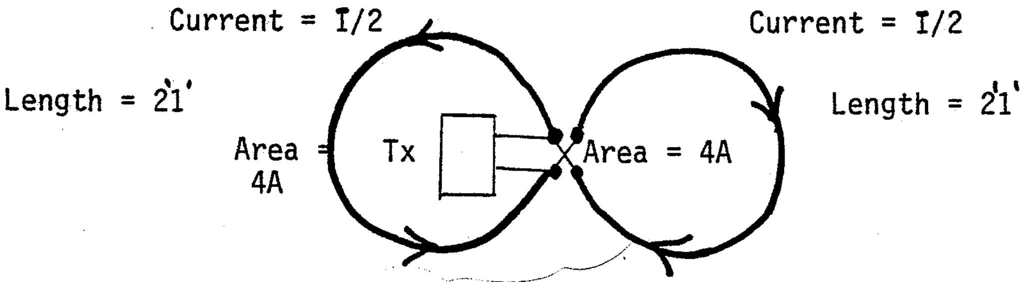
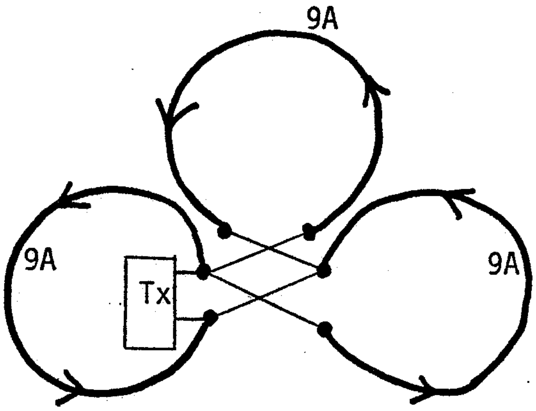


Figure 8 Loop Configuration

DIA. = 28 FT.

The resistance and inductance seen by the transmitter is again ‘R’ and ‘L’. Although the total area is increased by 8 times, the current in each loop is reduced by one-half. The overall increase in moment is 4 times and yet the loop is still driven by the same transmitter. To further increase the moment we can go to a cloverleaf configuration as show below. The moment increase is 9 times.



Length = 31'

Moment = 9 x M

Current = I/3

Length = 31'

Length = 31'

Cloverleaf Configuration

The same principle applies if we want to increase the moment by 16, 25, 36, ...times at the cost of heavier loop weight.

7. Operating Procedure:

The transmitter has a motor driven LEDEX switch which connects to different driving circuitry; connects the tuning capacitors and selects the number of turns in the loop. There are two knobs on the front panel to do the same that are done by the LEDEX switch. We prefer to operate these knobs manually. The following table shows the setting of switch positions for different frequencies.

TRUTH TABLE (SWITCH POSITIONS)

* Range of Freq. Controls	Range of Freq. (Hz)	No. of Turns Selection	L.F. Switch Position	H.F. Switch Position
1.1 - 6.3	1 - 42	10	1	0
6.4 - 7.3	42 - 84	10	2	0
7.4 - 8.3	84 - 160	7	3	0
8.4 - 9.3	160 - 330	5	4	0
9.4 - 10.3	330 - 620	3	5	0
10.4 - 11.3	620 - 1300	3	6	0
11.4 - 12.3	1300 - 2600	3	7	1
12.4 - 13.3	2600 - 5200	3	7	2
13.4 - 14.3	5200 - 10500	3	7	3
14.4 - 15.3	10500 - 21000	3	7	4
15.4 - 16.3	21000 - 43000	3	7	5

* A.B - refers to coarse control at A
and fine control at B

Step 1 - Connect the cable from the motor generator to the Tx. Start the generator.

Step 2 - Connect one to three loops in the sockets marked on the front panel. When one loop is used, connect it to (J_1, J_2) or (J_3 and J_4) terminals. When two loops are used, connect them to (J_1, J_2) and (J_3, J_4.). Also twist the turn for (J_3, J_4) cable to have the transmitting dipole moment along the same direction as the other loop.
When using three loops connect on the terminals (J_{1A}, J_{2A}); (J_{3A}, J_{4A};) and (J_{5A}, J_{6A}.)

Step 3 - Turn the coarse and fine frequency selection switches to select the proper frequency. It is preferable to continue from low to high frequencies of operation.

Step 4 - Select the L.F. and H.F. switch positions for the particular frequency. These switches only turn anti-clockwise.

Step 5 - Turn on the power switch. Watch the D.C. voltmeter to obtain more than 40 volts of reading. The SCR's will start firing and the average current will be shown on the D.C. amp-meter. The other meter is not connected. Because of the different current wave forms at different frequencies, the actual current at the particular frequency is quite a bit larger than shown on the meter.

Step 6 - To change frequency, change the frequency control knobs and the L.F. and H.F. switches to obtain the proper frequency. When all settings are right, the current will be shown on the meter.

If two loops are connected, before we operate the coarse frequency control to 7 and 8, we should disconnect one loop. Put the power on and then connect the other loop. This is required because low impedance of the loops connected in parallel.

TRANSMITTER (Tx) TESTS

MEASUREMENT OF OUTPUT CURRENTS

A. TEST SET-UP

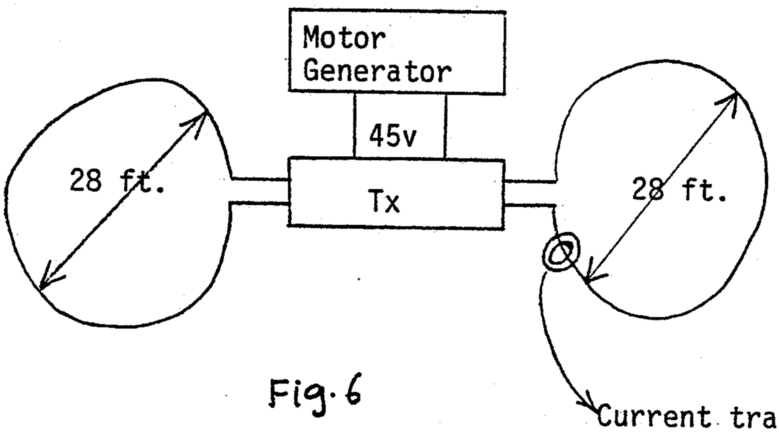
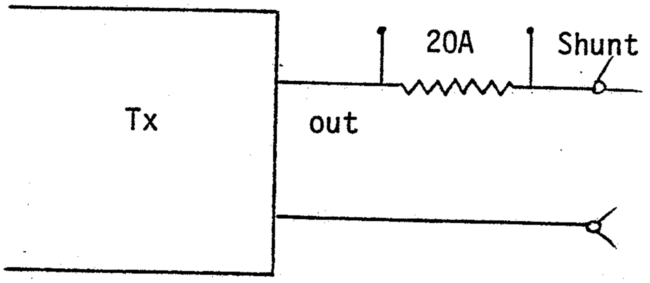


Fig. 6

Current transformer for H.F. current measurements.

B. METHODS

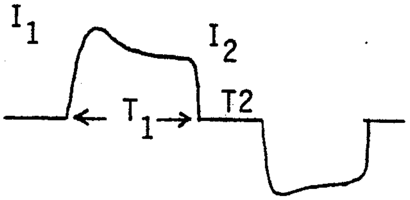
Low frequency current measurements



Shunt to measure L.F. current (20A/50mV)

Fig. 7

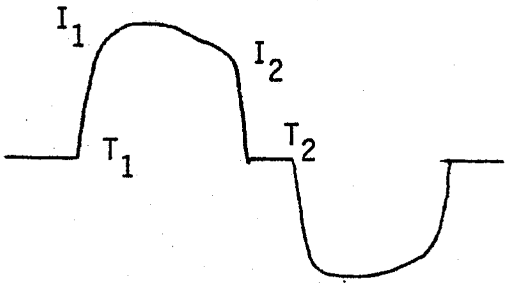
C. RESULTS



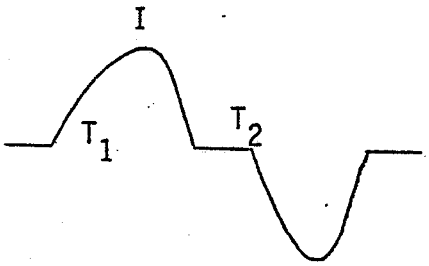
GEOPROBE LIMITED

Freq. Switch Position	Turn	Two Loop in Each Turn I_1(amps)	Two Loop in Each Turn I_2(amps)	One Loop in Each Turn I_1(amps)	One Loop in Each Turn I_2(amps)	T_1(MS)	T_2(MS)
1 : 1	10	40	32	20	16	400	125
1 : 2	10	40	32	20	16	350	120
1 : 3	10	40	32	20	16	320	100
1 : 4	10	40	32	20	16	290	90
1 : 5	10	40	32	20	16	265	85
1 : 6	10	40	32	20	16	240	75
1 : 7	10						
1 : 8	10	40	32	20	16	205	68
2 : 1	10	40	32	20	16	200	64
2 : 2	10	40	32	20	16	190	57
2 : 3	10	36	28	18	14	160	52
2 : 4	10	36	28	18	14	140	46
2 : 5	10	36	28	18	14	132	42
2 : 6	10	36	28	18	14	120	40
2 : 7	10						
2 : 8	10	36	28	18	14	106	34
3 : 1	10	40	30	20	15	100	32
3 : 2	10	40	30	20	15	90	28
3 : 3	10	40	30	20	15	80	24
3 : 4	10	40	30	20	15	72	22
3 : 5	10	46	30	20	15	68	20
3 : 6	10	40	30	20	15	60	20
3 : 7	10						
3 : 8	10	40	30	20	15	52	16
4 : 1	10	40	30	20	15	48	16
4 : 2	10	36	28	18	14	35	14
4 : 3	10	36	28	18	14	40	12
4 : 4	10	36	28	18	14	36	10
4 : 5	10	34	28	17	14	31	10
4 : 6	10	33	28	17	14	30	10
4 : 7	10						
4 : 8	10	32	28	16	14	26	8
5 : 1	10	32	26	16	13	25.0	7
5 : 2	10	30	28	15	14	22.5	5
5 : 3	10	28	26	14	13	20	5
5 : 4	10	30	28	15	14	23.5	5
5 : 5	10	30	28	15	14	17.5	5
5 : 6	10	30	26	15	13	15.5	3.5
5 : 7	10						
5 : 8	10	30	30	15	15	14.0	3.5

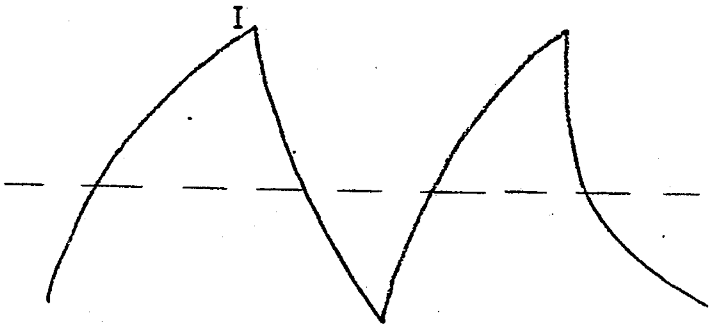
Freq. Switch Position	Turn	Two Loop in Each Turn		One Loop in Each Turn		T_1(MS)	T_2(MS)
		I_1(amps)	I_2(amps)	I_1(amps)	I_2(amps)		
6 : 1	10	30	30	15	15	13	3
6 : 2	10	30	30	15	15	11.5	2.5
6 : 3	10	30	30	15	15	9.5	2.0
6 : 4	10	30	30	15	15	10	2.0
6 : 5	10	30	30	15	15	9	1.6
6 : 6	10	30	30	15	15	8.4	1.4
6 : 7	10						
6 : 8	10	30	30	15	15	7.4	1.0



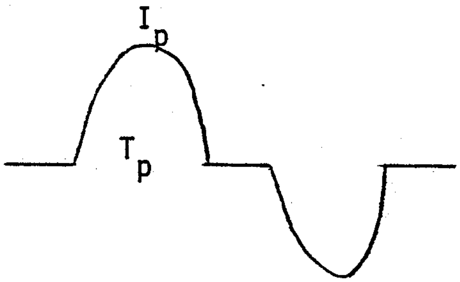
Freq. Switch Position	Turn	Two Loop in Each Turn I (amps)	One Loop in Each Turn I (amps)	T_1(MS)	T_2(MS)
7 : 1	10	30	15	6.8	1.0
7 : 2	10	30	15	6.0	.8
7 : 3	10	30	15	5.8	.8
7 : 4	7	40	20	5.0	.8
7 : 5	7	40	20	4.6	.6
7 : 6	7	40	20	4.4	.6
7 : 7	7				
7 : 8	7	40	20	3.8	.4
8 : 1	7	40	20	3.6	.4
8 : 2	7	36	20	3.4	.2
8 : 3	7	36	20	3.0	.2
8 : 4	5				
8 : 5	5				
8 : 6	5				
8 : 7	5				
8 : 8	5	40	20	2.0	.1
9 : 1	5	40	24	2	.1
9 : 2	5	40	24	1.8	0
9: 3	5	40	24	1.6	0
9 : 4	4	46	24	1.5	0
9 : 5	4				
9 : 6	4				
9 : 7	4				
9 : 8	4	40	20	1.1	0



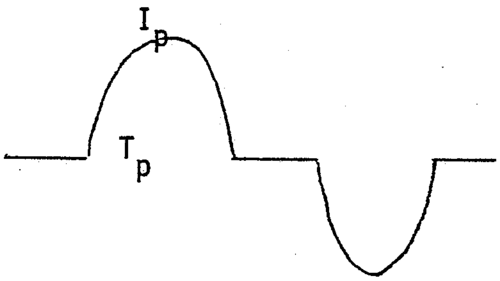
Freq. Switch Position	Turn	Two Loop in Each Turn I (amps)	One Loop in Each Turn I (amps)
10 : 1	4	40	20
10 : 2	4	36	18
10 : 3	4	32	16
10 : 4	3	42	21
10 : 5	3	36	18
10 : 6	3	36	18
10 : 7	3		
10 : 8	3	32	16
11 : 1	3	30	15
11 : 2	3	30	15
11 : 3	3	28	14



Freq. Switch Position	Turn	Cap uf	Two Loop		One Loop	
			(Ipx Turns) AMP. TURN PER LOOP	Tp (us)	AMP TURN Per Loop	Tp (us)
11 : 4	2	30	40	150	60	220
11 : 5	2	30	40	150	60	220
11 : 6	2	30	40	150	60	220
11 : 7	2	30				
11 : 8	2	30	40	150	60	220
12 : 1	2	30	40	160	60	220
12 : 2	2	30	40	150	60	220
12 : 3	2	30	40	150	50	200
12 : 4	1	30	36	75	50	110
12 : 5	1	30	36	75	52	110
12 : 6	1	30	36	75	52	110
12 : 7	1	30				
12 : 8	1	30	36	75	52	110
13 : 1	1	30	36	75	55	110
13 : 2	1	30	36	75	55	110
13 : 3	1	30	36	75	55	110
13 : 4	1	30	25	40	40	60
13 : 5	1	7.5	25	40	40	60
13 : 6	1	7.5	25	40	40	60
13 : 7	1					
13 : 8	1	7.5	28	40	40	60



Freq. Switch Position	Turns	Cap (uf)	Two Loop		One Loop	
			Ip (amps)	Tp (us)	Ip (amps)	Tp (us)
14 : 1	1	7.5	28	40	40	60 (sine)
14 : 2	1	7.5	28	40	40	60 "
14 : 3	1	7.5	28	40	30	(overlap sine
14 : 4	1	2.7	20	28	30	37
14 : 5	1	2.7	25	28	30	37
14 : 6	1	2.7	25	28	40	37 (sine)
14 : 7	1	2.7				
14 : 8	1	2.7	20	28	36	37 (sine)
15 : 1	1	2.7	20	28	30	Sine Wave
15 : 2	1	2.7	24	28	20	" "
15 : 3	1	2.7	24	28(sine)	20	" "
15 : 4	1	.97	10	28(noisy)	20	" "
15 : 5	1	.97			28	" "
15 : 6	1	.97			30	" "
15 : 7	1	.97				
15 : 8	1	.97	12	28	20	" "
16 : 1	1	.97	14	sine	20	" "
16 : 2	1	.97	20	sine	16	" "
16 : 3	1	.97	15	sine	15	" "



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$$\text{FREQ.} = 2^{(\text{Coarse} - 1)} \times \frac{(7 + \text{Fine})}{8} \times \frac{10^6}{2^{20}} \text{ Hz}$$

GEOPROBE LIMITED

POSSIBLE FREQUENCY COMBINATIONS

Switch Position	Frequencies	Switch Position	Frequencies
Coarse:Fine	Hertz	Coarse:Fine	Hertz
1 : 1	0.95367	6 : 1	30.517576
1 : 2	1.072878	6 : 2	34.332273
1 : 3	1.1920875	6 : 3	38.14697
1 : 4	1.3112962	6 : 4	41.80907912
1 : 5	1.430505	6 : 5	45.776364
1 : 6	1.549714	6 : 6	49.591061
1 : 7	1.6689221	6 : 7	53.405758
1 : 8	1.788131	6 : 8	57.220455
2 : 1	1.907349	7 : 1	61.035152
2 : 2	2.1457676	7 : 2	68.664546
2 : 3	2.3841862	7 : 3	76.29394
2 : 4	2.61306813	7 : 4	83.61815824
2 : 5	2.88009699	7 : 5	91.552728
2 : 6	3.099442125	7 : 6	99.182122
2 : 7	3.33786075	7 : 7	106.811516
2 : 8	3.57627935	7 : 8	114.44091
3 : 1	3.814697	8 : 1	122.0703
3 : 2	4.291534125	8 : 2	137.3270875
3 : 3	4.76837125	8 : 3	152.587875
3 : 4	5.22613489	8 : 4	167.236311
3 : 5	5.7220455	8 : 5	183.10545
3 : 6	6.198882625	8 : 6	198.3642375
3 : 7	6.67571975	8 : 7	213.623025
3 : 8	7.152556875	8 : 8	228.8818125
4 : 1	7.629394	9 : 1	244.1406
4 : 2	8.58306825	9 : 2	274.658175
4 : 3	9.5367425	9 : 3	305.17575
4 : 4	10.45226978	9 : 4	334.472632
4 : 5	11.444091	9 : 5	366.2109
4 : 6	12.39776525	9 : 6	396.728475
4 : 7	13.3514395	9 : 7	427.24605
4 : 8	14.30511375	9 : 8	457.763625
5 : 1	15.258788	10 : 1	488.2812
5 : 2	17.1661365	10 : 2	549.31635
5 : 3	19.073485	10 : 3	610.3515
5 : 4	20.90453956	10 : 4	668.945244
5 : 5	22.888182	10 : 5	732.4218
5 : 6	24.7955305	10 : 6	793.45695
5 : 7	26.702879	10 : 7	854.4921
5 : 8	28.6102275	10 : 8	915.52725

Switch Position Coarse:Fine	Frequencies Hertz	Switch Position Coarse:Fine	Frequencies Hertz
11 : 1	976.5624	14 : 1	7812.4992
11 : 2	1098.6327	14 : 2	8789.0616
11 : 3	1220.703	14 : 3	9765.624
11 : 4	1337.890488	14 : 4	10703.1239
11 : 5	1464.8436	14 : 5	11718.7488
11 : 6	1586.9139	14 : 6	12695.3112
11 : 7	1708.9842	14 : 7	13671.8736
11 : 8	1831.0545	14 : 8	14648.436
12 : 1	1953.1248	15 : 1	15624.998
12 : 2	2197.2654	15 : 2	17578.12275
12 : 3	2441.406	15 : 3	19531.2475
12 : 4	2675.780976	15 : 4	21406.24726
12 : 5	2929.6872	15 : 5	23437.497
12 : 6	3173.8278	15 : 6	25390.62175
12 : 7	3417.9684	15 : 7	27343.7465
12 : 8	3662.109	15 : 8	29296.87125
13 : 1	3906.2496	16 : 1	31249.996
13 : 2	4394.5308	16 : 2	35156.2445
13 : 3	4882.812	16 : 3	39062.495
13 : 4	5351.561952	16 : 4	42812.49454
13 : 5	5859.3744	16 : 5	46874.994
13 : 6	6347.6556	16 : 6	50781.2435
13 : 7	6835.9368	16 : 7	54687.493
13 : 8	7324.218	16 : 8	58593.7425

	D C B A	BINARY CODE
1.	0000	0.95367
2.	0001	1.907349
3.	0010	3.814697
4.	0011	7.529394
5.	0100	15.258788
6.	0101	30.517576
7.	0110	61.035152
8.	0111	122.0703
9.	1000	244.1406
10.	1001	488.2812
11.	1010	976.5624
12.	1011	1953.1248
13.	1100	3906.2496
14.	1101	7812.4992
15.	1110	15624.998
16.	1111	31249.996

	Z Y X	BINARY CODE
1.	000	1
2.	001	1.125
3.	010	1.25
4.	011	1.375
5.	100	1.5
6.	101	1.625
7.	110	1.75
8.	111	1.875

ATIO OF FIELDS (H(Z)/H(R))*L*W*MU
ERTICAL DIPOLE SOURCE

ON

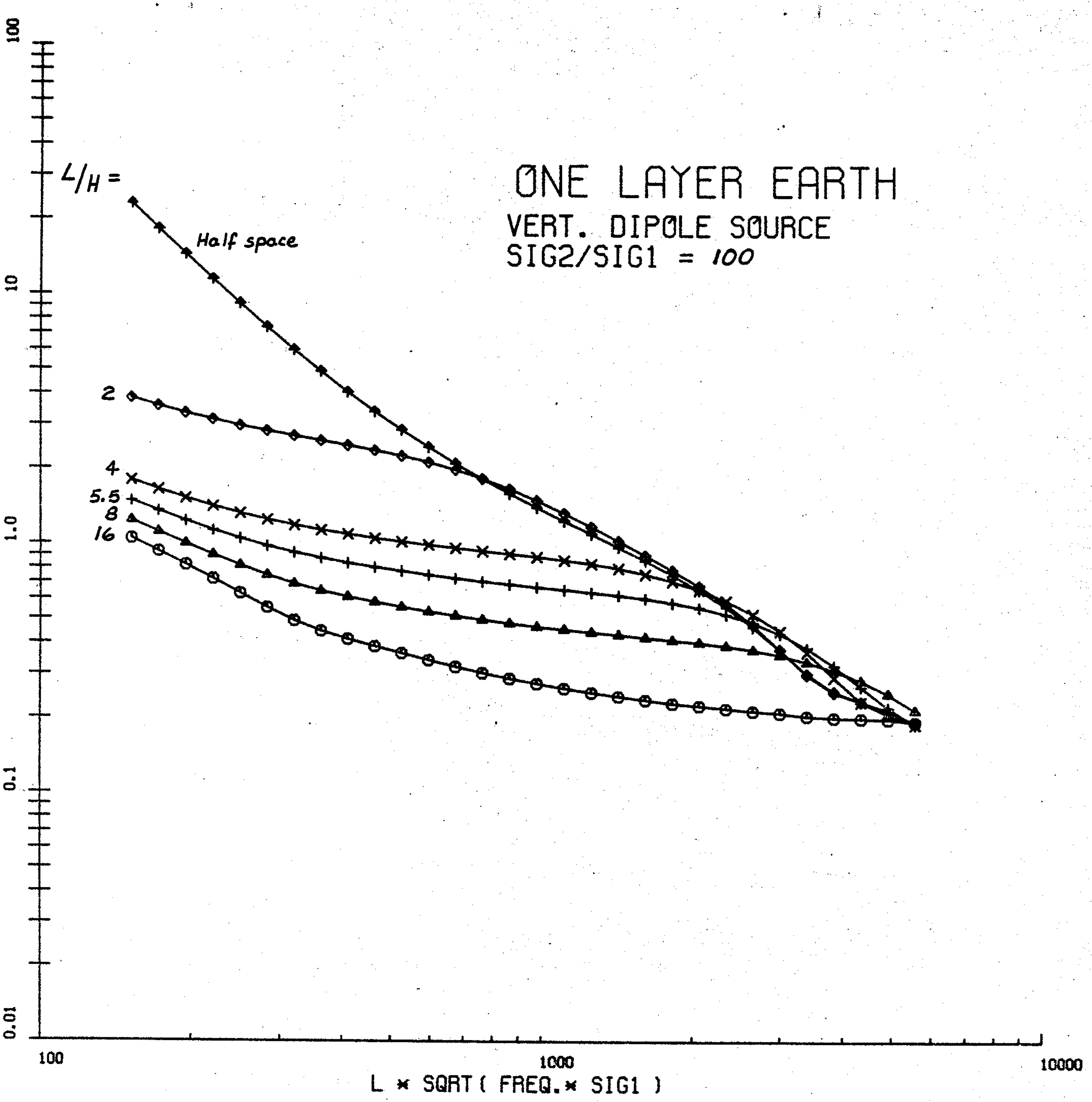
ONE LAYER EARTH

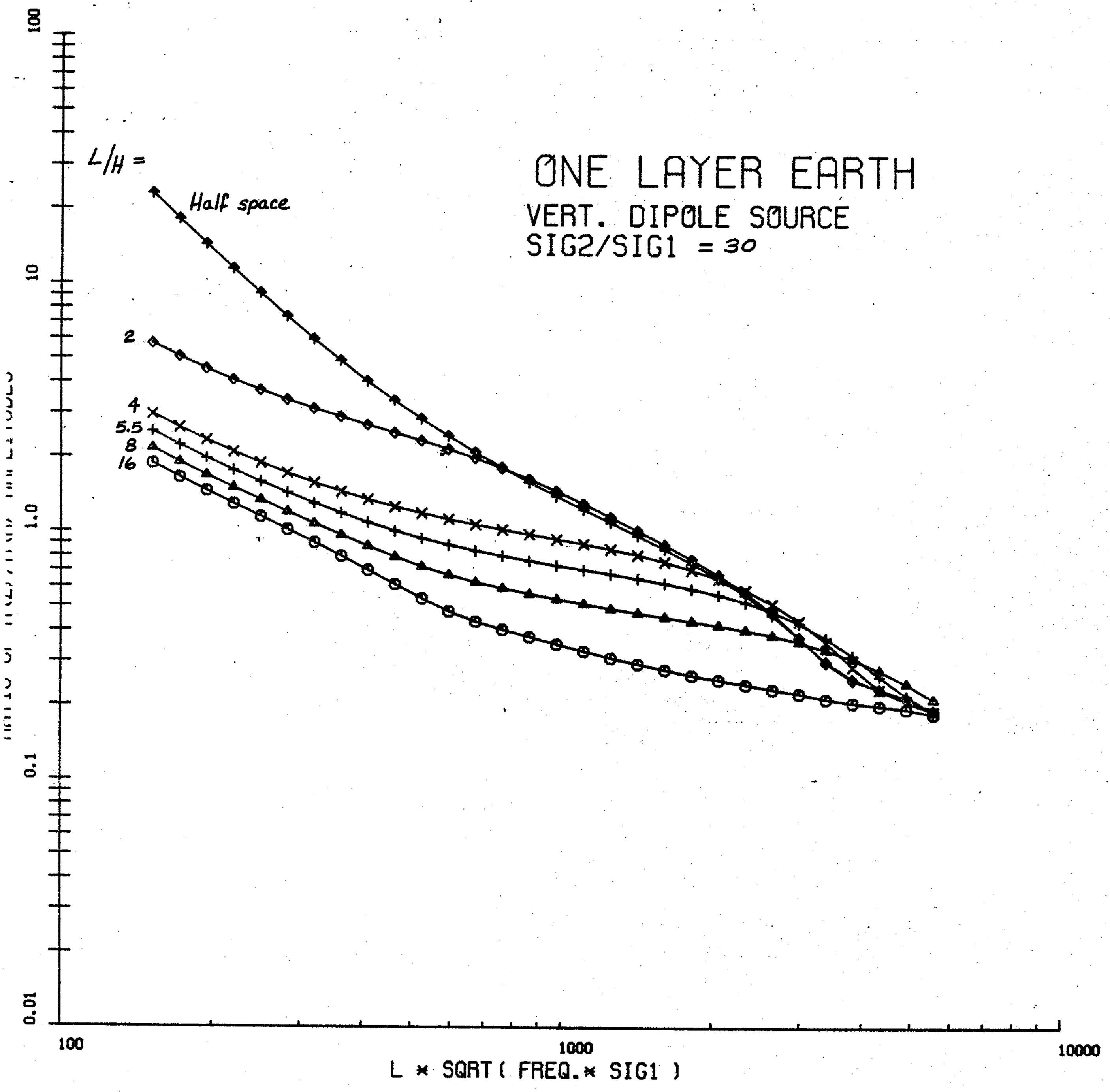
OF CURVES FOR L/H VALUES

NSTANT SIG2/SIG1 RATIO

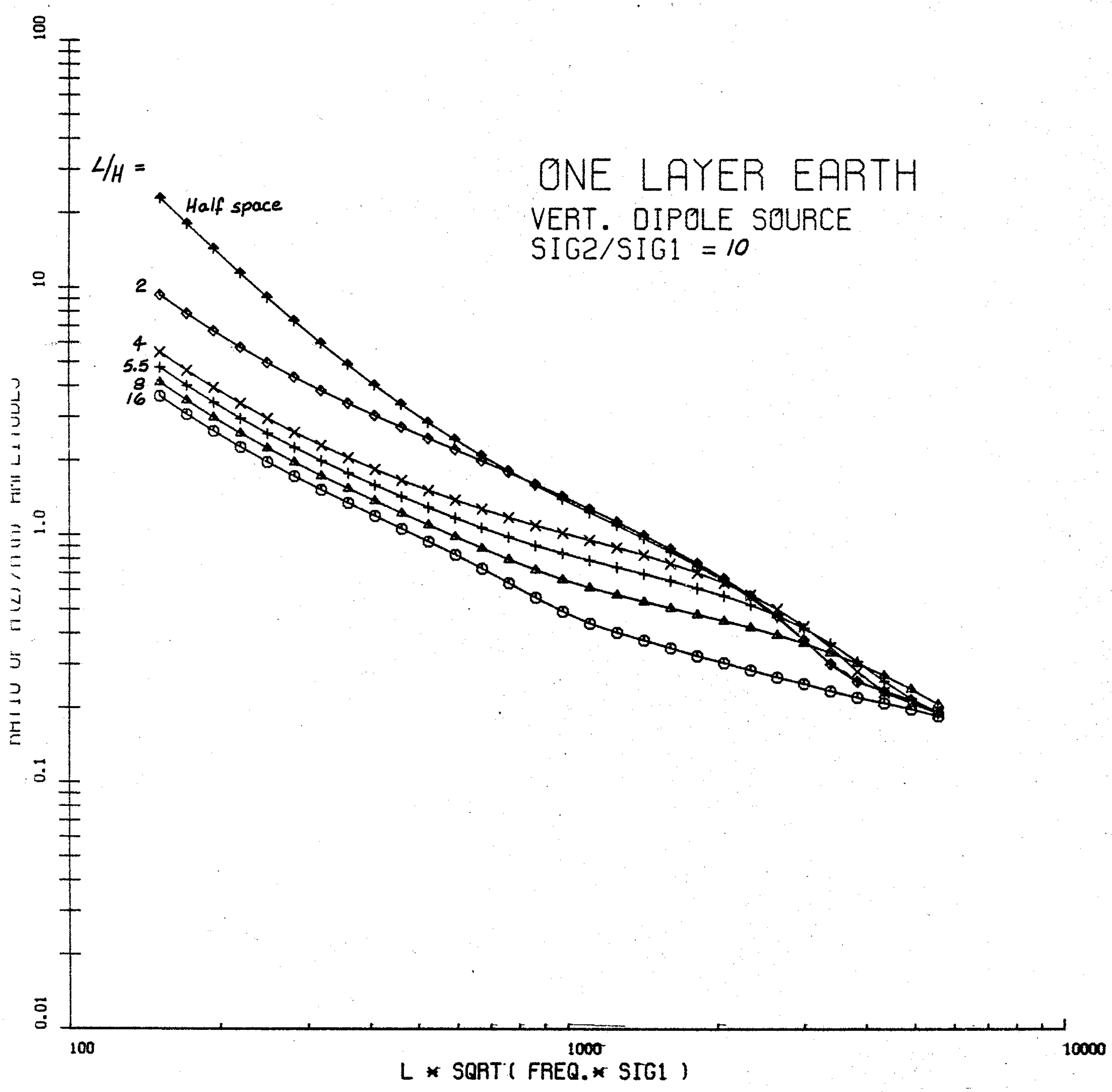
OPEN FILE
DOSSIER PUBLIC
546
GEOLOGICAL SURVEY
COMMISSION GEOLOGIQUE
OTTAWA

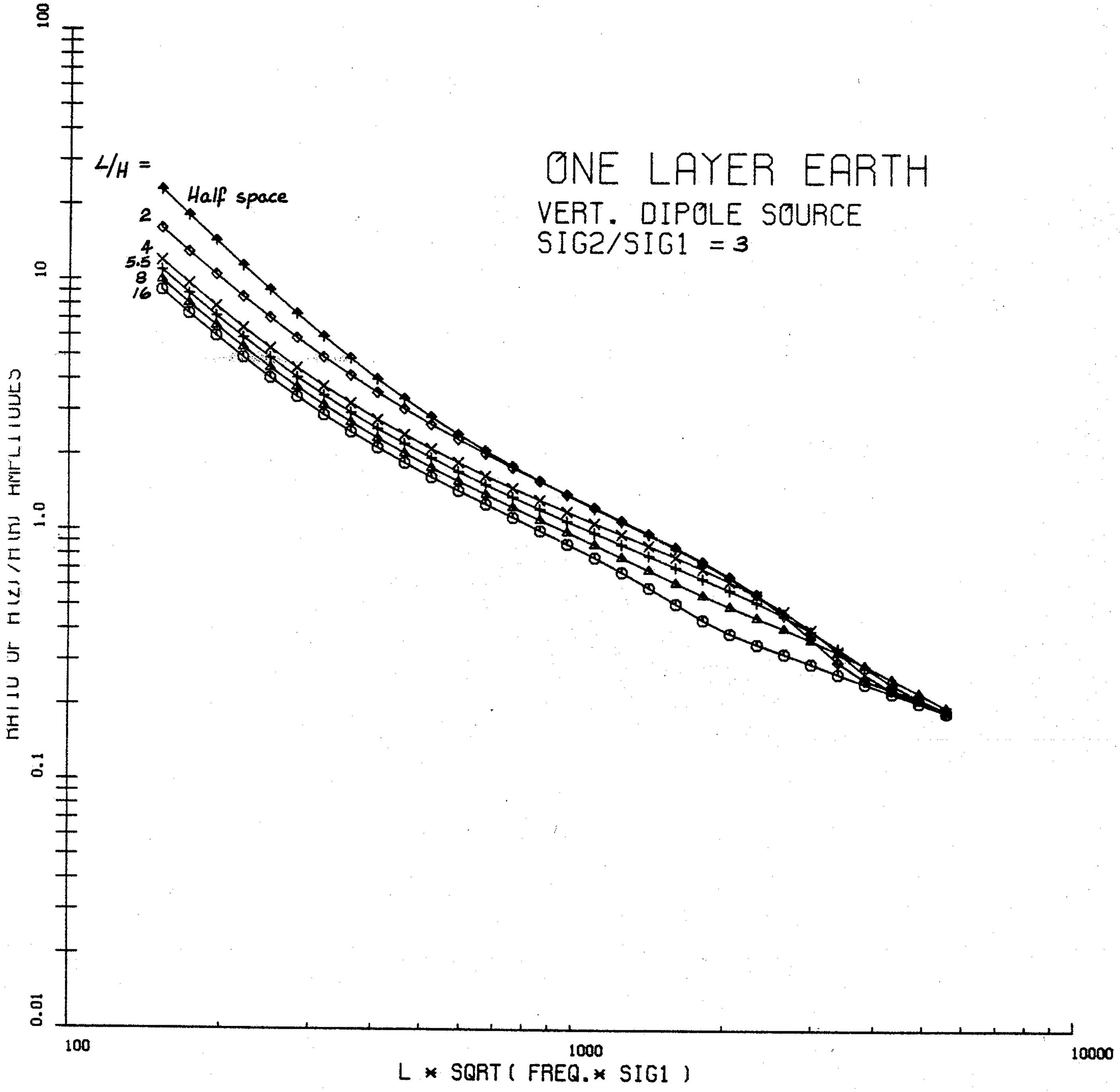
C-1

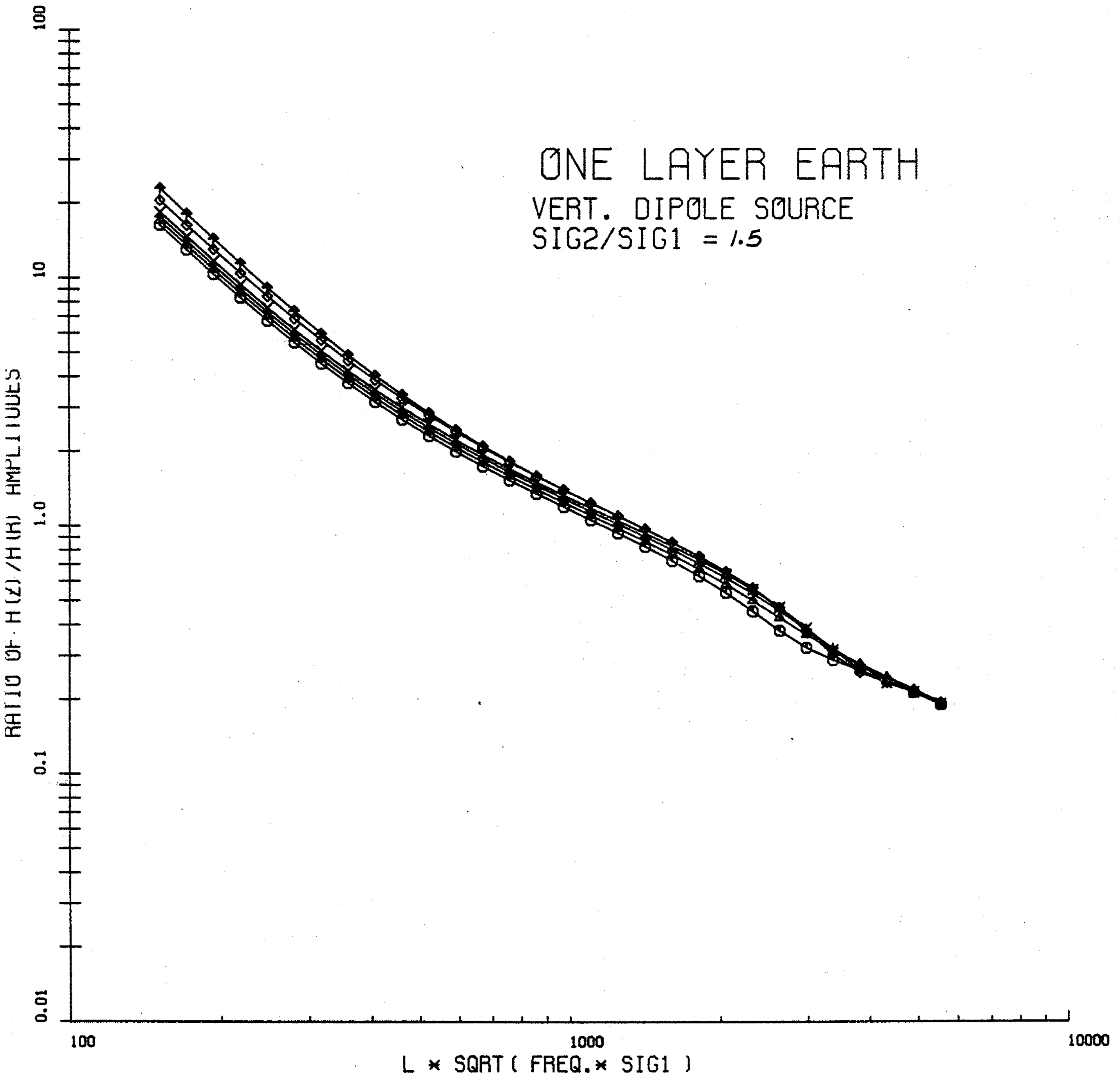

ONE LAYER EARTH
VERT. DIPOLE SOURCE
SIG2/SIG1 = 100
L/H =
Half space
2
4
5.5
8
16
100
10
1.0
0.1
0.01
100
1000
10000
L * SQRT(FREQ.* SIG1)

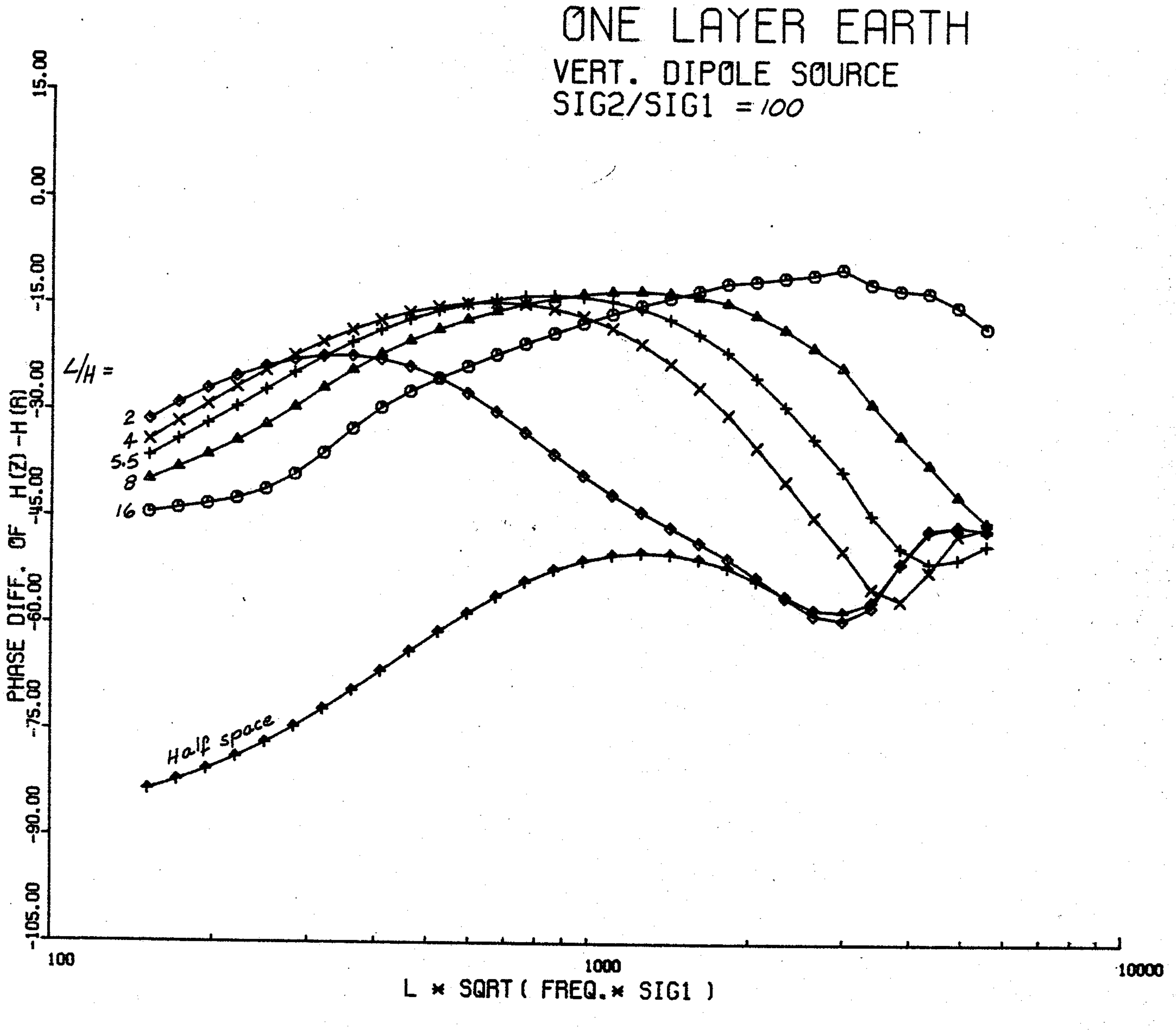


ONE LAYER EARTH
VERT. DIPOLE SOURCE
SIG2/SIG1 = 30
L/H =
Half space
2
4
5.5
8
16
100
10
1.0
0.1
0.01
100
1000
10000
L * SQRT(FREQ.* SIG1)


ONE LAYER EARTH
VERT. DIPOLE SOURCE
SIG2/SIG1 = 10
L/H =
Half space
2
4
5.5
8
16
RATIO OF H(Z)/H(0) AMPLITUDES
100
10
1.0
0.1
0.01
100
1000
10000
L * SQRT(FREQ.* SIG1)


ONE LAYER EARTH
VERT. DIPOLE SOURCE
SIG2/SIG1 = 3
L/H =
Half space
2
4
5.5
8
16
RATIO OF H(Z)/H(R) AMPLITUDES
100
10
1.0
0.1
0.01
100
1000
10000
L × SQRT (FREQ. × SIG1)


ONE LAYER EARTH
VERT. DIPOLE SOURCE
SIG2/SIG1 = 1.5
RATIO OF H(Z)/H(R) AMPLITUDES
100
10
1.0
0.1
0.01
100
1000
10000
L × SQRT(FREQ.× SIG1)



ONE LAYER EARTH

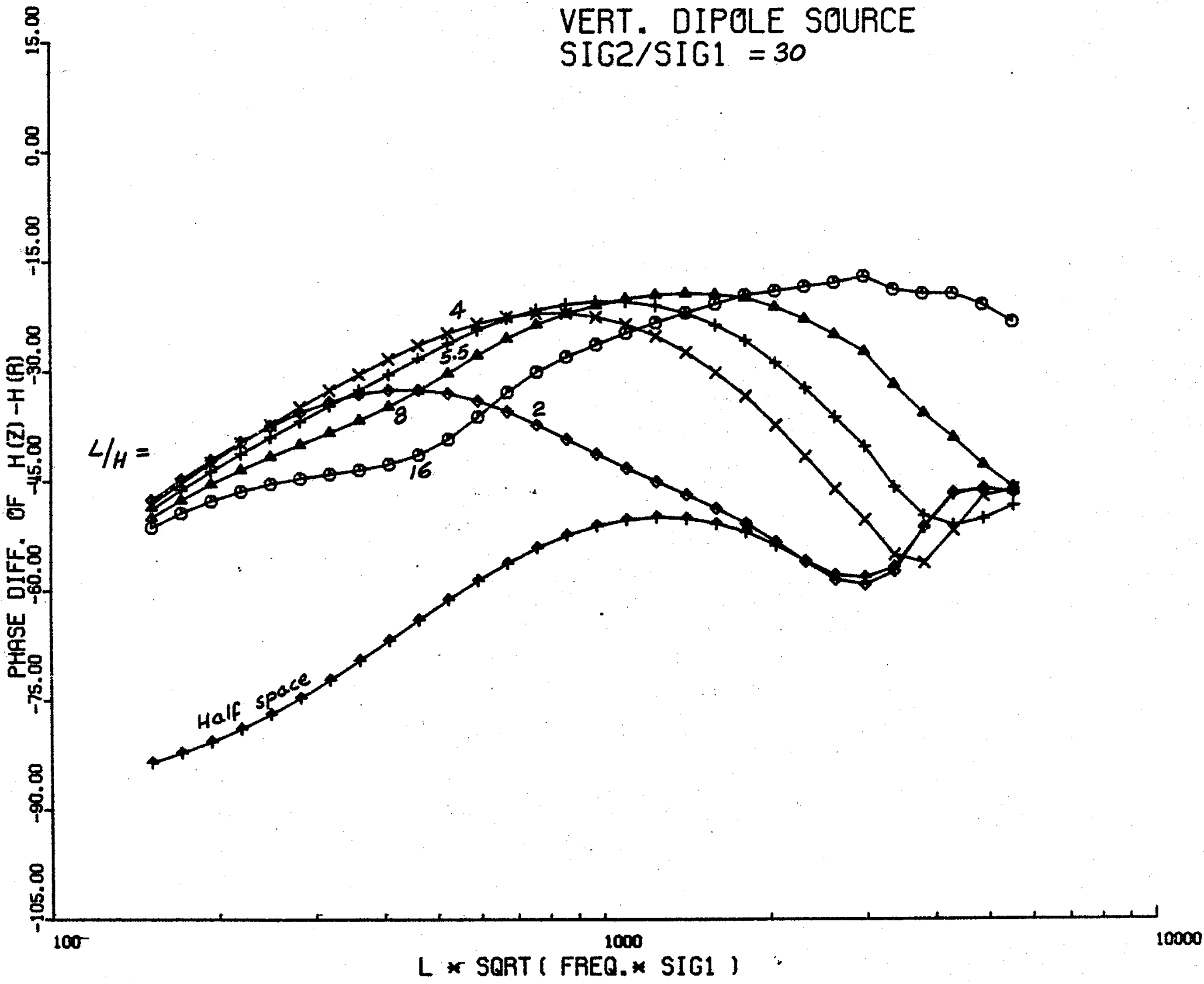
VERT. DIPOLE SOURCE

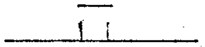
SIG2/SIG1 = 100

C-7

ONE LAYER EARTH

VERT. DIPOLE SOURCE
SIG2/SIG1 = 30

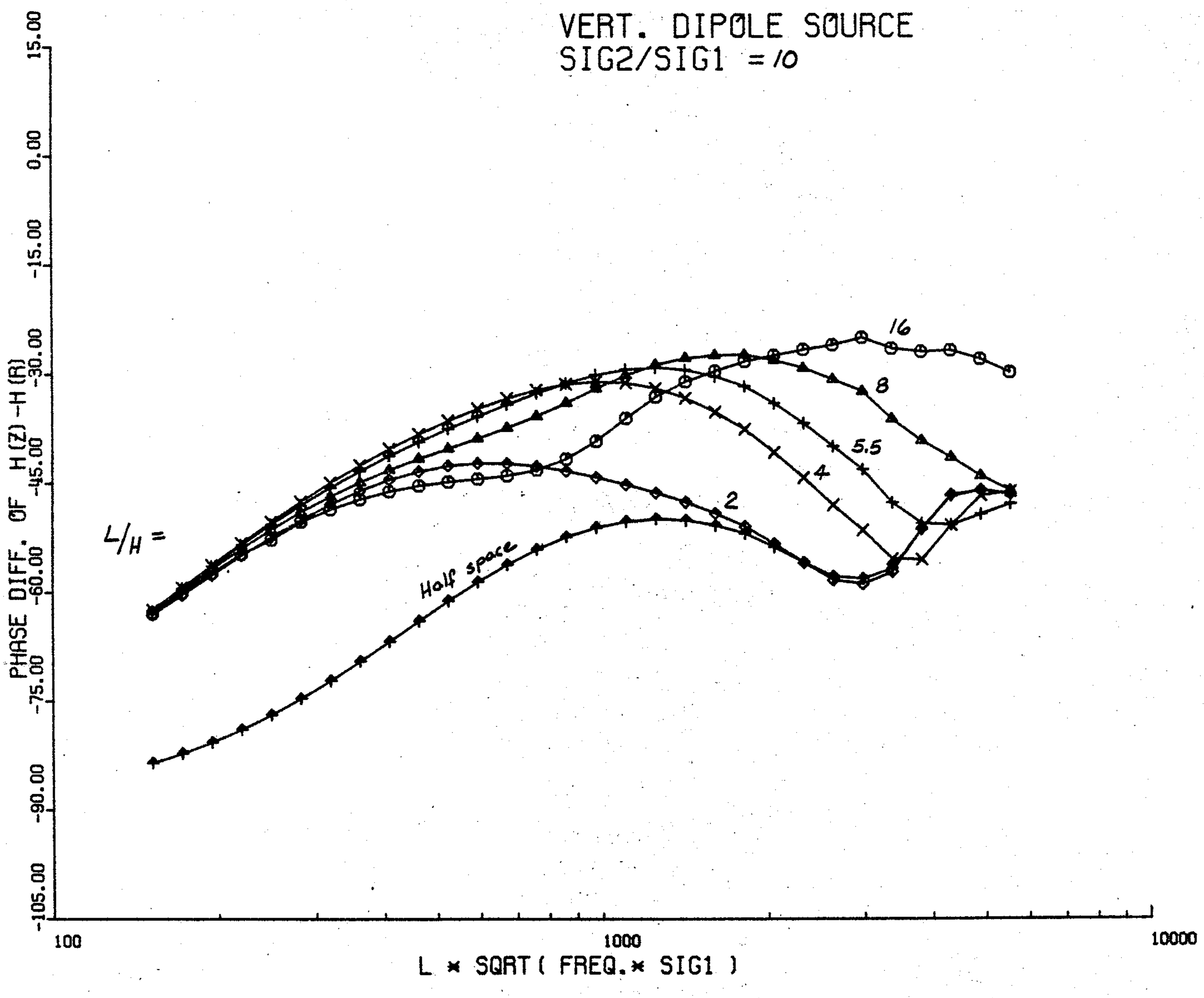


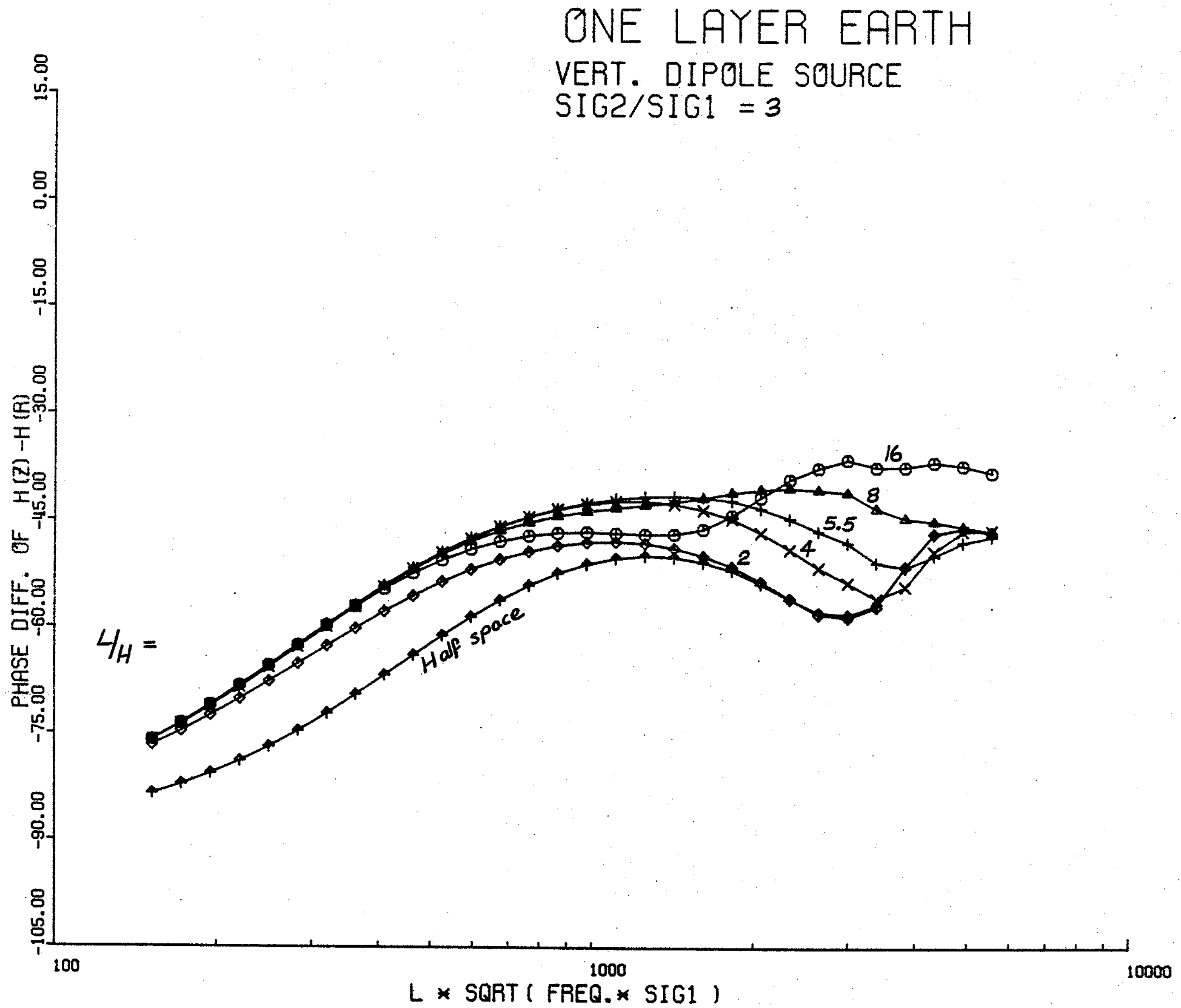


C-8

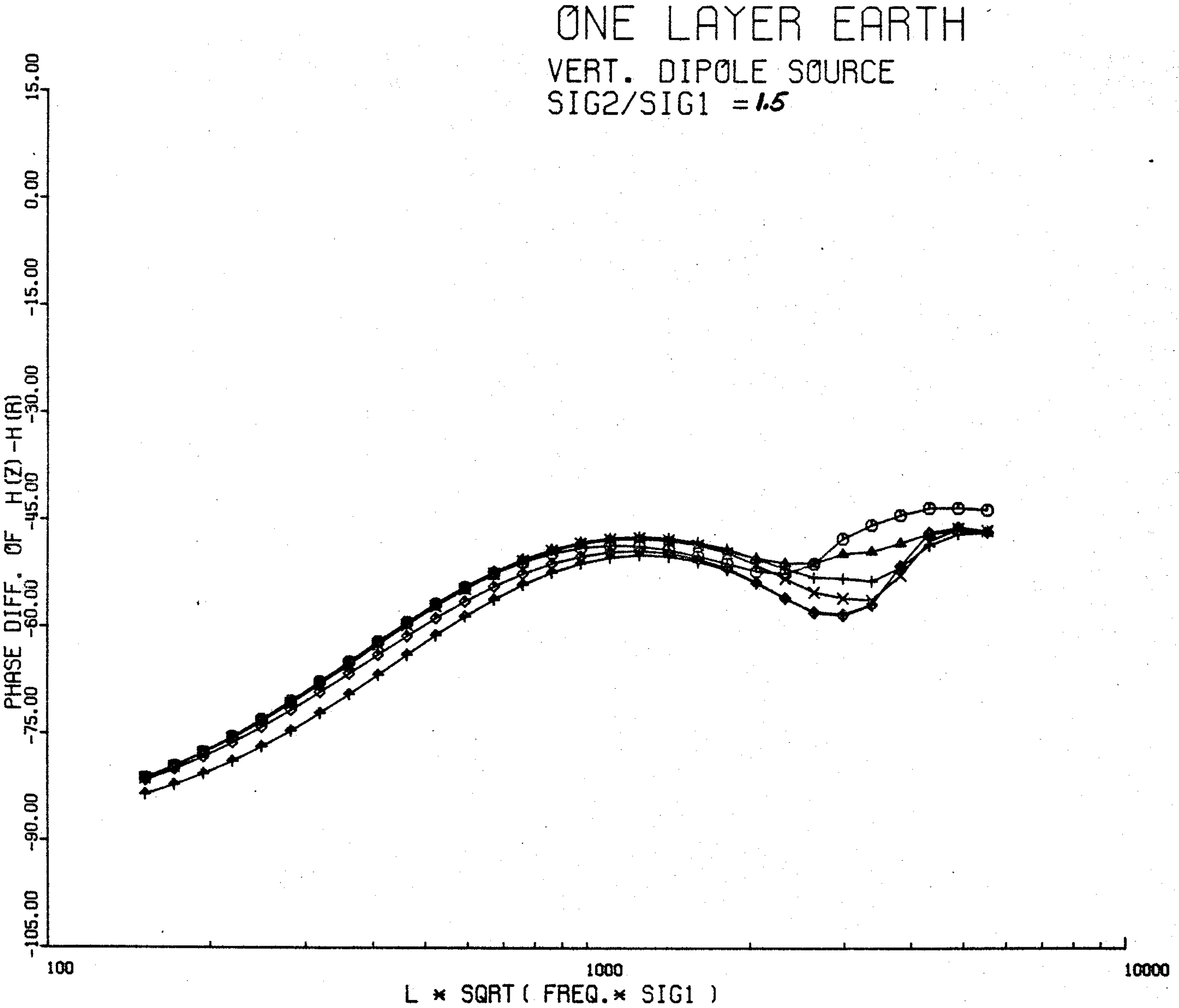
ONE LAYER EARTH

VERT. DIPOLE SOURCE
SIG2/SIG1 = 10




ONE LAYER EARTH
VERT. DIPOLE SOURCE
SIG2/SIG1 = 3
PHASE DIFF. OF H(Z)-H(R)
15.00
0.00
-15.00
-30.00
-45.00
-60.00
-75.00
-90.00
-105.00
100
1000
10000
L × SQRT(FREQ.× SIG1)
L/H =
16
8
5.5
4
2
Half space

C-10


ONE LAYER EARTH
VERT. DIPOLE SOURCE
SIG2/SIG1 = 1.5
PHASE DIFF. OF H(Z)-H(R)
15.00
0.00
-15.00
-30.00
-45.00
-60.00
-75.00
-90.00
-105.00
100
1000
10000
L × SQRT(FREQ.× SIG1)

C-11

11

ATIO OF FIELDS (H(Z)/H(R))*L*W*MU
ERTICAL DIPOLE SOURCE.

ON

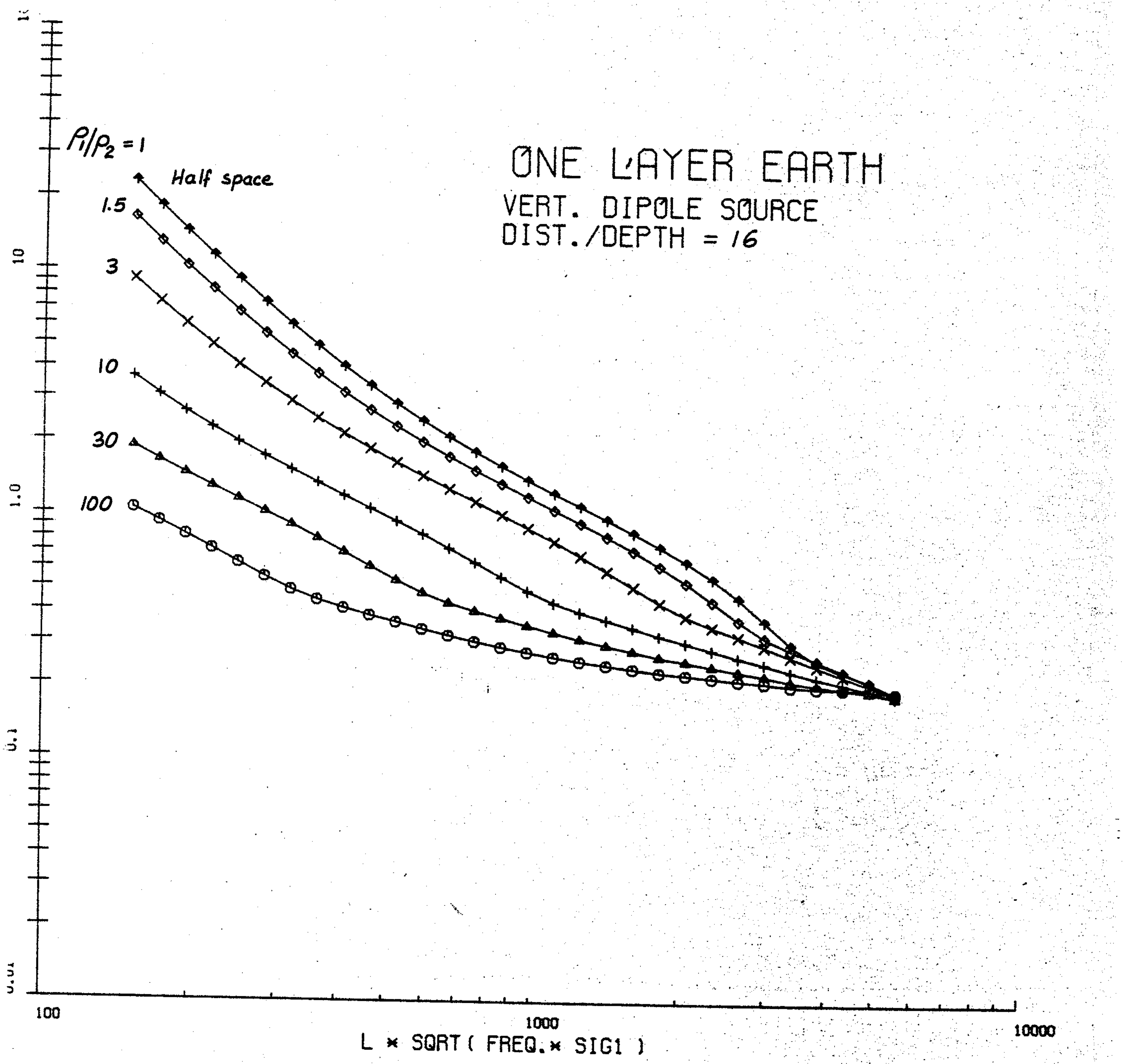
ONE LAYER EARTH

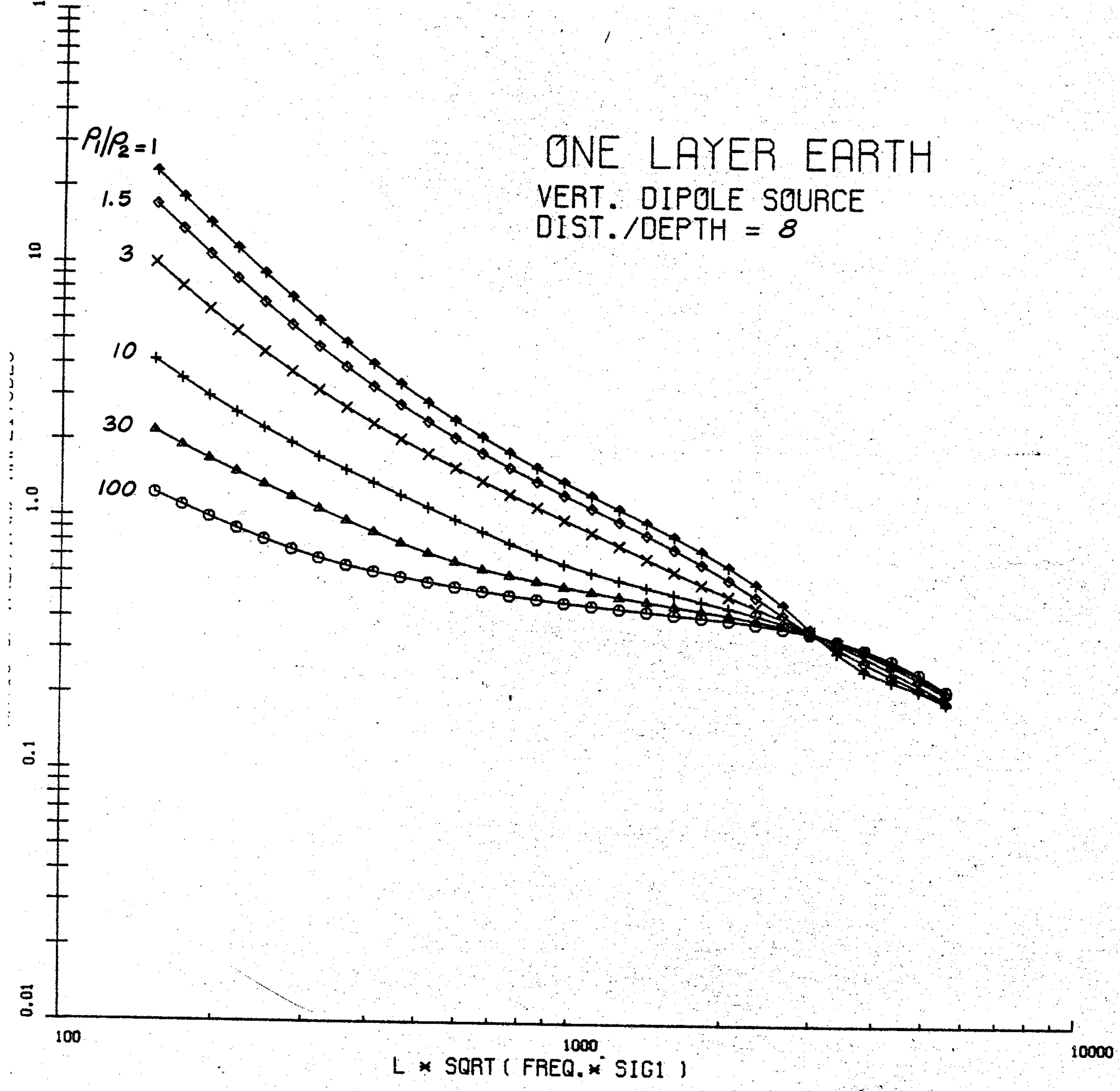
OF CURVES FOR SIG2/ SIG1

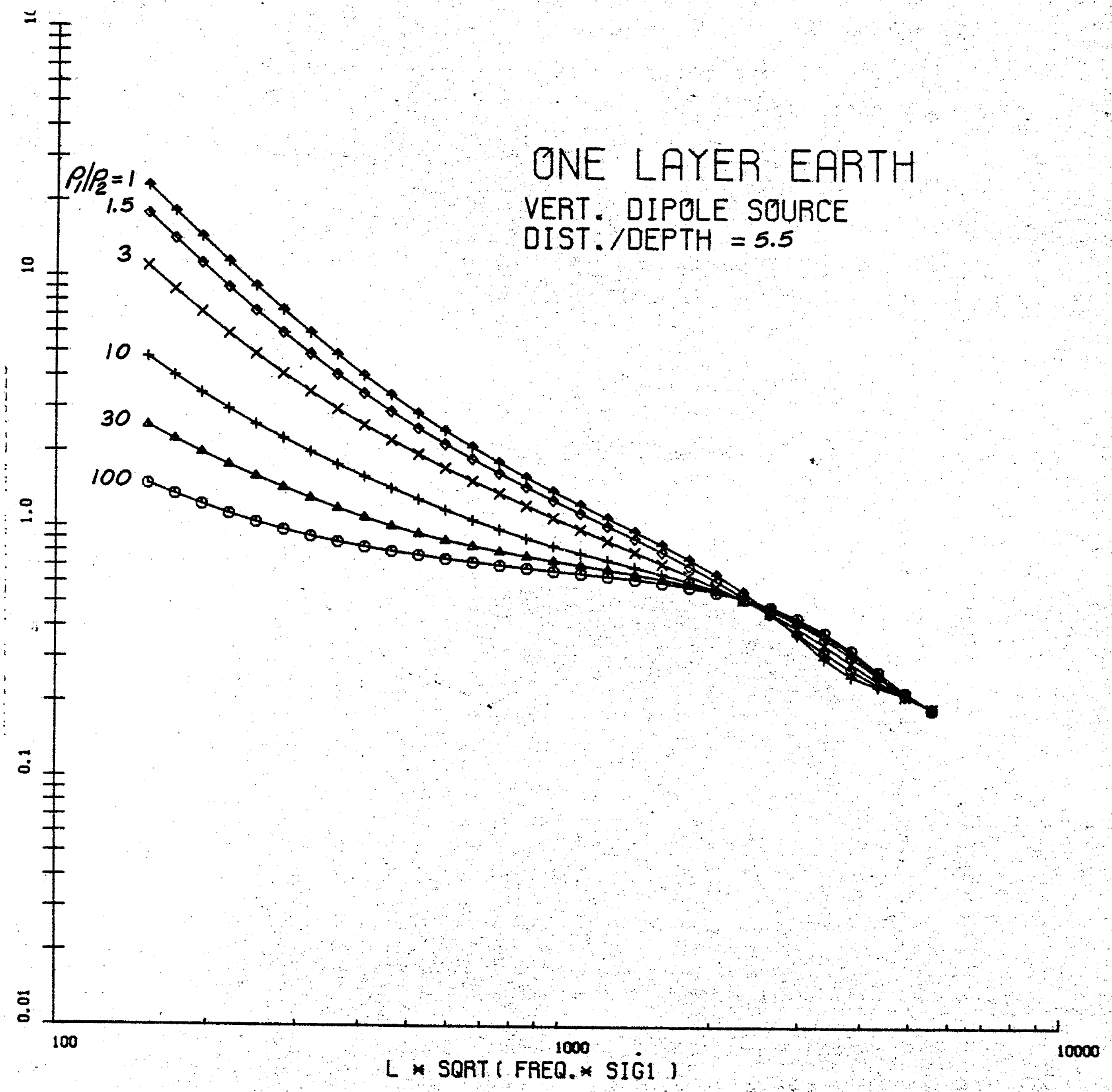
NSTANT DIST./DEPTH RATIO

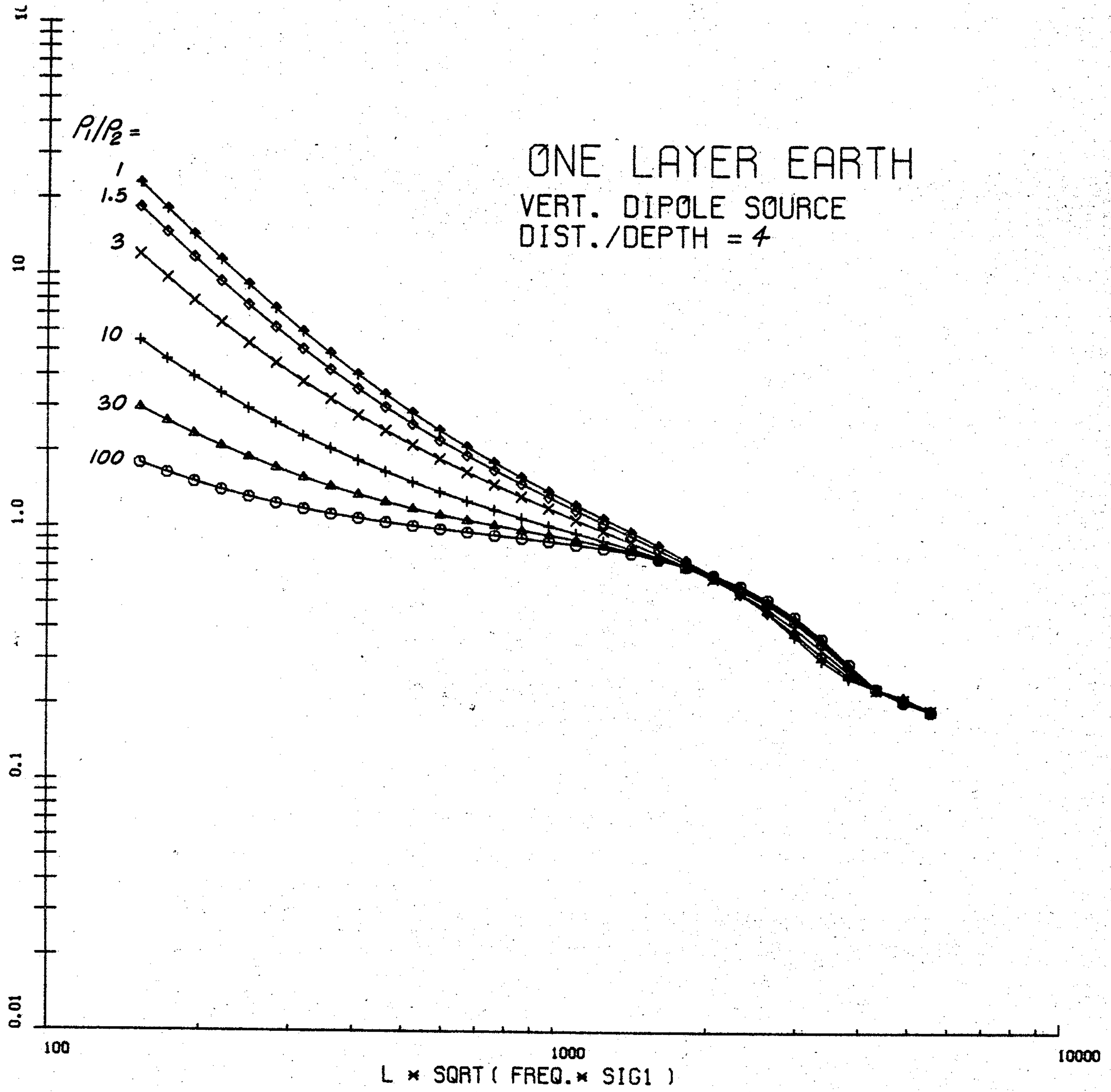
OPEN FILE
DOSSIER PUBLIC
546
GEOLOGICAL SURVEY
COMMISSION GEOLOGIQUE
OTTAWA

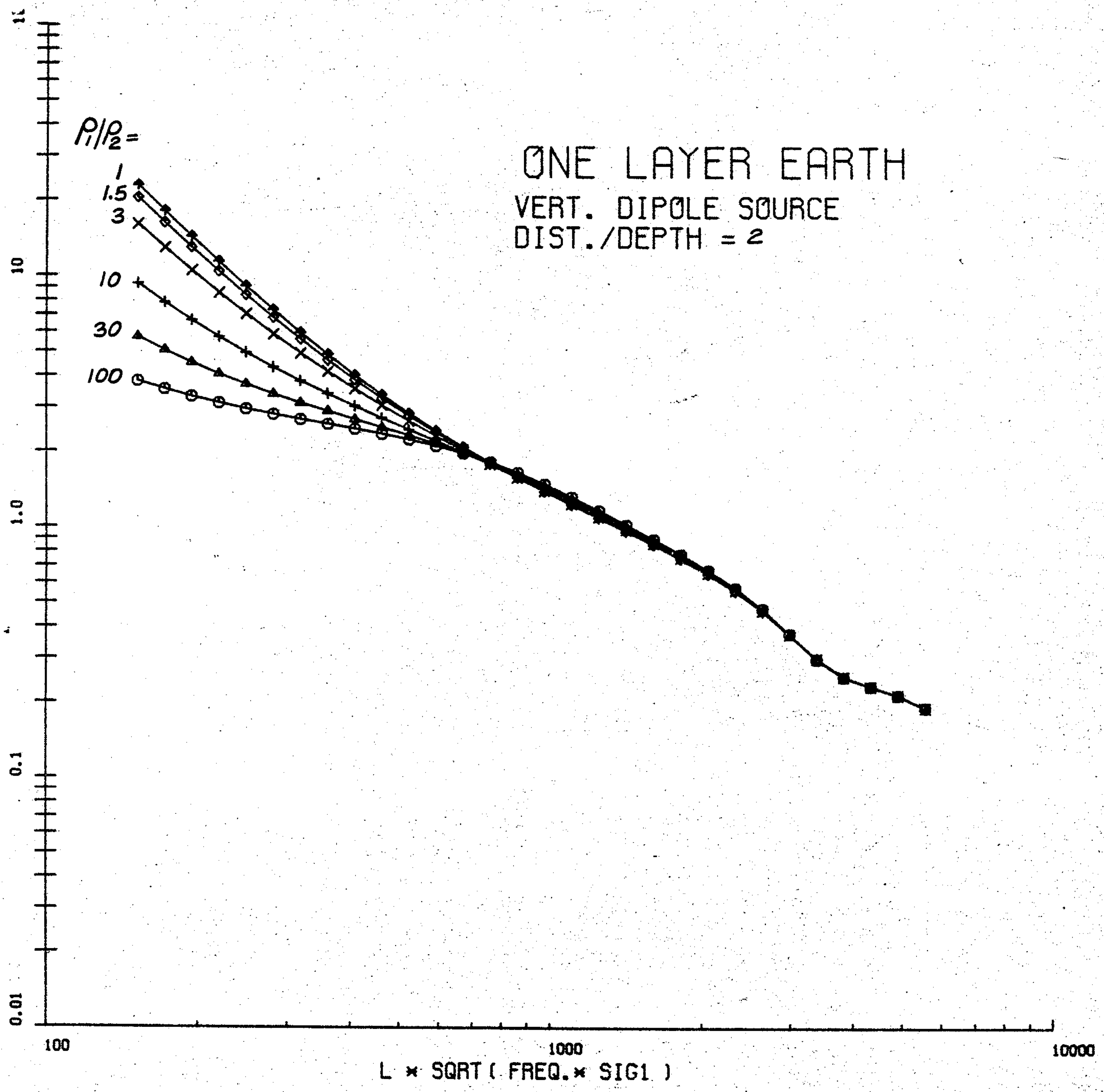
C-12

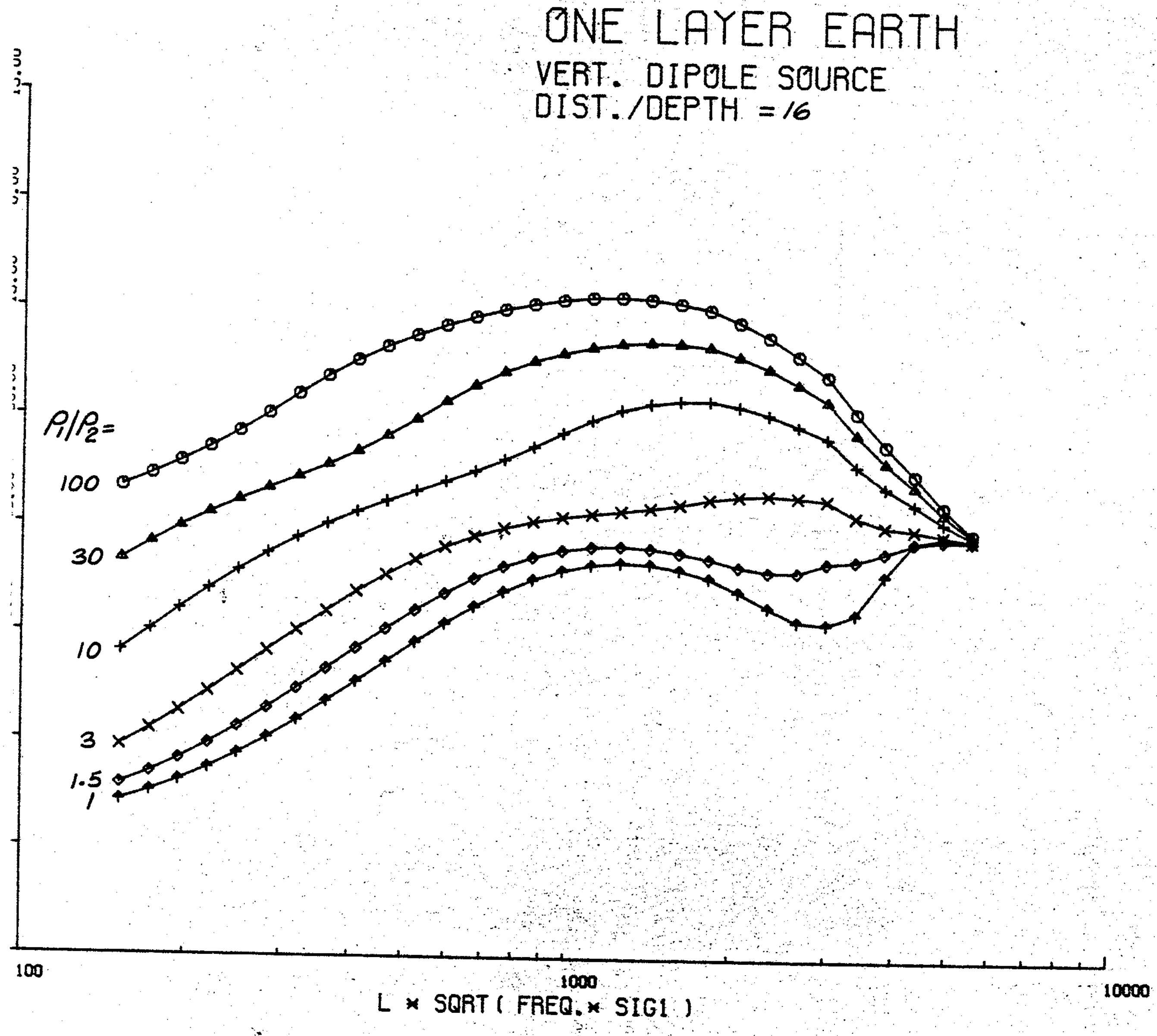

ONE LAYER EARTH
VERT. DIPOLE SOURCE
DIST./DEPTH = 16
$\rho_1/\rho_2 = 1$
Half space
1.5
3
10
30
100
10
1.0
0.1
0.01
100
1000
10000
L * SQRT (FREQ. * SIG1)

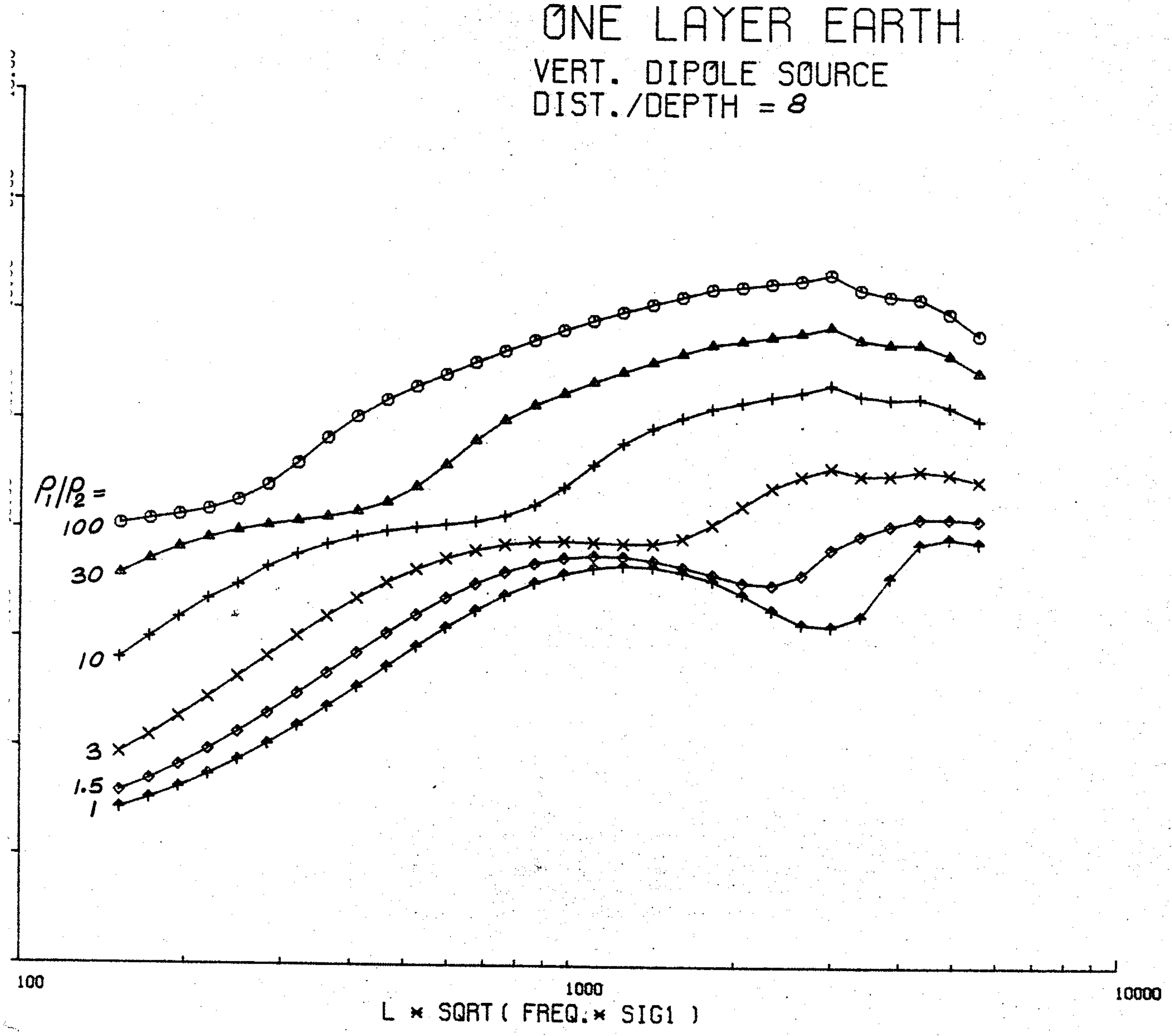

ONE LAYER EARTH
VERT. DIPOLE SOURCE
DIST./DEPTH = 8
ρ_1/ρ_2 = 1
1.5
3
10
30
100
11
10
1.0
0.1
0.01
100
1000
10000
L × SQRT (FREQ. × SIG1)

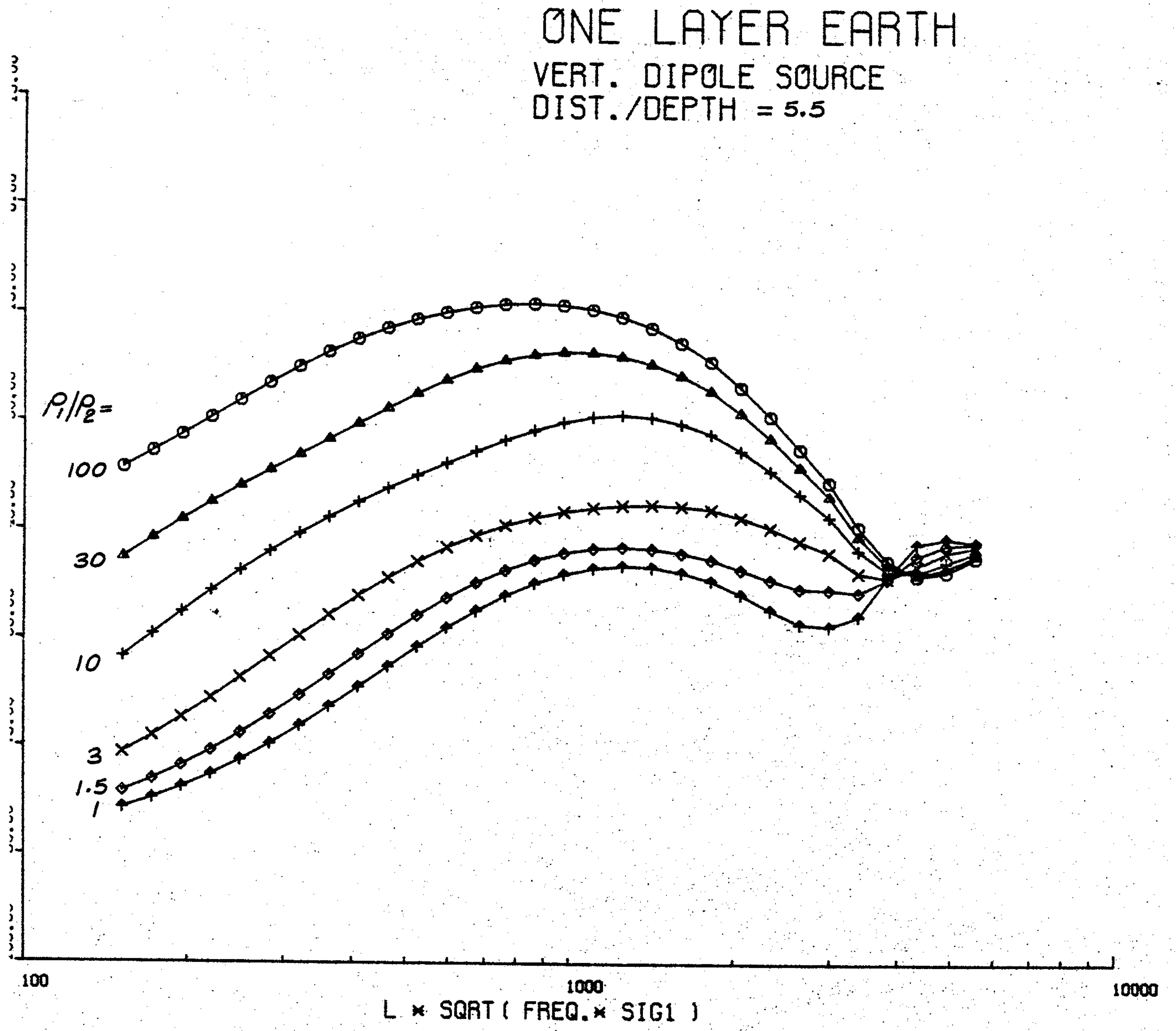

ONE LAYER EARTH
VERT. DIPOLE SOURCE
DIST./DEPTH = 5.5
$\rho_1/\rho_2 = 1$
1.5
3
10
30
100
10
1.0
0.1
0.01
100
1000
10000
L * SQRT (FREQ. * SIG1)


ONE LAYER EARTH
VERT. DIPOLE SOURCE
DIST./DEPTH = 4
ρ_1/ρ_2 =
1
1.5
3
10
30
100
10
1.0
0.1
0.01
100
1000
10000
L × SQRT(FREQ.× SIG1)


ONE LAYER EARTH
VERT. DIPOLE SOURCE
DIST./DEPTH = 2
ρ_1/ρ_2 =
1
1.5
3
10
30
100
0.01
0.1
1.0
10
100
1000
10000
L * SQRT(FREQ.* SIG1)

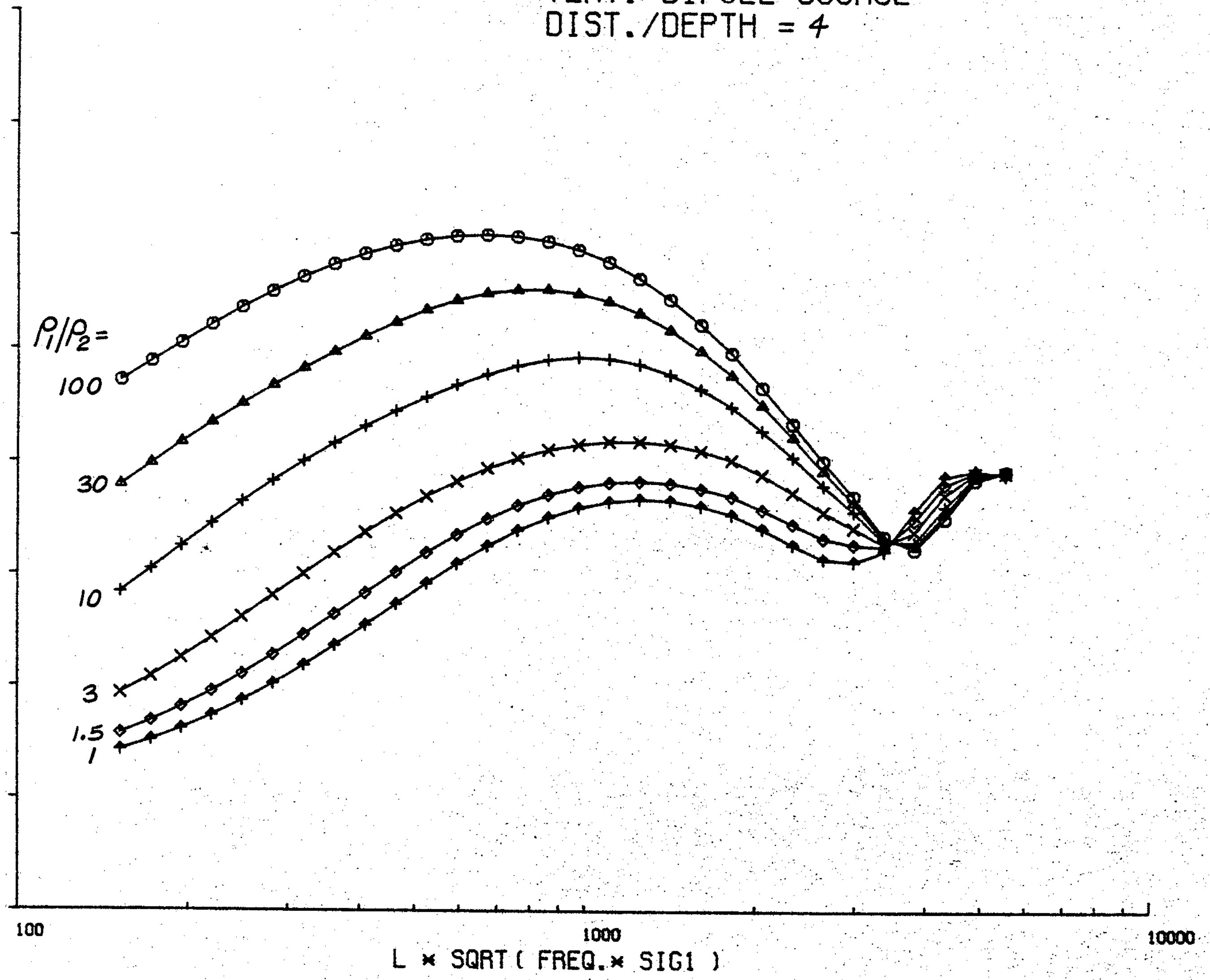

ONE LAYER EARTH
VERT. DIPOLE SOURCE
DIST./DEPTH = 16
ρ_1/ρ_2=
100
30
10
3
1.5
1
100
1000
10000
L × SQRT (FREQ. × SIG1)

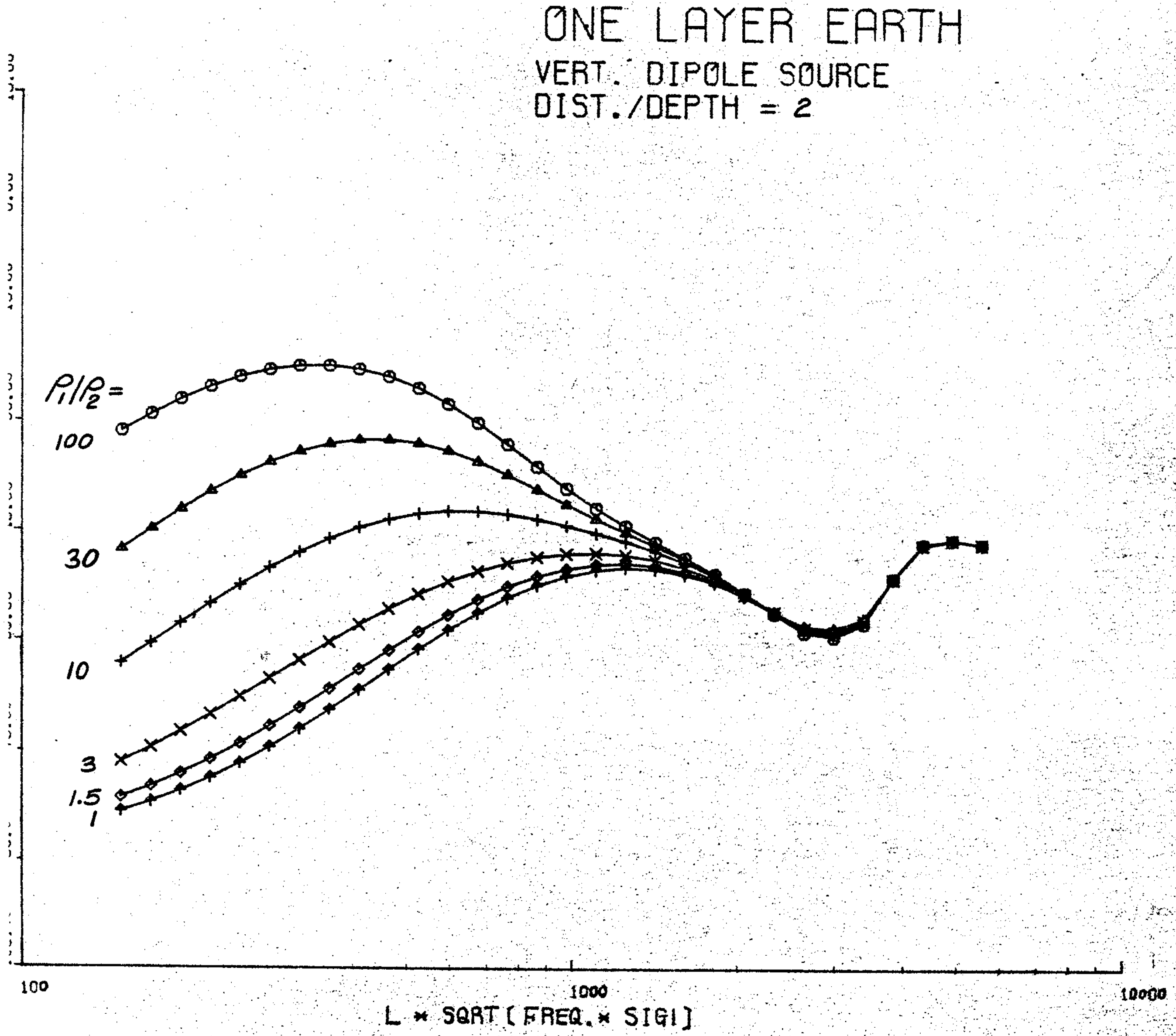

ONE LAYER EARTH
VERT. DIPOLE SOURCE
DIST./DEPTH = 8


ØNE LAYER EARTH
VERT. DIPØLE SØURCE
DIST./DEPTH = 5.5
$\rho_1/\rho_2=$
100
30
10
3
1.5
1
100
1000
10000
L * SQRT (FREQ.* SIG1)

ØNE LAYER EARTH

VERT. DIPØLE SØURCE
DIST./DEPTH = 4




ONE LAYER EARTH
VERT. DIPOLE SOURCE
DIST./DEPTH = 2
$\rho_1/\rho_2 =$
100
30
10
3
1.5
1
100
1000
10000
L * SQRT[FREQ. * SIG1]