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OPERATING MANUAL

for

EM16R VLF RESISTIVITY METER
(Attachment to EM16)

Revised Jan. 1979

EM16R - VLF Resistivity Meter (Attachment to EM16)

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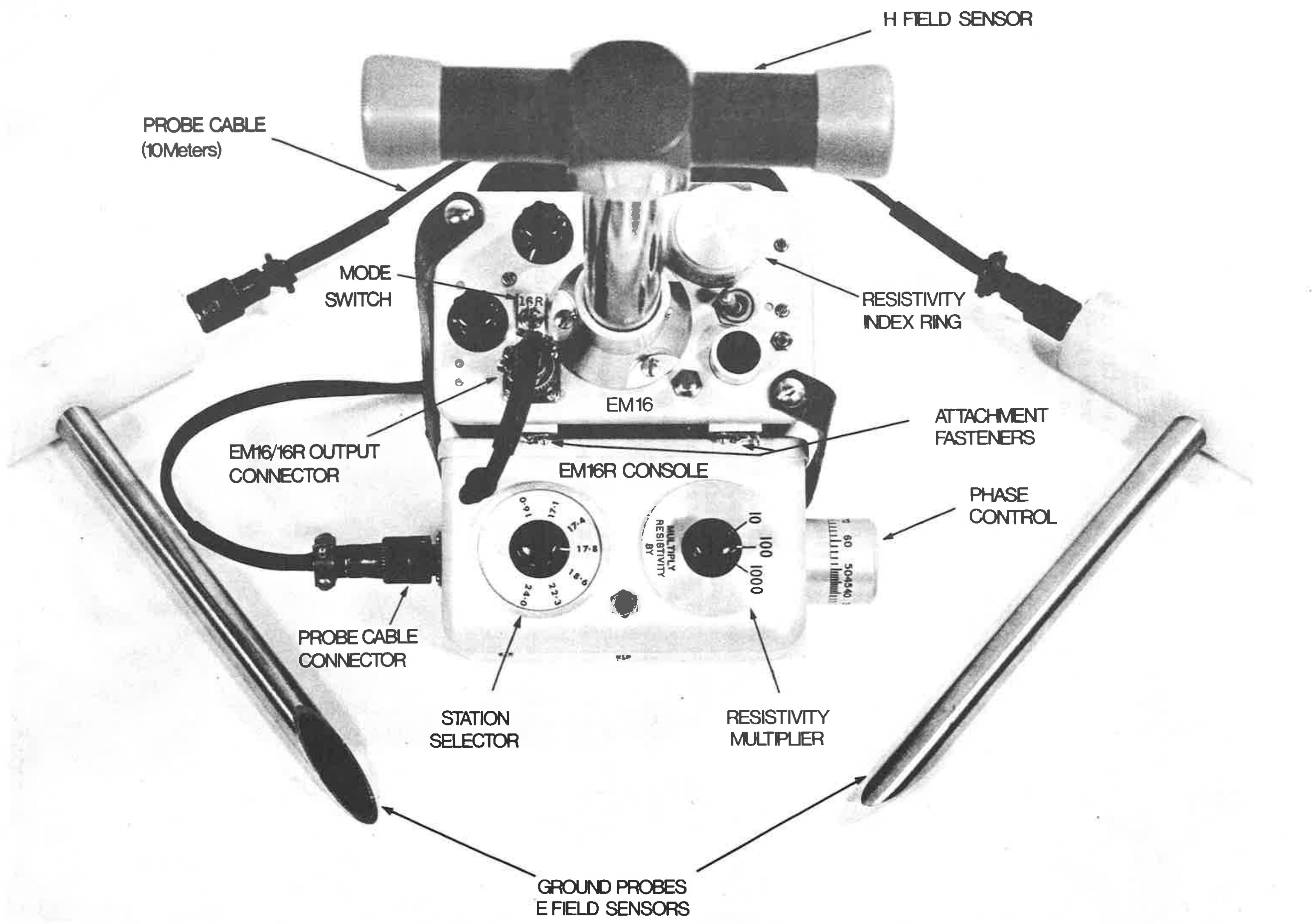
EM16R SPECIFICATIONS

MEASURED QUANTITY	•Apparent Resistivity of the ground in ohm-meters •Phase angle between E_x and H_y in degrees
RESISTIVITY RANGES	• 10 - 300 ohm-meters • 100 - 3000 ohm-meters •1000 - 30000 ohm-meters
PHASE RANGE	0-90 degrees
RESOLUTION	•Resistivity: ± 2% full scale •Phase : ± 0.5^{o}
OUTPUT	Null by audio tone. Resistivity and phase angle read from graduated dials.
OPERATING FREQUENCY	15-25 kHz VLF Radio Band. Station selection by means of rotary switch.
INTERPROBE SPACING	10 meters
PROBE INPUT IMPEDANCE	100 MΩ in parallel with 0.5 picofarads
DIMENSIONS	19 x 11.5 x 10 cm. (attached to side of EM16)
WEIGHT	1.5 kg (including probes and cable)


H FIELD SENSOR
PROBE CABLE (10Meters)
MODE SWITCH
RESISTIVITY INDEX RING
EM16
ATTACHMENT FASTENERS
EM16/16R OUTPUT CONNECTOR
EM16R CONSOLE
PHASE CONTROL
MULTIPLY RESISTIVITY BY
10 100 1000
PROBE CABLE CONNECTOR
STATION SELECTOR
RESISTIVITY MULTIPLIER
GROUND PROBES E FIELD SENSORS

FIELD PROCEDURE

1. Mounting of The EM16R Console To The EM16 Unit

Align the EM16R console, in respect to the EM16 cover, so that the station selector on the console is close to the EM16R output receptacle on the EM16 control plate. See photograph on facing page.

To mount the console on the EM16 use 4 stud fasteners.

To connect the EM16 console with the EM16 electrically, plug the EM16R console output plug in the corresponding receptacle on the EM16 control panel.

2. Orientation

The instrument measures resistivity along a line in the same direction as the station. After a VLF transmitting station has been selected EM16 is used to determine the direction to the transmitter.

The MODE selector switch is thrown to EM16, and the QUADRATURE/RESISTIVITY dial is turned to zero. With the two receiver coils in the handle of the EM16 in a horizontal plane, with the EM16R unit underneath, turn the whole instrument in a horizontal plane until the station signal goes to null. At this time the long axis of the EM16 handle (signal coil) is pointing towards the station, and the short axis (reference coil) is maximum coupled to the magnetic field. Switch mode to EM16R.

The EM16 QUADRATURE Knob zero line is used as a cursor for the EM16R RESISTIVITY Index ring, and the EM16R RESISTIVITY Index ring zero line is the cursor for the EM16R QUADRATURE Knob.

All EM16 calibrations are in black, all EM16R calibrations are in red.

3. Taking a Reading

To take a reading, orient the unit so that the shorter handle arm is at the right angle to the direction of the station and in the horizontal plane, as described in 2.

For convenience and stability the instrument can be laid on the ground during the reading, with the EM16R console beneath. Connect the probes to the EM16R console receptacle through the 10 meters long probe cable.

Ensure that the station selector switch on the EM16 and EM16R are both turned to the desired station frequency.

Push the probes into the ground 10 metres apart in the direction of the station, that is to say aligned with the long axis of the handle. The cable end with a red marker sleeve goes to the probe nearest the top of the EM16 instrument case, the unmarked cable goes to the probe off in the direction of the EM16 coil handle. Set the resistivity multiplier switch to x1000 position, rotate the EM16R RESISTIVITY CONTROL (same knob as for QUADRATURE when using EM16) for minimum sound intensity in the speaker.

Turn the phase control knob on the EM16R console to further minimize the sound.

Resistivity is read from the position of the red zero line on the quadrature dial against the red numerals on the index ring. Multiply by 1000 in this case to obtain actual resistivity in ohm meters.

If the number on the resistivity index ring is 3 or less, use a lower resistivity multiplier scale and re-do the nulling procedure.

The x10 resistivity multiplier scale should be used in the case of a resistivity reading of 300 ohm meters or less.

Record the phase angle by which the measured electrical field component leads the reference magnetic field component. This is 45^{o} for homogeneous conditions, as when the depth of the layer being measured is more than one or two skin depths. When a lower layer more resistive is present the phase angle will generally decrease, and increases when a more conductive layer is present.

GEONICS LIMITED

TECHNICAL NOTE TN-1

EM16R (RADIOHM) Two-Layer Interpretation Curves

INTRODUCTION

This technical note provides a series of graphs, which permit the user of the Geonics EM16R to determine whether the subsurface electrical resistivity is constant down to the depth of penetration of the instrument or whether a two-layer situation is present. Furthermore, in the case of a two-layered earth, if either the resistivity of the upper layer or the lower layer, or the thickness of the upper layer is known, the use of these curves yields the value of the other two unknown parameters.

Typical applications of the EM16R using these curves might include determining the presence and depth of permafrost, locating and determining the depth to resistive gravel deposits or bedrock, and correcting the data from horizontal-loop electromagnetic surveys for the presence of a conductive overburden to yield more accurate values for the depth and conductivity-thickness product of subsurface conductors.

HOMOGENEOUS HALF SPACE

The EM16R measures the ratio and the phase angle between the horizontal electric and magnetic fields of the wave propagated by distant VLF radio transmitters in order to determine the electrical resistivity of the ground. In the case where the earth is of uniform resistivity there is a phase angle of 45° between these field components.

EM16R (RADIOHM) Two-Layer Interpretation Curves

The EM16R is calibrated to read resistivity and this phase angle directly and in the case where the earth is of uniform resistivity down to the depth of penetration it reads the correct resistivity and indicates a phase angle of 45°. This effective depth of penetration depends both on the electrical resistivity itself and very slightly on the frequency, as is shown in figure 1. If the terrain resistivity is 1000 ohm meters the instrument effectively senses down to at least 100 meters or 330 ft., if the resistivity be 200 ohm meters the penetration depth is 45 meters or 145 ft.

Should the results of the survey indicate a measured value of resistivity ρ_a and a phase angle of 45° the use of figure 1 will yield a minimum depth to which that value of resistivity is correct i.e. should the survey result give a value of 1500 ohm meters and a phase angle of approximately 45° the user knows that the resistivity is 1500 ohm meters down to at least 120 meters or 390 ft.

TWO-LAYER GEOMETRY

Suppose, however, that horizontal stratification exists and the earth is better represented by the geometry shown in figure 2. If the thickness of the upper layer t_1 is greater than the corresponding depth of penetration shown for the value ρ_1 on figure 1 the EM16R will still correctly read the value of ρ_1. If, however, the value of t_1 is less then the depth of penetration two things will happen. Firstly, the value of resistivity read by the instrument will no longer be the true value of ρ_1, since it will be influenced by the presence of ρ_2, and secondly, the phase angle will no longer be 45°. A value for this angle of other than 45° is always the key to a multi-layered earth situation.

Since the resistivity indicated by the instrument is no longer the correct resistivity we shall call it the apparent resistivity. Referring again to figure 2 it is seen that there are now three unknown quantities vis ρ_1, ρ_2, and t_1. The EM16R measures only two pieces of information, the apparent resistivity ρ_a, and the phase angle. Therefore, in the general case we are missing one piece of information and this must be supplied by the user. Let us assume for the time being that survey has been carried out in an environment which is represented by figure 3. When the operator was at station "A" he measured a resistivity of 600 ohm meters and a phase angle of 45°. He, therefore, knew that the earth was homogenous at 600 ohm meters down to a depth of at least 88 meters or 290 ft. At station "B" the instrument read 330 ohm meters and a phase angle of 68°. The operator assumes from a knowledge of the geology that the upper layer resistivity is still 600 ohm meters. To interprete this situation under the assumption of a two-layer case reference must be made to figures 4 through 13. Each of these figures refers to a different value of ρ_1 as seen in the upper right hand corner. Turning to the figure for ρ_1 equals 600 ohm meters (figure 8) we would use the curve in the following manner: locate on the vertical axis the reading of apparent resistivity as shown by the EM16R, locate on the horizontal axis the value of phase angle as shown by the EM16R. At the intersection of these two points read off from the parametric curve the value for the thickness of the upper layer and the resistivity of the lower layer. For example, suppose that the apparent resistivity shown by the EM16R was 330 ohm meters and the phase angle 68°. The intersection of these values on figure 8 indicates a value for the thickness of the upper layer of 40 meters and a resistivity for the lower layer of 30 ohm meters.

Conversely, had the instrument readings at station "B" been 5400 ohm meters with a phase angle of 32^{o} we would know that the resistivity of the lower layer was 10,000 ohm meters and that the layer thickness was 7 meters. This second example might be typical of a permafrost environment in which measurements were carried out in the discontinuous zone, and the high resistivity might then be indicative of massive ground ice. It should be noted that each of the curves for the various values of ρ_2 terminate at a phase angle of 45^{o} to $\rho_a = \rho_2$. Thus if it is desired to interpolate between the various curves for a different value of ρ_2 one starts the curve at the corresponding value for ρ_a i.e. should we require a curve for 5000 ohm meters the start for this curve would occur at a phase angle of 45^{o} and a value for apparent resistivity of 5000 ohm meters, and the curve can then be easily sketched in using the curve for 10,000 and 3000 ohm meters as models.

The example given above assumed that the known quantity was ρ_1, since nearby measurements had given this value and a phase angle of 45^{o}. In the case where the operator assumes that he knows ρ_2 (for example the bedrock resistivity) and wishes to determine ρ_1 and t_1 the various figures are examined to determine which gives values of apparent resistivity and phase angle which agree with the measured values; ρ_1 and t_1 are then read off the appropriate figure. For example, the operator knows the bedrock resistivity to be approximately 3000 ohm meters from nearby outcrops. In an other area he measured an apparent resistivity of 1000 ohm meters and a phase angle of 31^{o}. A scan of the two layer curves shows that figure 8 gives a best fit to the data and thus the upper layer resistivity is 600 ohm meters and the depth of bedrock approximately 35 meters.

LIMITING CASES

It was stated above that, in the general case, one of the unknown quantities would have to be supplied by the operator. It will now be shown that in two limiting cases the interpretation curves give only two pieces of information.

Consider for example the lower region of figures 7 to 14. For all of these cases ρ_2 is much less than ρ_1, i.e. the lower layer is the more conductive. Comparison of these figures shows that for this case the values of ρ_a and phase angle are a function of ρ_2 and t_1 only and are independent of ρ_1. Thus, for the case of a highly conductive lower layer the EM16R yields the lower layer resistivity and the upper layer thickness independently of the resistivity of the upper layer.

Consider now the upper region of figures 5 and 6 for which ρ_2 is much greater than ρ_1 and the upper layer is much thinner that the penetration depth as given by figure 1. Suppose that the instrument reads an apparent resistivity of 1800 ohm meters and a phase angle of 18^o. Figure 5 would lead to ρ_1 = 30 ohm meters, ρ_2 = 10,000 ohm meters, and t_1 = 1.2 meters. But figure 6 would yield ρ_1 = 100 ohm meters, ρ_2 = 10,000 ohm meters, and t_1 = 4.0 meters. Thus there is an ambiguity in the intepretation; however, if we divide t_1 by ρ_1 in each case we find that for both cases we obtain t_1/ρ_1 = 0.040 mhos = σ_1 t_1. In the case where the upper layer is both thin and highly conductive relative to the lower layer the results of the EM16R give the resistivity of the lower layer and the conductivity thickness product of the upper layer, which is often a useful result. If a knowledge of the upper layer resistivity is available from other sources (i.e. an adjacent reading where the earth is not two-layered as indicated by a 45^o phase angle) it is then, of course, possible to separate out the thickness of the upper layer.

Finally, another very useful application of the EM16R occurs in the case where we can consider the lower layer to be much more resistive than the upper layer and the upper layer is also assumed to be relatively thick. This case can arise if a thick layer of conductive overburden overlies resistive bedrock. Such a geometry can introduce serious errors in the interpretation of horizontal-loop electromagentic surveys (i.e. Geonics EM17 or EM17L). It has been shown by Lowrie and West (Geophysics, Volume 30, Number 4, August 1965, pp 624-632) that the presence of a conductive overburden rotates the phasor diagram, which is used for the interpretation of such survey results so as to make the conductor appear to be more deeply buried than it is and also to appear to be a better conductor in the sense that the ratio of inphase to quadrature response is enhanced. This effect is particularly strong at large intercoil spacing i.e. 400 ft.

For example, assume such a survey is carried out with 400 ft. intercoil spacing and that a vertical conductor is overlain by 7 meters of 10 ohm meter material. The conductivity thickness product for the overburden is then 0.7 mhos. The Argand diagram for this case would be rotated by approximately 25°. Suppose that the peak to peak inphase and quadrature phase amplitudes were 20% and 9% respectively. Ignoring the presence of the overburden would result in estimates of the depth and conductivity thickness of 120 ft. and 13 mhos. If, however, the correction factor for the overburden is taken into account the reinterpreted depth and conductivity thickness product are 80 ft. and 3.6 mhos so that substantial errors can result from ignoring the effect of the overburden. Referring to figure 4 it is seen that the EM16R with the two-layer interpretation curves easily resolves up to 10 meters of 10 ohm meter material and that furthermore the interpreted thickness of this material is relatively independent of the assumed resistivity for the basement rock. Figure 15 is a re-compilation of the two-layer curves for $\rho_2 = \infty$ and the caption on this figure illustrates a simple procedure to determine the conductivity-thickness product directly from the EM16R results.

FREQUENCY CORRECTION

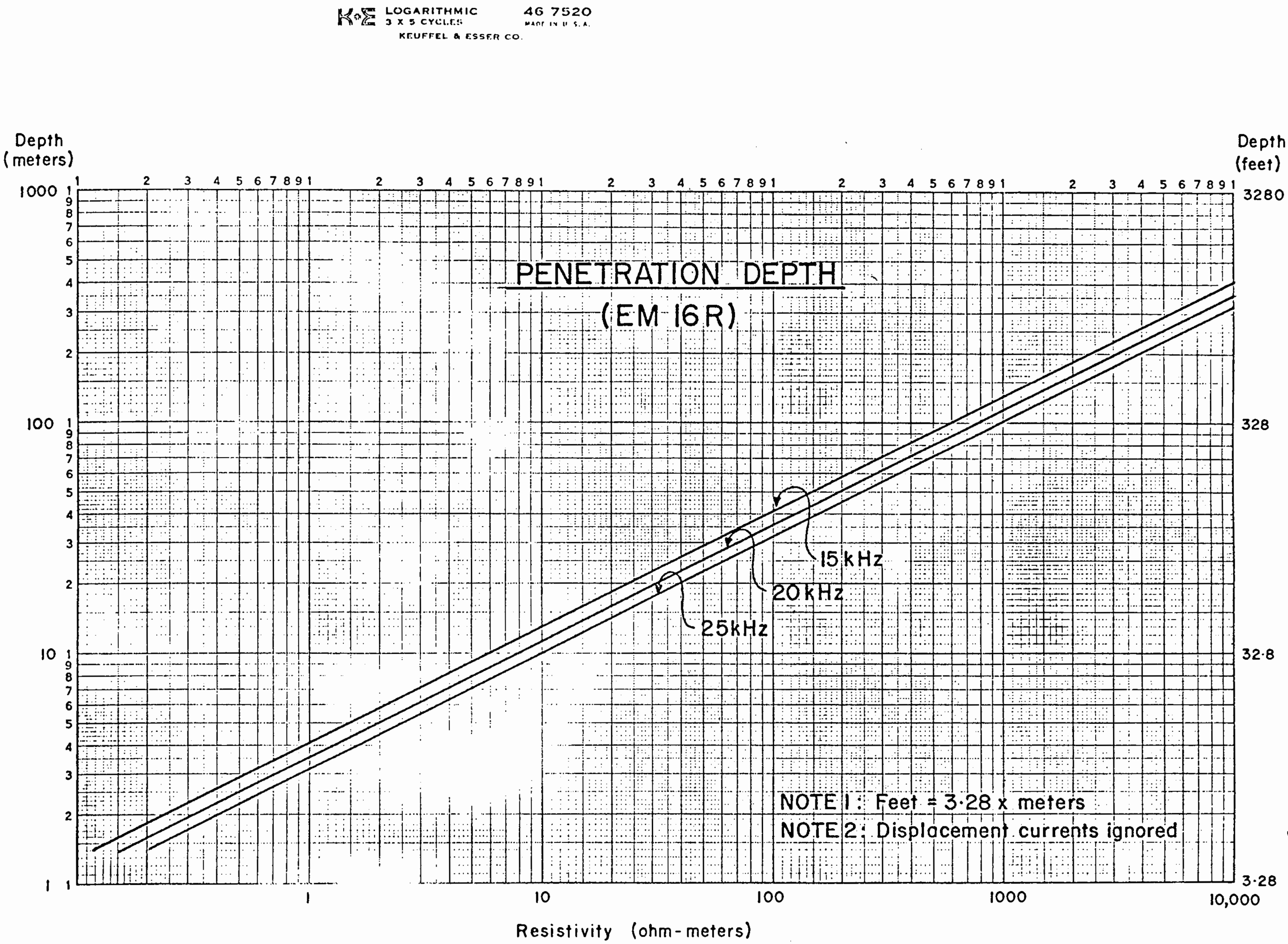
These curves have been calculated for a frequency of 20 kHz. Should a station operating at a frequency of other than 20 kHz be employed the values of thickness and conductivity-thickness will be slightly in error. Figure 14 gives the correction factor for both as a function of station frequency.

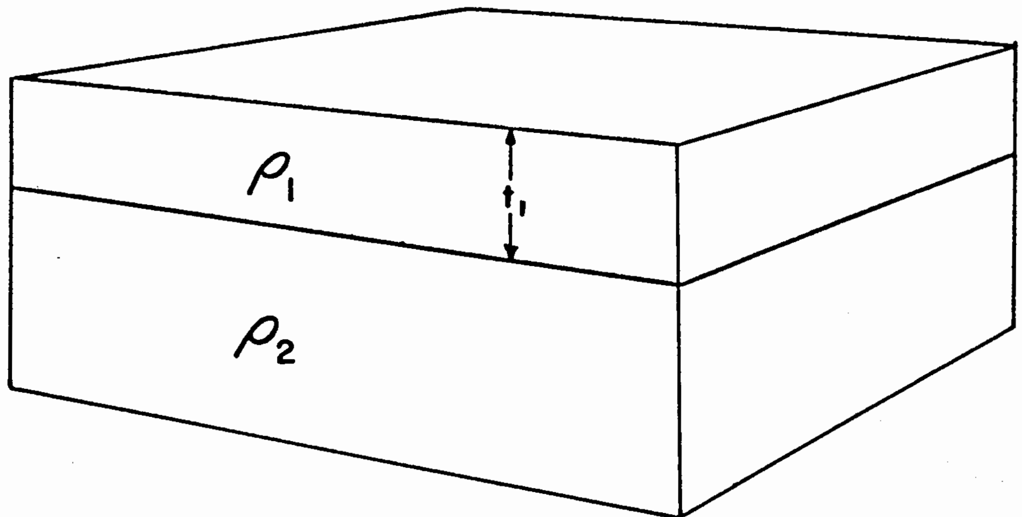
The two-layer curves are given for a reasonable selection of values of ρ_1. Should it be necessary to operate inbetween these values it is suggested that the relevent data from the bracketing figures be plotted out and interpolation carried through.

EM16R (RADIOHM) Two-Layered Interpretation Curves

SUMMARY

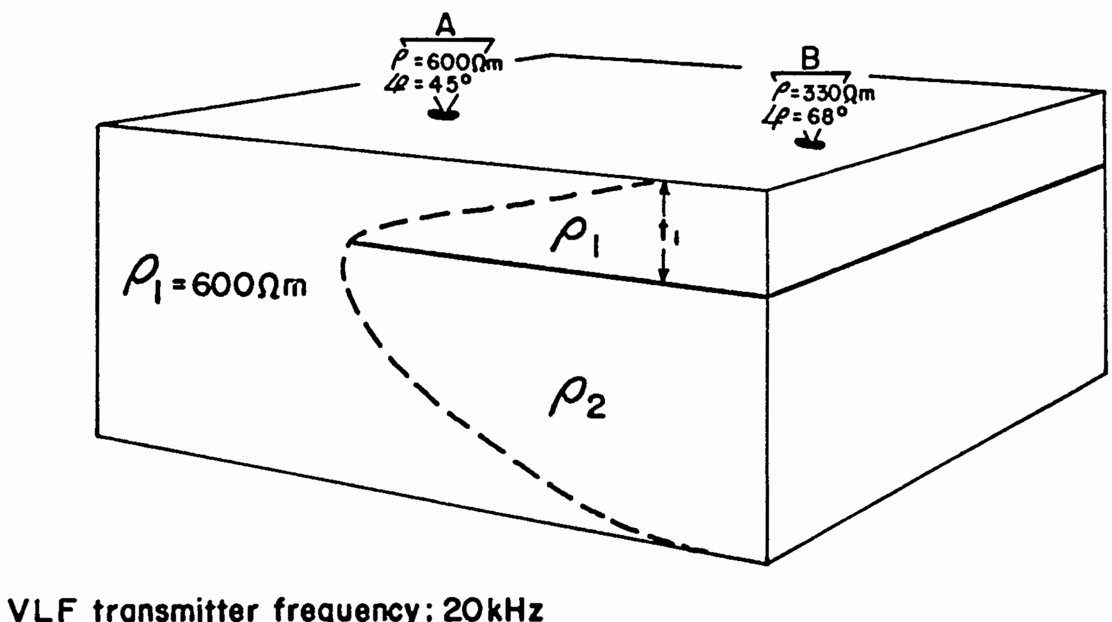
The curves presented in this note should prove useful in planning surveys, particularly for engineering geophysical applications. They illustrate the type of environment in which the EM16R will prove to be effective as well as those in which conventional resistivity may have to be employed. It is hoped that this technical note will assist owners of the Geonics EM16R in obtaining more useful data from their survey results. The principle advantages of the Geonics EM16R are the simplicity of the measurement technique and the speed with which it can be carried out, added to the fact that is is a one-man operation. These curves show that in many cases of practical interest the use of the EM16R will produce survey data which is almost equivalent to that with normal resistivity gear at a fraction of the cost and at much higher speed.


K+E LOGARITHMIC 3 X 5 CYCLES KEUFFEL & ESSER CO. 46 7520 MADE IN U.S.A.
PENETRATION DEPTH
(EM 16R)
15 kHz
20 kHz
25 kHz
NOTE 1: Feet = 3·28 x meters
NOTE 2: Displacement currents ignored
Depth (meters)
Depth (feet)
Resistivity (ohm-meters)
1
10
100
1000
10,000
3·28
32·8
328
3280



ρ1
t1
ρ2

Fig. 2



A
ρ = 600Ωm
φ = 45°
B
ρ = 330Ωm
φ = 68°
ρ1
t1
ρ1 = 600Ωm
ρ2
VLF transmitter frequency: 20kHz

Fig. 3

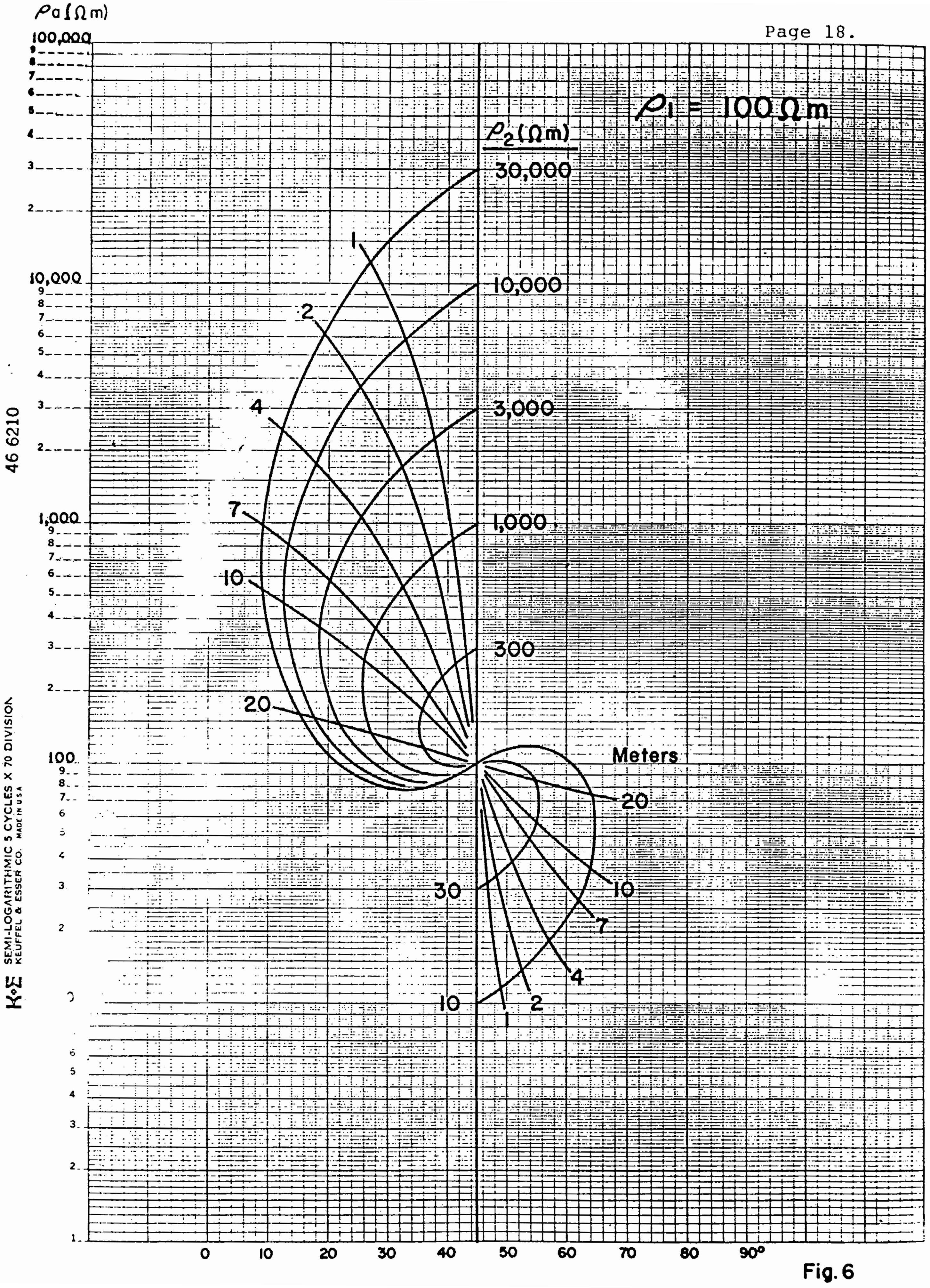

ρa (Ωm)
ρ1 = 100 Ωm
ρ2 (Ωm)
30,000
10,000
3,000
1,000
300
30
10
Meters
1
2
4
7
10
20
100,000
10,000
1,000
100
0
10
20
30
40
50
60
70
80
90°
46 6210
K&E SEMI-LOGARITHMIC 5 CYCLES X 70 DIVISION
KEUFFEL & ESSER CO. MADE IN U.S.A.

Fig. 6

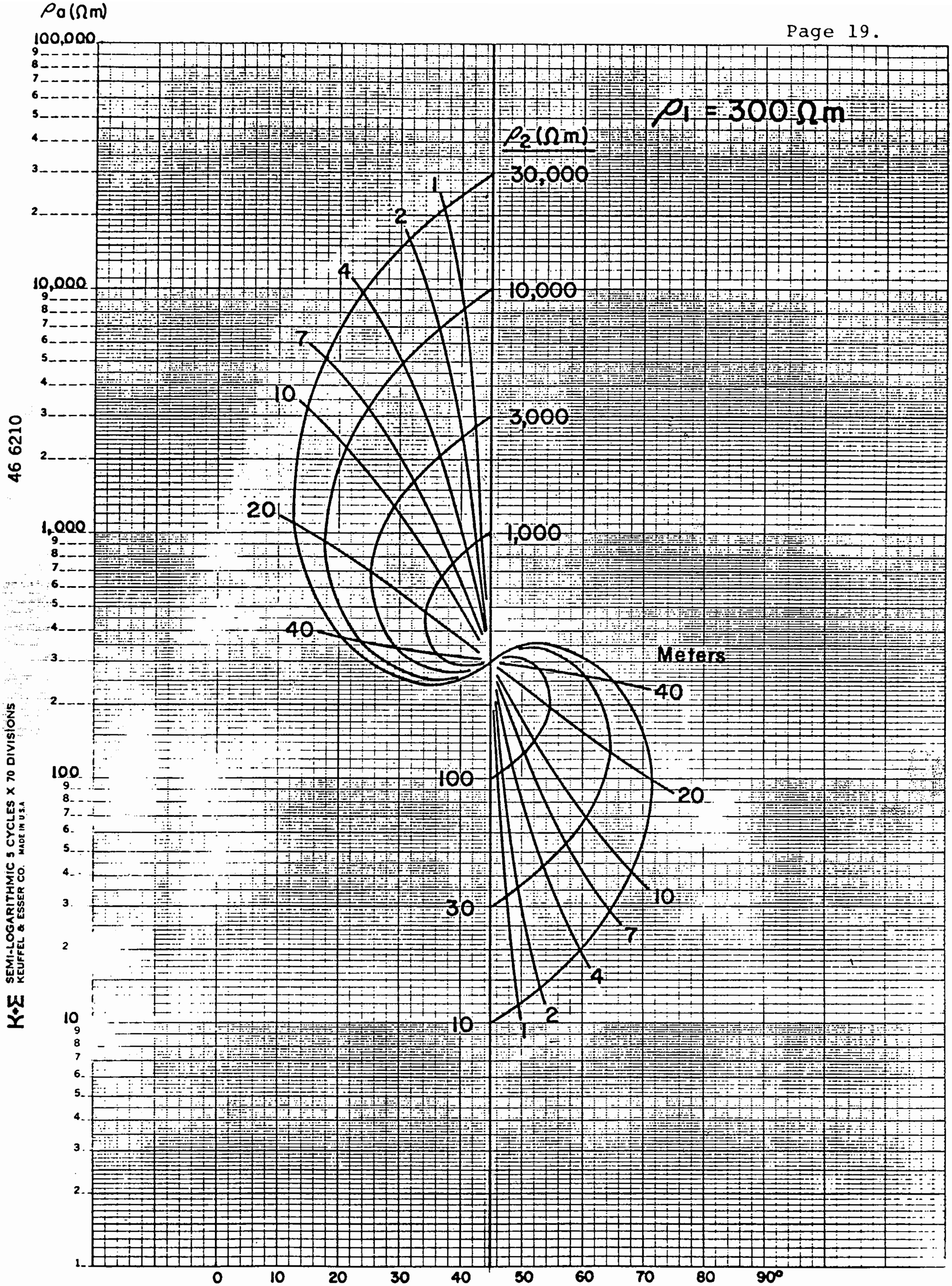

ρa (Ωm)
100,000
10,000
1,000
100
10
1
ρ1 = 300 Ωm
ρ2 (Ωm)
30,000
10,000
3,000
1,000
100
30
10
Meters
1
2
4
7
10
20
40
0
10
20
30
40
50
60
70
80
90°
46 6210
K+E SEMI-LOGARITHMIC 5 CYCLES X 70 DIVISIONS
KEUFFEL & ESSER CO. MADE IN U.S.A.

Fig. 7

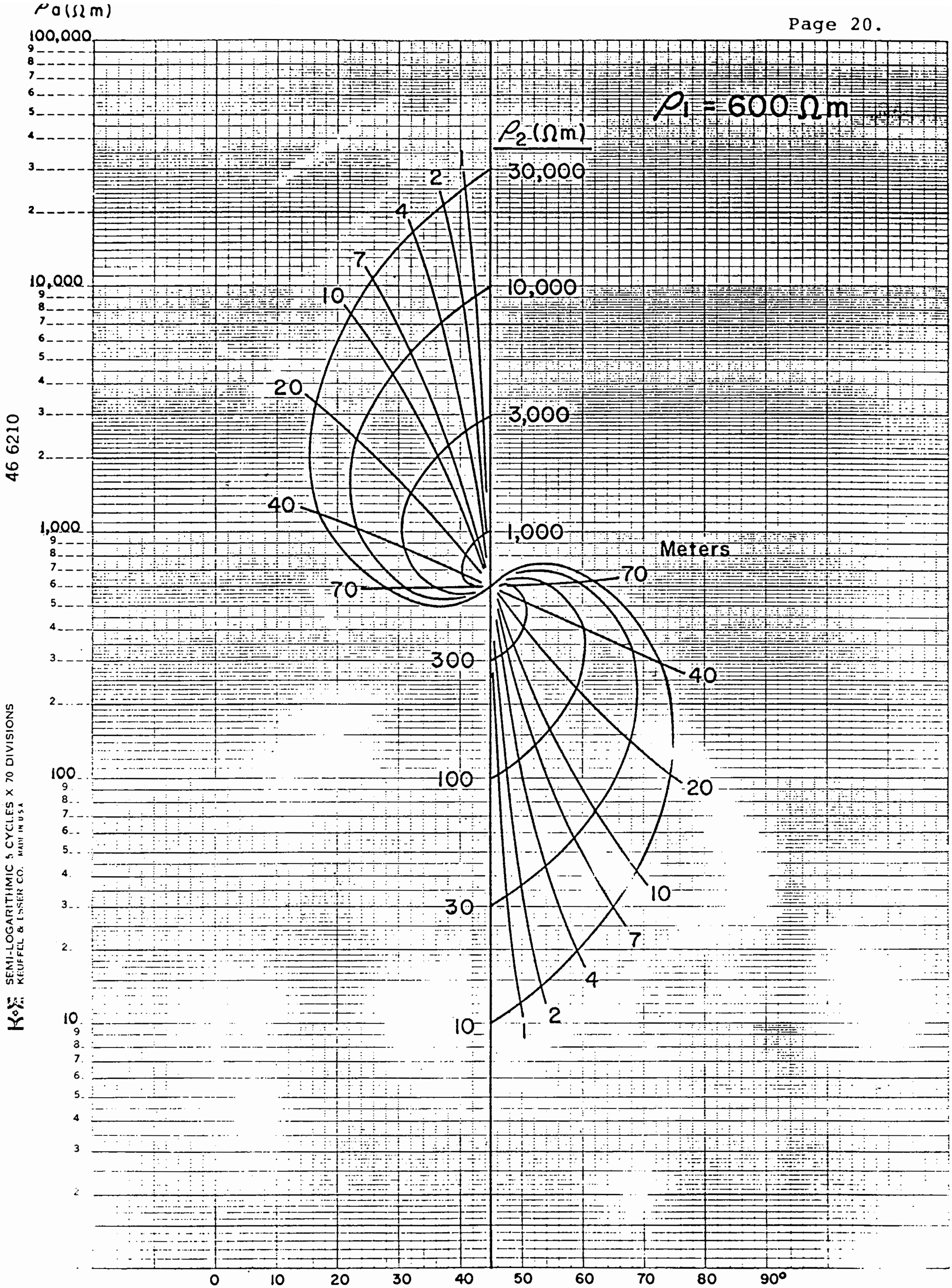
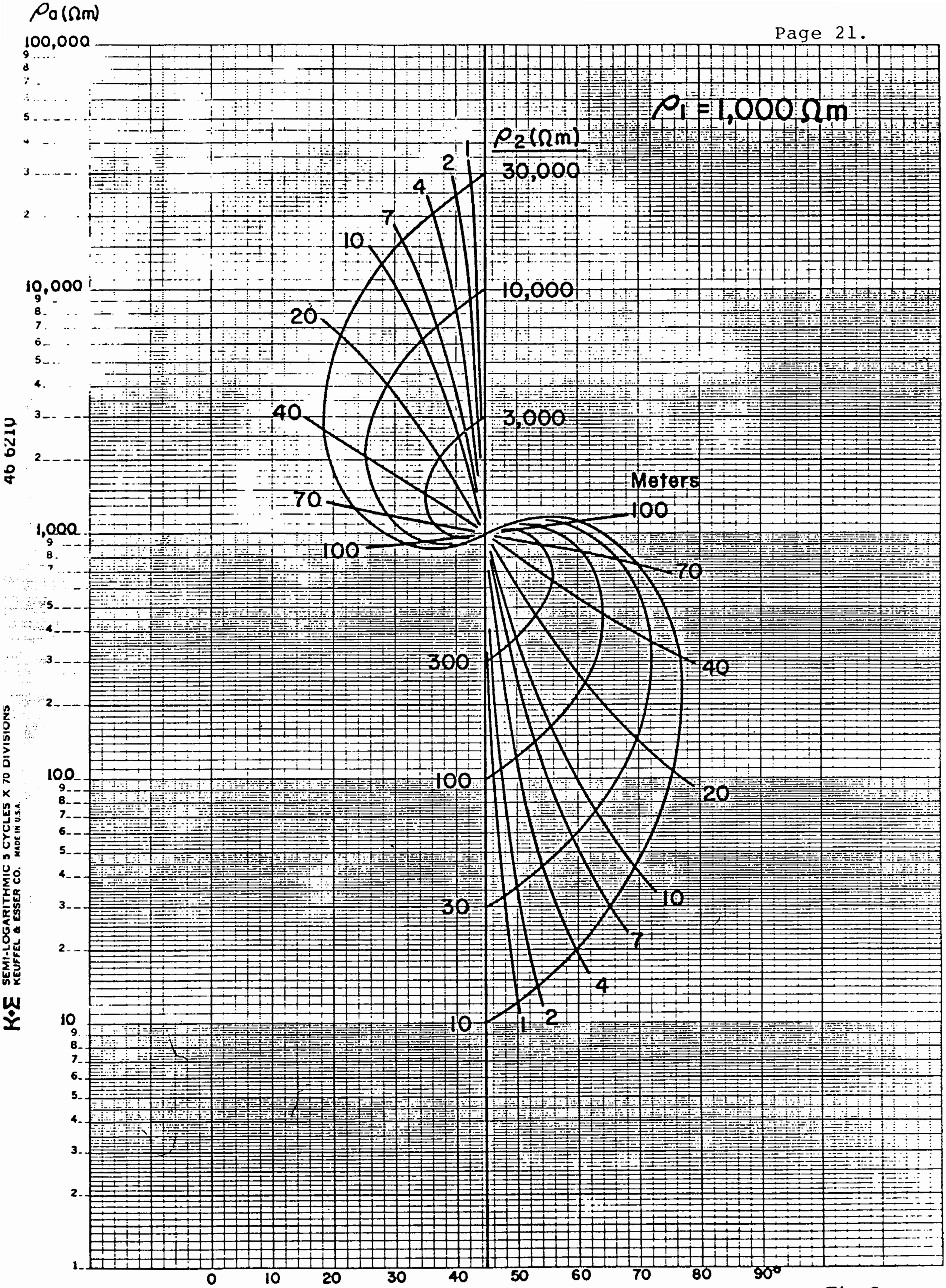

ρa (Ωm)
100,000
10,000
1,000
100
10
ρ1 = 600 Ωm
ρ2 (Ωm)
30,000
10,000
3,000
1,000
300
100
30
10
1
2
4
7
10
20
40
70
Meters
0
10
20
30
40
50
60
70
80
90°
46 6210
K&E SEMI-LOGARITHMIC 5 CYCLES X 70 DIVISIONS
KEUFFEL & ESSER CO. MADE IN U.S.A.

Fig.



ρ_a (Ωm)
100,000
10,000
1,000
100
10
ρ_1 = 1,000 Ωm
ρ_2 (Ωm)
30,000
10,000
3,000
300
100
30
10
Meters
1
2
4
7
10
20
40
70
100
0
10
20
30
40
50
60
70
80
90°
46 6210
K&E SEMI-LOGARITHMIC 5 CYCLES X 70 DIVISIONS
KEUFFEL & ESSER CO. MADE IN U.S.A.

Fig. 9

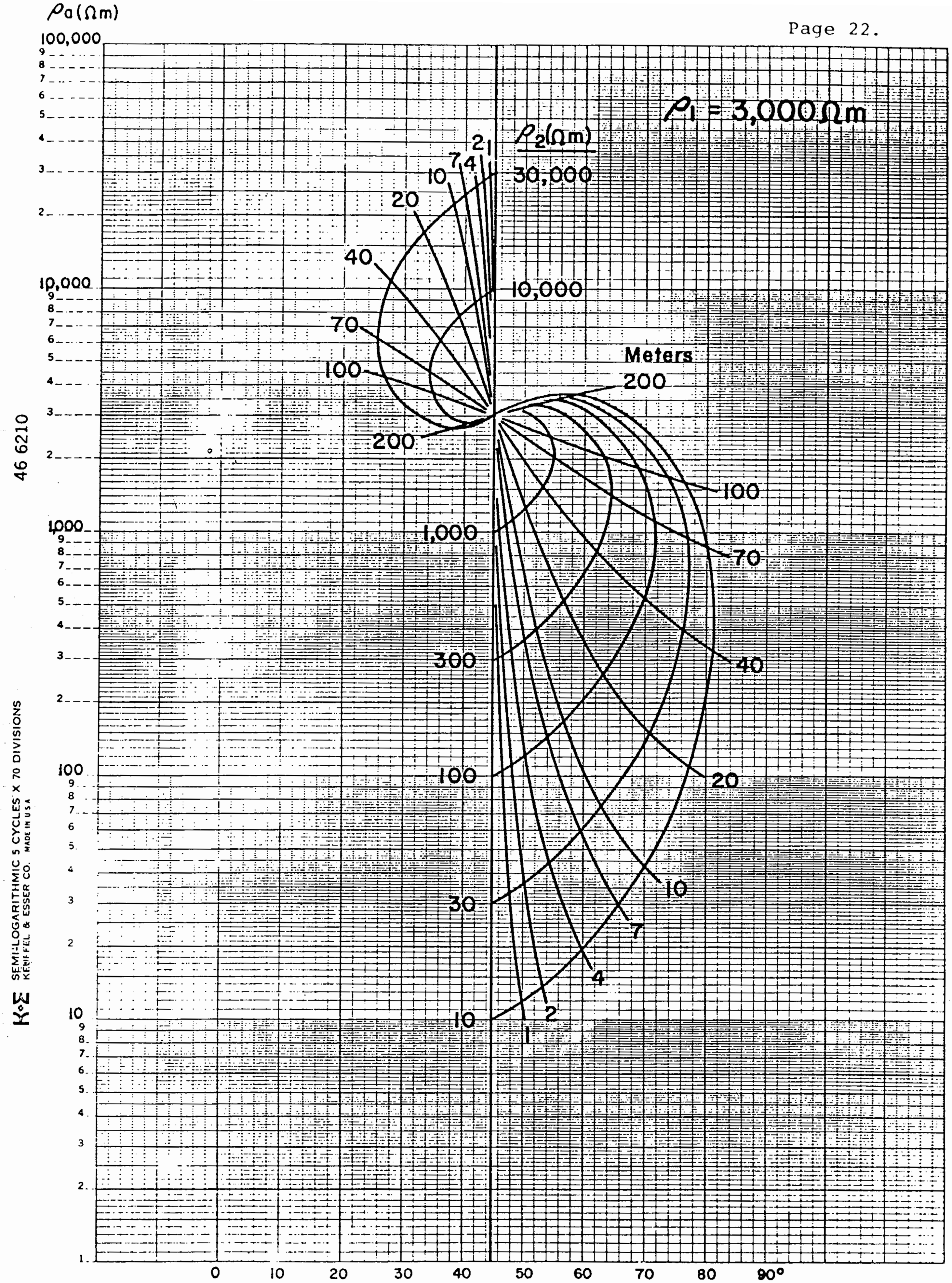

ρa (Ωm)
ρ1 = 3,000 Ωm
ρ2 (Ωm)
30,000
10,000
1,000
300
100
30
10
Meters
200
100
70
40
20
10
7
4
2
1
0
10
20
30
40
50
60
70
80
90°
46 6210
K·E SEMI-LOGARITHMIC 5 CYCLES X 70 DIVISIONS
KEUFFEL & ESSER CO. MADE IN U.S.A.

Fig. 10

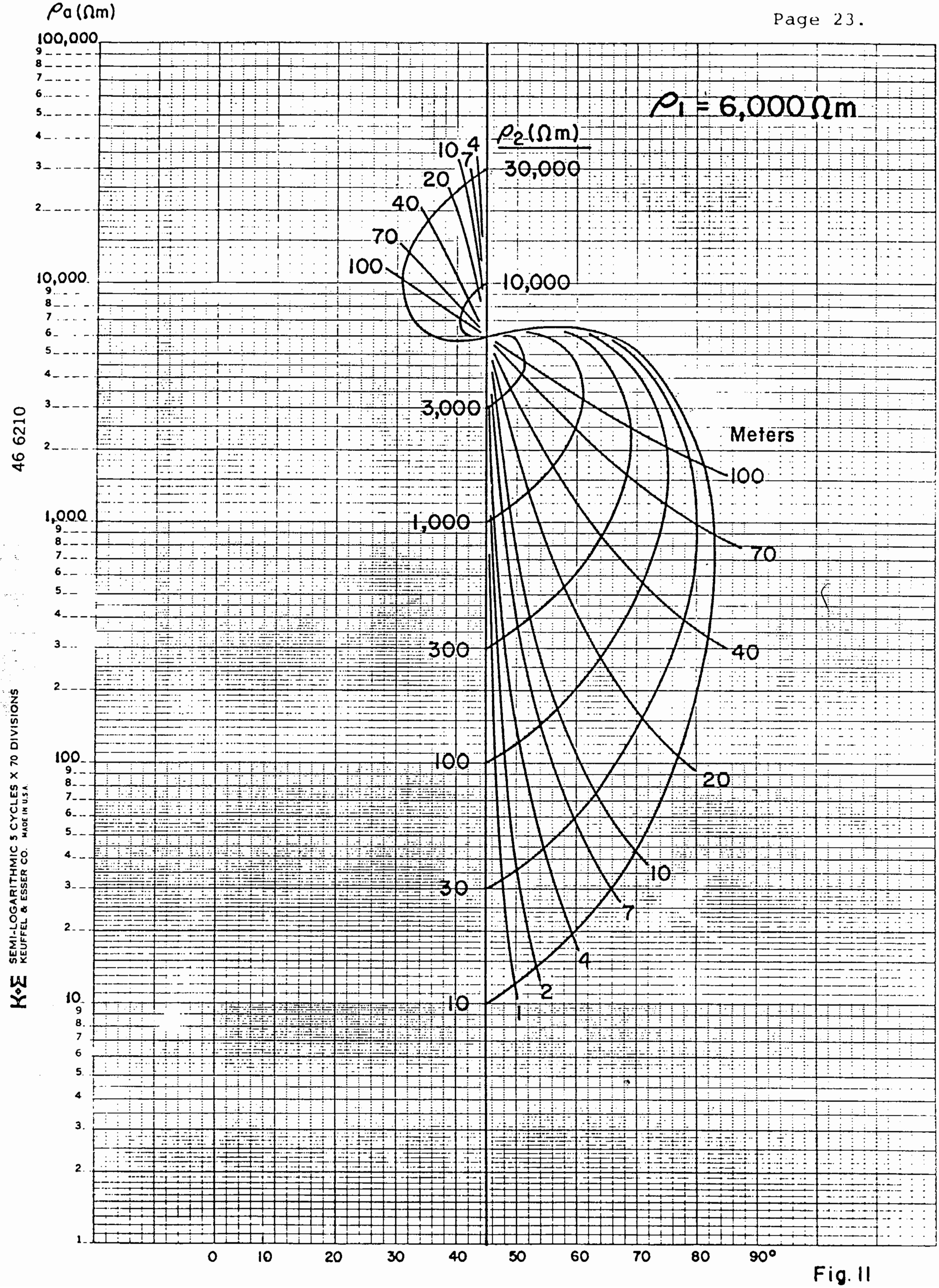

ρa (Ωm)
ρ1 = 6,000 Ωm
ρ2 (Ωm)
30,000
10,000
3,000
1,000
300
100
30
10
Meters
100
70
40
20
10
7
4
2
1
0 10 20 30 40 50 60 70 80 90°
KξE SEMI-LOGARITHMIC 5 CYCLES X 70 DIVISIONS
KEUFFEL & ESSER CO. MADE IN U.S.A.
46 6210

Fig. 11

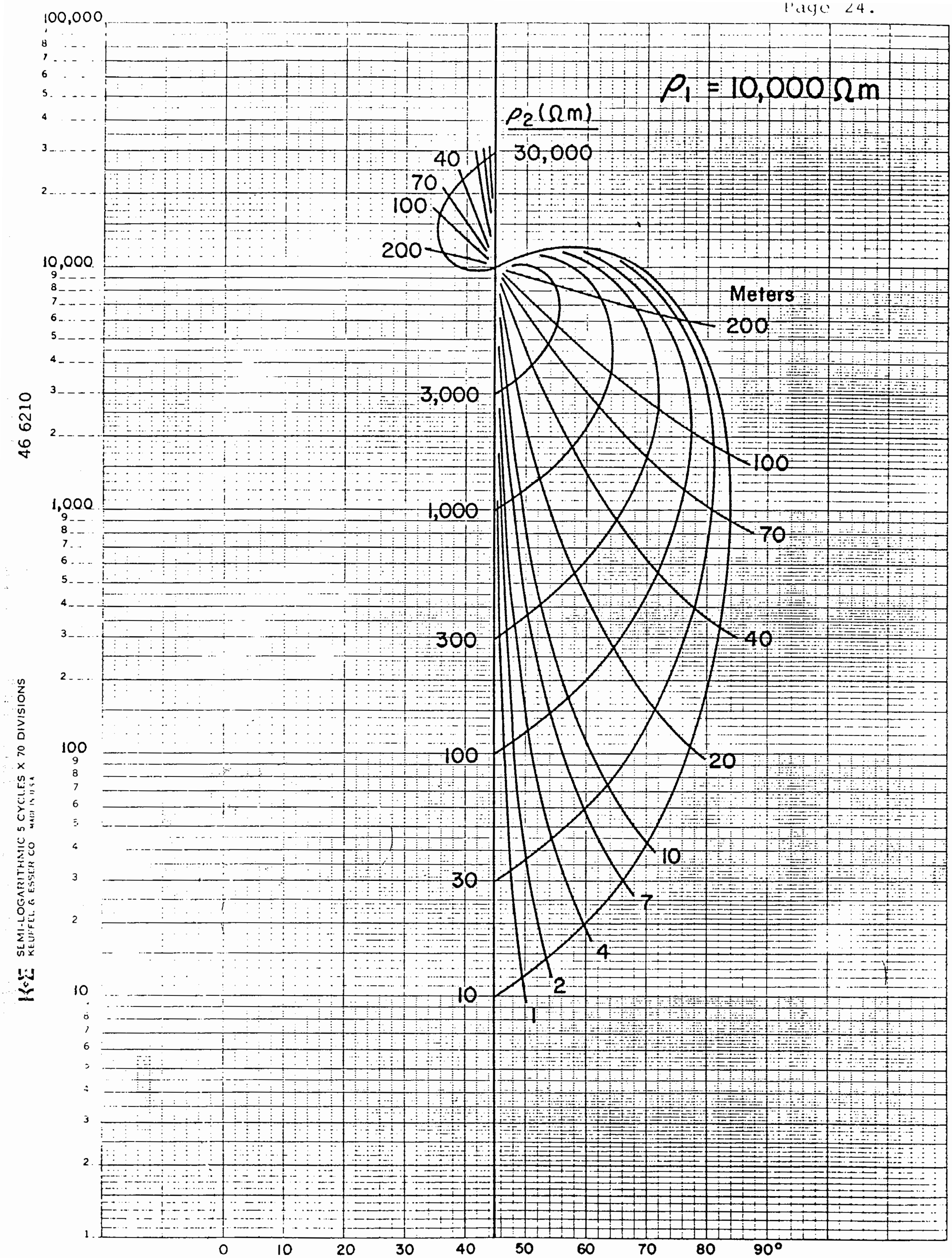
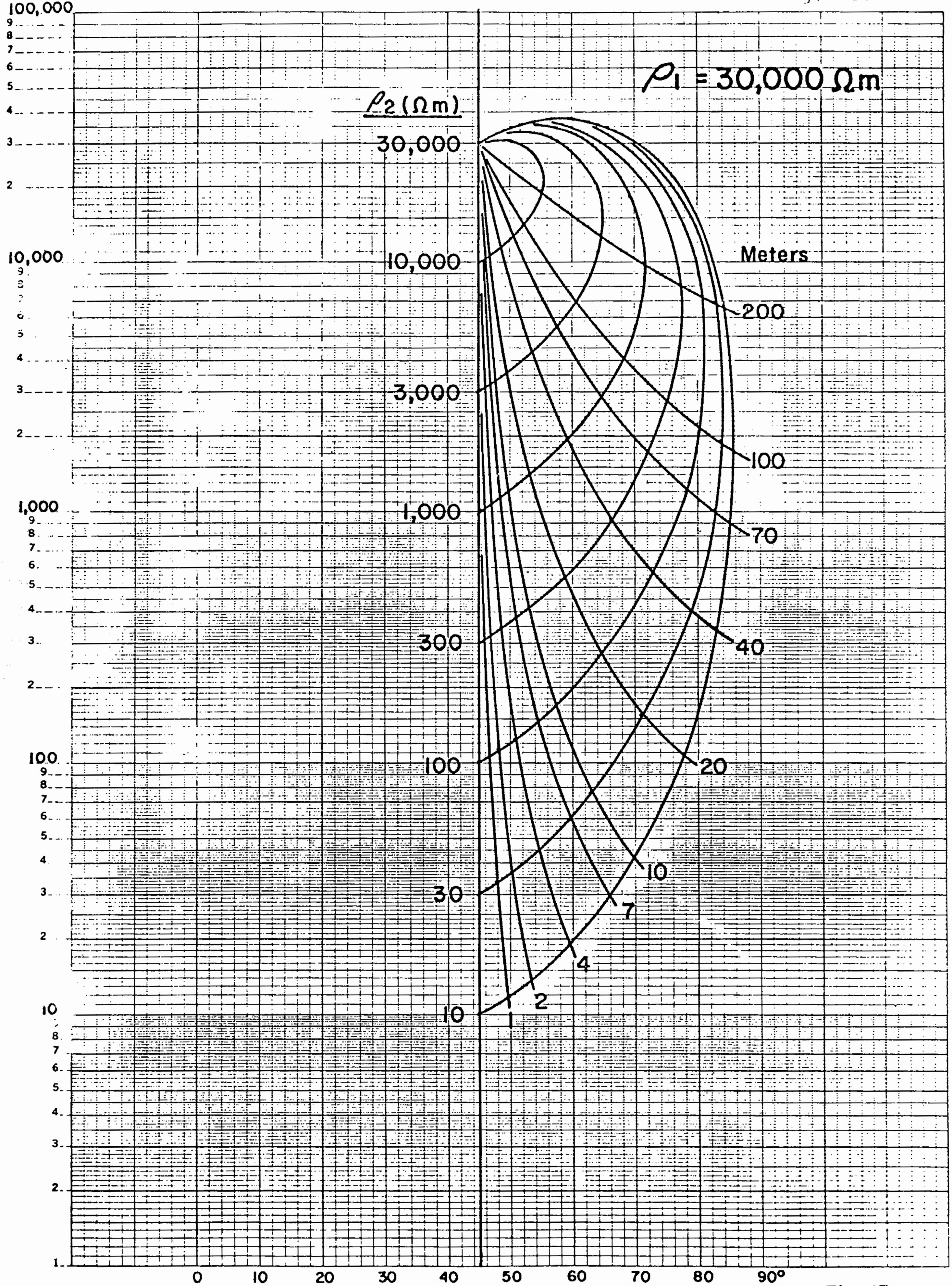

ρ1 = 10,000 Ωm
ρ2 (Ωm)
30,000
40
70
100
200
Meters
200
3,000
100
1,000
70
300
40
100
20
10
30
7
4
2
10
1
100,000
10,000
1,000
100
10
0
10
20
30
40
50
60
70
80
90°
46 6210
SEMI-LOGARITHMIC 5 CYCLES X 70 DIVISIONS
KEUFFEL & ESSER CO. MADE IN U.S.A.

Fig. 12



ρ_1 = 30,000 Ωm
ρ_2 (Ωm)
Meters
100,000
10,000
1,000
100
10
30,000
10,000
3,000
1,000
300
100
30
10
200
100
70
40
20
10
7
4
2
1
0
10
20
30
40
50
60
70
80
90°

Fig. 13.

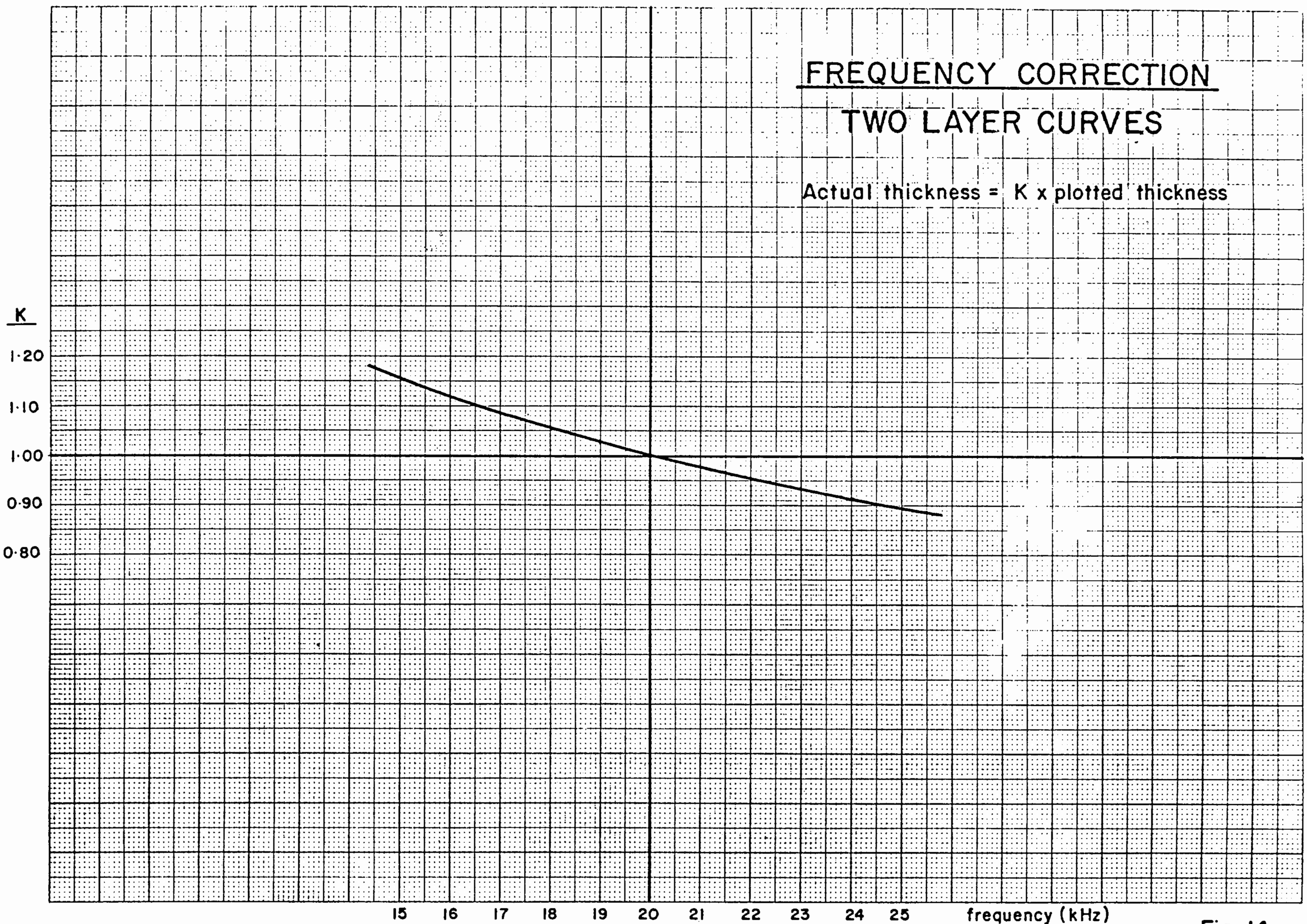
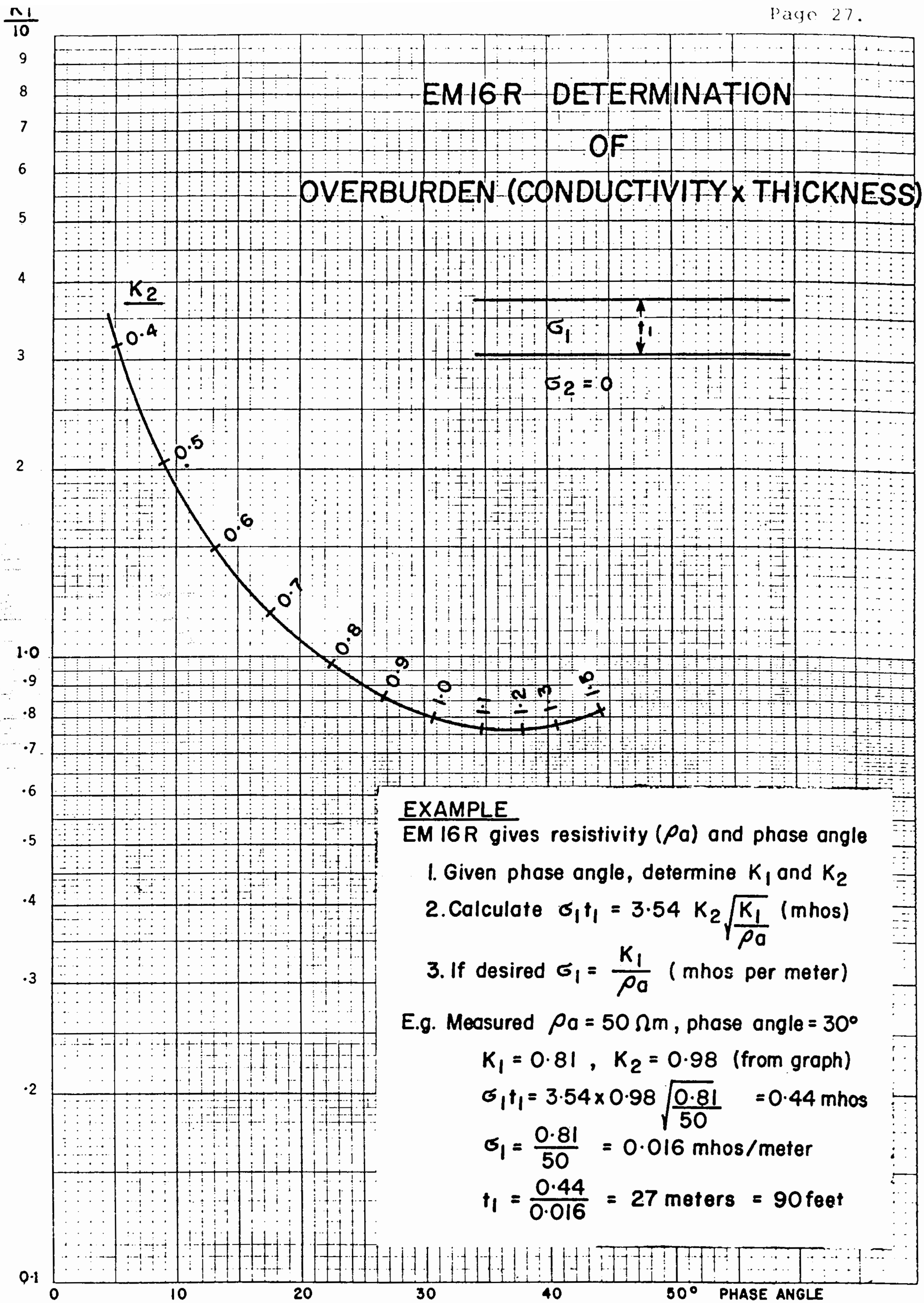

FREQUENCY CORRECTION
TWO LAYER CURVES
Actual thickness = K x plotted thickness
K
1·20
1·10
1·00
0·90
0·80
15
16
17
18
19
20
21
22
23
24
25
frequency (kHz)

Fig. 14



EXAMPLE

EM 16R gives resistivity (ρa) and phase angle

1. Given phase angle, determine K_1 and K_2
2. Calculate $\sigma_1 t_1 = 3{\cdot}54 \; K_2 \sqrt{\frac{K_1}{\rho a}}$ (mhos)
3. If desired $\sigma_1 = \frac{K_1}{\rho a}$ (mhos per meter)

E.g. Measured $\rho a = 50 \, \Omega m$, phase angle $= 30°$

$K_1 = 0{\cdot}81$, $K_2 = 0{\cdot}98$ (from graph)

$\sigma_1 t_1 = 3{\cdot}54 \times 0{\cdot}98 \sqrt{\frac{0{\cdot}81}{50}} = 0{\cdot}44$ mhos

$\sigma_1 = \frac{0{\cdot}81}{50} = 0{\cdot}016$ mhos/meter

$t_1 = \frac{0{\cdot}44}{0{\cdot}016} = 27$ meters $= 90$ feet

Fig. 15

Field Data Inversion - Two-Layer Earth Model

An interesting formulation for the inversion of EM16R-type data was described in the paper "VLF Magnetotellurics in Ore Exploration and Structural Geology" by Grissemann and Reitmayr* and delivered at the 48th SEG Meeting in San Francisco. With their kind permission the algorithm is given here. Programs for both the HP65 and the HP67 are also included.

Consider a two-layered earth in which

ρ_1 is the resistivity of the upper layer
t is the thickness of the upper layer
ρ_2 is the resistivity of the substrate

Measurement with the EM16R yields two quantities viz. the apparent resistivity and the phase angle, thus one of the three unknowns must be assumed. The technique described herein assumes that ρ_1 is known or assumed, and that ρ_2 and t are to be determined.

The algorithm is as follows:

Given	ρa	- apparent resistivity (Ω m)
	ψ	- phase angle (degrees)
	ρ_1	- upper layer resistivity (Ω m)
	f	- known frequency of the VLF station (Hz)
To find	t	- upper layer thickness (m)
	ρ_2	- substrate resistivity (Ω m)

$$k = \frac{\rho a}{\rho_1}$$

$$ReQ = \sqrt{k}\cos(45 - \psi)$$

$$A = \sqrt{\frac{k+1 - 2\ ReQ}{k+1 + 2\ ReQ}} \qquad \text{if } \psi < 45^0$$

$$= -\sqrt{\frac{k+1 - 2\ ReQ}{k+1 + 2\ ReQ}} \qquad \text{if } \psi > 45^0$$

* Christoph Grissemann & Gernot Reitmayr
Bundesanstalt für Geowissenschaften und Rohstoffe
Postfach 510153
3000 Hannover, F.R.Germany

$$\alpha = \cos^{-1}\left[\frac{ReQ-1+A^2\ (ReQ+1)}{2A\ ReQ}\right]$$

$$t = \frac{\alpha}{\sqrt{\dfrac{4\pi\cdot f\cdot 4\pi x10^{-7}}{\rho_1}}}$$

$$L = A\exp(\alpha);$$ if $|L|>1$ data does not fit two-layer theory

$$\rho_2 = \left[\frac{1+L}{1-L}\right]^2 \rho_1$$

HP 65 Program

1) Key in the program. DSP 3

2) Calculate $\sqrt{\dfrac{1.579 \times 10^{-2}\ f(kHz)}{\rho_1}}$ STO 4

3) ρa (Ω m) STO 1

4) ψ (deg) STO 2

5) ρ_1 (Ω m) STO 3

6) Press A whence

   (a) ρ_2 is indicated on the display

   (b) t is stored in register 5

7) In the event that the data does not fit two-layer theory a flashing zero will be indicated by the display. Press any key to stop.

8) Store new data in registers 1-3 and recalculate by pressing A again.

9) Note: In the event that a new value for ρ_1 is adopted do not forget to recalculate the quantity in (2) above.

HP 65 PROGRAM LISTING

Variables ρa, ψ , ρ_1, f (Ω m, degrees, kHz)

0 3144 CLRPGM

1	23	LBL	26	51	−	51	71	x	76	01	1
2	11	A	27	41	↑	52	3406	RCL6	77	3522	x≤y
3	3401	RCL1	28	41	↑	53	61	+	78	00	0
4	3403	RCL3	29	3406	RCL6	54	01	1	79	81	÷
5	81	÷	30	04	4	55	51	−	80	3406	RCL6
6	3305	STO5	31	71	x	56	3406	RCL6	81	61	+
7	35	g	32	61	+	57	81	÷	82	01	1
8	41	DEG	33	81	÷	58	3407	RCL7	83	3406	RCL6
9	04	4	34	31	f	59	81	÷	84	51	−
10	05	5	35	09	√	60	02	2	85	81	÷
11	3402	RCL2	36	3307	STO7	61	81	÷	86	41	↑
12	51	−	37	3402	RCL2	62	32	f^{-1}	87	71	x
13	31	f	38	04	4	63	05	Cos	88	3403	RCL3
14	05	Cos	39	05	5	64	3308	STO8	89	71	x
15	3405	RCL5	40	3522	x≤y	65	3404	RCL4	90	24	RTN
16	31	f	41	3501	NOP	66	81	÷	91	23	LBL
17	09	√	42	12	B	67	3305	STO5	92	12	B
18	71	x	43	35	g	68	3408	RCL8	93	01	1
19	3306	STO6	44	42	RAD	69	32	f^{-1}	94	42	CHS
20	3405	RCL5	45	3406	RCL6	70	07	e^x	95	33	STO
21	01	1	46	01	1	71	3407	RCL7	96	71	x
22	61	+	47	61	+	72	71	x	97	07	7
23	3406	RCL6	48	3407	RCL7	73	3306	STO6	98	24	RTN
24	02	2	49	41	↑	74	35	g	99		
25	71	x	50	71	x	75	06	ABS	100		

HP 67 Program

1) Key in the program. gSCI , DSP 3

2) f (kHz) STO O

3) Press A.
When the 1.000 appears key in $\rho a (\Omega\ m)$, press R/S
When the 2.000 appears key in ψ (deg), press R/S
When the 3.000 appears key in $\rho_1 (\Omega\ m)$, press R/S

4) On completion of the program running ρ_2 $(\Omega\ m)$ will display for about 5 seconds, followed by t (m) for about 5 seconds. The program then automatically displays the 1.000 indicated in (3) above for the entry of the new value of ρa etc. In the event that copying down of either ρ_2 or t was not achieved, ρ_2 is available in register 6 and t is available in register 5.

5) In the event that the data does not fit two-layer theory an ERROR will be displayed. Press A twice and the 1.000 will reappear for the entry of new data.

HP 67 PROGRAM LISTING

Variables ρa, ψ, ρ_1, f (Ω m, degrees, kHz)

1	312511	LBLA	31	51	–	61	81	÷	91	61	+
2	01	1	32	41	↑	62	02	2	92	01	1
3	84	R/S	33	41	↑	63	81	÷	93	3406	RCL6
4	3301	STO1	34	3406	RCL6	64	3263	Cos^{-1}	94	51	–
5	02	2	35	04	4	65	3308	STO8	95	81	÷
6	84	R/S	36	71	x	66	3400	RCL0	96	41	↑
7	3302	STO2	37	61	+	67	01	1	97	71	x
8	03	3	38	81	÷	68	83	•	98	3403	RCL3
9	84	R/S	39	3154	$\sqrt{\ }$	69	05	5	99	71	x
10	3303	STO3	40	3307	STO7	70	07	7	100	3306	STO6
11	3541	DEG	41	3402	RCL2	71	09	9	1	3184	-x-
12	3401	RCL1	42	04	4	72	43	E EXP	2	3405	RCL5
13	3403	RCL3	43	05	5	73	42	CHS	3	3184	-x-
14	81	÷	44	3271	x≤y	74	02	2	4	2211	GTOA
15	3305	STO5	45	312212	GSBB	75	71	x	5	312512	LBLB
16	04	4	46	3542	RAD	76	3403	RCL3	6	01	1
17	05	5	47	3406	RCL6	77	81	÷	7	42	CHS
18	3402	RCL2	48	01	1	78	3154	$\sqrt{\ }$	8	337107	STOx7
19	51	–	49	61	+	79	81	÷	9	3522	RTN
20	3163	Cos	50	3407	RCL7	80	3305	STO5	10	312513	LBLC
21	3405	RCL5	51	41	↑	81	3408	RCL8	11	00	0
22	3154	$\sqrt{\ }$	52	71	x	82	3252	e^x	12	81	÷
23	71	x	53	71	x	83	3407	RCL7	13		
24	3306	STO6	54	3406	RCL6	84	71	x	14		
25	3405	RCL5	55	61	+	85	3306	STO6	15		
26	01	1	56	01	1	86	3564	ABS	16		
27	61	+	57	51	–	87	01	1	17		
28	3406	RCL6	58	3406	RCL6	88	3271	x≤y	18		
29	02	2	59	81	÷	89	312213	GSBC	19		
30	71	x	60	3407	RCL7	90	3406	RCL6	120		

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Reprint From

GEOLOGICAL SURVEY OF CANADA

Paper 75-1 Part A

Report of Activities April - October 1974

64\.

VLF RESISTIVITY (RADIOHM) SURVEY, AGRICOLA LAKE AREA, DISTRICT OF MACKENZIE

Project 670041

W. J. Scott
Resource Geophysics and Geochemistry Division

Introduction

During the last week of July 1974, a VLF resistivity survey was carried out over the Agricola Lake massive sulphide prospect. Measurements were made along the soil survey lines (Cameron, this publication, report 55, Fig. 1) using the Radiohm technique (Collett and Becker, 1968). In this technique, the apparent resistivity of the earth is determined by a magnetotelluric measurement of the radiated field from a remote radio transmitter.

The quantities measured are the horizontal components of the radial electric field (E_x) and the tangential magnetic field (H_y), and the phase difference between E_x and H_y. A value for apparent resistivity is derived from the approximate expression:

$$\rho a = \frac{1}{\mu \;\omega} \left| \frac{Ex}{Hy} \right|^2$$

ρa = the apparent resistivity in ohm-metres

where μ = the magnetic permeability of the medium (assumed = $4 \pi \times 10^{-7}$ Henrys per metre)

ω = the angular frequency of the signal $2\pi f$, where f is the frequency in h_z

The instrument used in this survey was a Geonics EM16R, which obtains H_y by means of an integral coil and E_x by means of two ground probes spaced 10 m apart. The measurement is made by orienting the instrument so that the coil is maximally coupled to H_y (determined from an audio signal) and inserting the two ground probes along the direction indicated by the

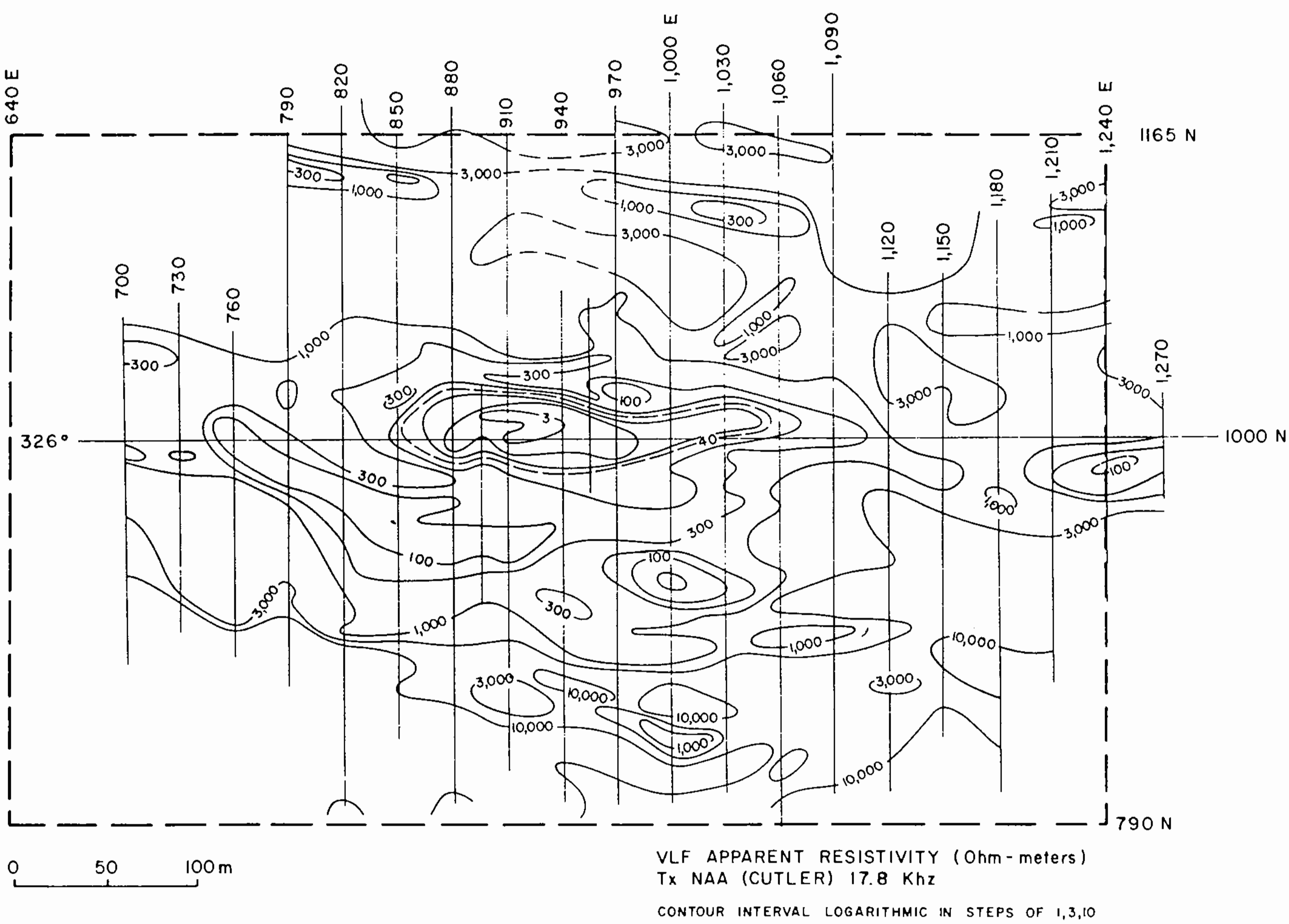

Figure 1. Contour map of VLF apparent resistivity, Agricola Lake massive sulphide prospect, N.W.T.

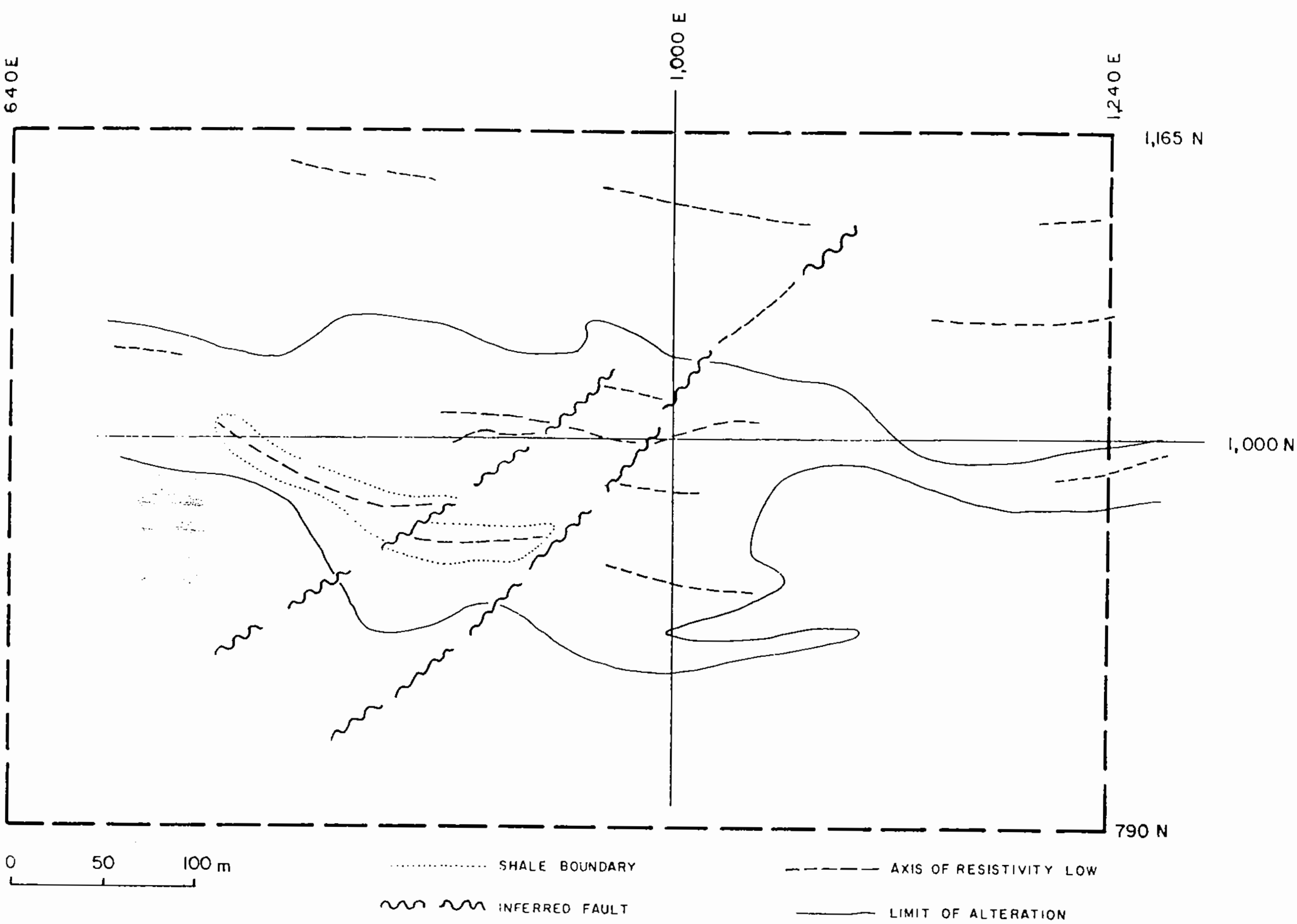

Figure 2. Geological interpretation of VLF apparent resistivity data, Agricola Lake massive sulphide prospect, N.W.T.

instrument orientation. After the audio signal is nulled by means of two controls, the phase angle and apparent resistivity values can be read directly from the instrument. The apparent transmitter azimuth may be determined from the orientation of the instrument.

For the present survey the signal utilized was from NAA, Cutler, Maine, at a frequency of 17.8 Kh_z. The transmitter azimuth was approximately parallel to the base line of the survey grid.

During four and a half field days some 900 measurements of resistivity, phase angle and transmitter azimuth were made by a crew of two, augmented at times by a third man to speed the work on rough ground. The readings were taken at intervals of 15 m on grid lines spaced at 30 m. When adjacent readings varied by a factor of 1.5 or more, intermediate readings were taken.

Results

Figure 1 shows a contour map of apparent resistivities obtained on the grid lines indicated; Figure 2 shows an interpretation based on these data. For purposes of clarity the grid lines are defined to run north-south, and the baseline east-west (true bearings notwithstanding). Directions referred to in this paper are understood to be grid directions.

The observed variation of apparent resistivities agrees in general with the preliminary geological interpretation of (*see* Cameron, op. cit., Fig. 2). In the northern part of the grid, apparent resistivities from 1000 to 4000 ohm-m reflect the presence of acid and intermediate volcanics, whose southern boundary agrees on the whole with the 1000 ohm-m contour.

Rather higher resistivities in the southern part of the grid correlate with a further sequence of acid and intermediate volcanics. In the south-central area, the 1000 ohm-m contour agrees with the northern limit of the volcanics. In the southeast, however, the resistivity data suggest that the unaltered volcanics may extend farther west beneath thin overburden, than indicated by the geological map.

The central area of low resistivity (less than 1000 ohm-m) in general coincides with the area mapped as hydrothermally altered volcanics. Within this zone are several prominent lows. Lying on the baseline from 850 E to 1060 E is a pronounced low, whose outline as shown by the dashed 40-ohm-m contour (Fig. 1) agrees with the part of the boundary of a massive sulphide zone indicated by diamond drilling by the

Yava Syndicate (Northern Miner, August 15, 1974). A small low at 990 N, 1240 E coincides with high metal values in the soil, and may be an extension of the main sulphide body.

The low trending southeast from 760 E on the baseline to 940 N, 940 E crosses a shale unit indicated by the presence of shale fragments in frost boils. In view of the lack of outcrop it is possible that the geology could be re-interpreted to place the shale member under this low as suggested in Figure 2. The results of a magnetic survey on the same grid (Kornik, this publication, report 62) support this interpretation. The low at 925 N, 1000 E appears from the magnetics not to be an extension of this feature, and may indicate a further concentration of sulphides.

The weak east-west low from 960 E to 1080 E at 1120 N coincides with rocks mapped as rusty-weathering intermediate volcanics; it is probable that the westward extension of the feature from 790 E to 870 E indicates the presence of more of this unit. A similar low from 1140 E to 1240 E at about 1060 N may also be associated with such a rock unit.

The traces of two faults trending northeast-southwest (Fig. 2) are picked on the basis of aberrations in the resistivity contours and offsets in the axes of low trends. Further faulting could probably be inferred as well, but would best be done on the basis of a combined interpretation of all the geophysical results. The two faults shown, however, are also indicated by the magnetic data (Kornik, op. cit.).

Discussion and Conclusion

Despite the fact that the area is well within the zone of continuous permafrost (Brown, 1967) there is a wide variation in apparent resistivities. For metallic sulphide mineralization this is to be expected, but it is less obvious that frozen rocks should exhibit such variation. Spot measurements on shale outcrops to the north of the grid give resistivities ranging from 10 to 200 ohm-m, while some measurements on outcrop within the zone of alteration yielded values of a few hundred ohm-m. It is reasonable to suppose that such low resistivities are the result of clay minerals in the rock, with the resultant retention of some pore water in the fluid phase, despite ground temperatures significantly below $0^{o}C$.

In the unaltered volcanics, however, particularly to the south, quite wide variations in resistivity did not appear to be related to known rock types, and subdivision of the volcanics on the basis of resistivity would at the present time appear unreliable. It is possible that further work, including laboratory measurements of resistivities at low temperatures, may clarify this problem.

The phase angle and azimuth data taken in this survey have not been shown, because they contain peculiarities which are difficult to interpret. Phase angles are theoretically limited to the range from 0 to 90 degrees, yet at a number of stations, particularly at the west end of the baseline, values much greater than 90 degrees were recorded. Strong variations were observed in the apparent azimuth of the transmitter, as indicated by the direction of H_y. It is probable that these variations are the result of the presence of a strong linear conductor in a region of generally high resistivity. It is hoped that further study will identify the cause of this variation.

The major disadvantage of VLF Radiohm measurements is the lack of penetration through any thickness of conductive overburden. In this study area, however, overburden was generally thin. There appeared to be no significant correlation of resistivity variation with the presence or absence of overburden.

The concept of Radiohm measurements, as embodied in the Geonics EM16R, is extremely useful, particularly in difficult conditions such as experienced at this site. Even in permafrost regions, there appears to be some utility in resistivity mapping as an aid to geological work.

Acknowledgments

The help of D. Eberle (Geological Survey of Germany), A. Williams (GSC), J. Williams (DOE) and Jim Thomas (GSC) in carrying out the field work is gratefully acknowledged.

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