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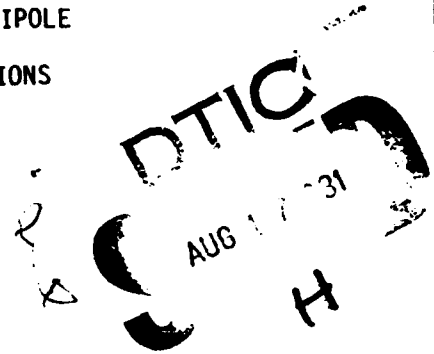


Electromagnetics Engineering Office  
Propagation Engineering Division  
Technical Report EMEO-PED-81-4

AD A102997

MUTUAL COUPLING IMPEDANCE BETWEEN THE  
HF CENTER-FED FIRST-RESONANT DIPOLE  
ANTENNA AND EARTH - NEC SOLUTIONS

By  
Harold F. Tolles



April 1981

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MILES A. MERKEL  
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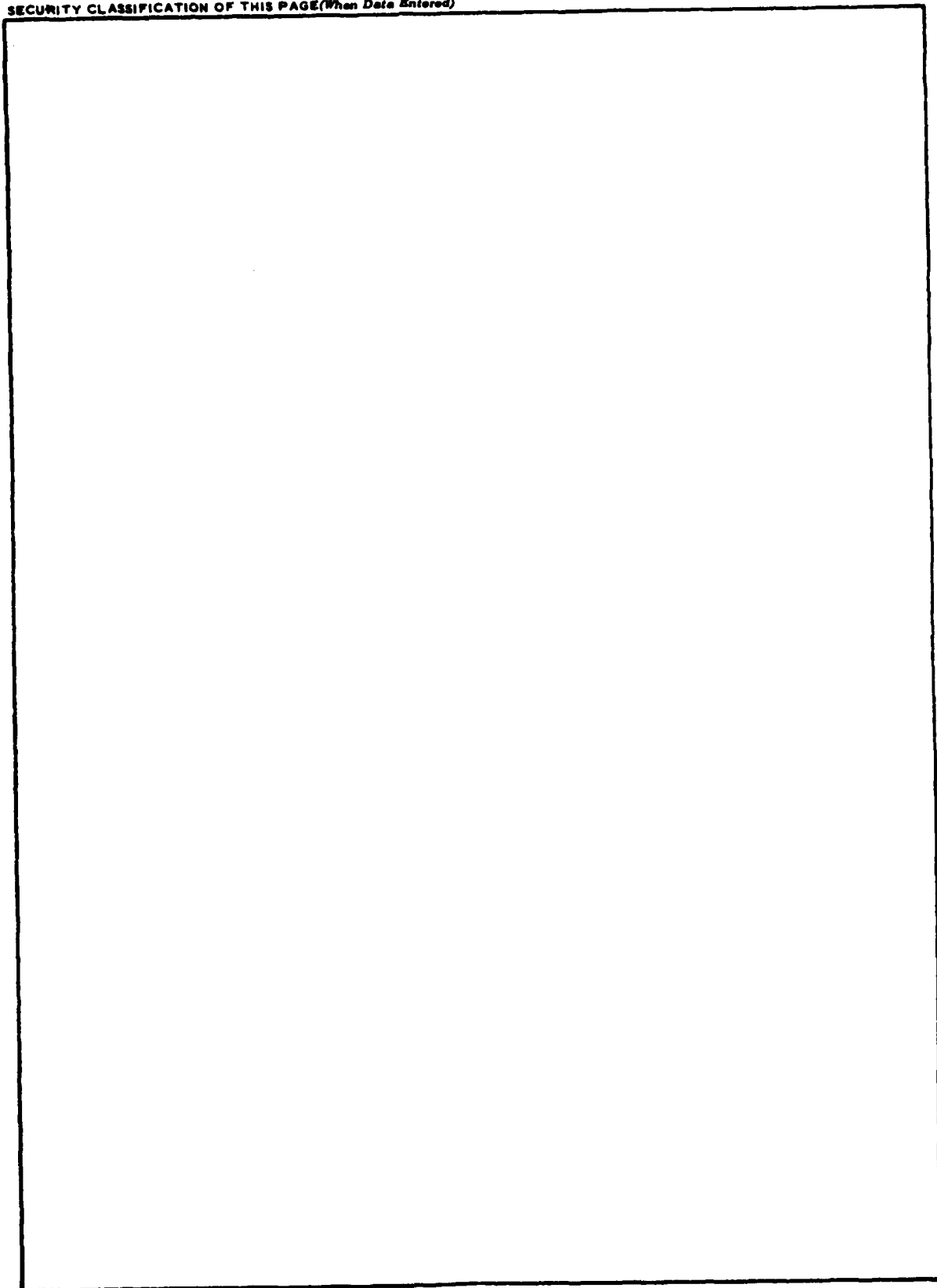
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I. INTRODUCTION.

The purpose of this report is to validate the Sommerfeld subroutine in our CDC-6500/6600 NEC program, and to present the results for the standard HF first-resonant dipole antenna in graphic form for analysis, reference, and subsequent comparisons.

Our original AMP (Antenna Modeling Program) used the Fresnel RCM (Reflection Coefficient Method) to obtain antenna-to-ground mutual coupling impedance, and it has been pointed out that a Sommerfeld method must be used when the height,  $H_\lambda$ , of any part of the dipole over earth is less than<sup>1,2</sup>

$$H_\lambda < \frac{0.70}{\sqrt{|\epsilon|}} \quad \text{wavelength} \quad 1$$

where,

$$\epsilon \doteq \epsilon_r - j \frac{1.79751 \times 10^4 \tau}{f_{\text{MHz}}} \quad \text{numeric}$$

$\epsilon_r$  = earth's relative dielectric permittivity; numeric

$\tau$  = earth's conductivity; mhos/meter

Using the HF frequency range together with earth's electrical properties listed in Table I, equation 1 is plotted on Figure 1.

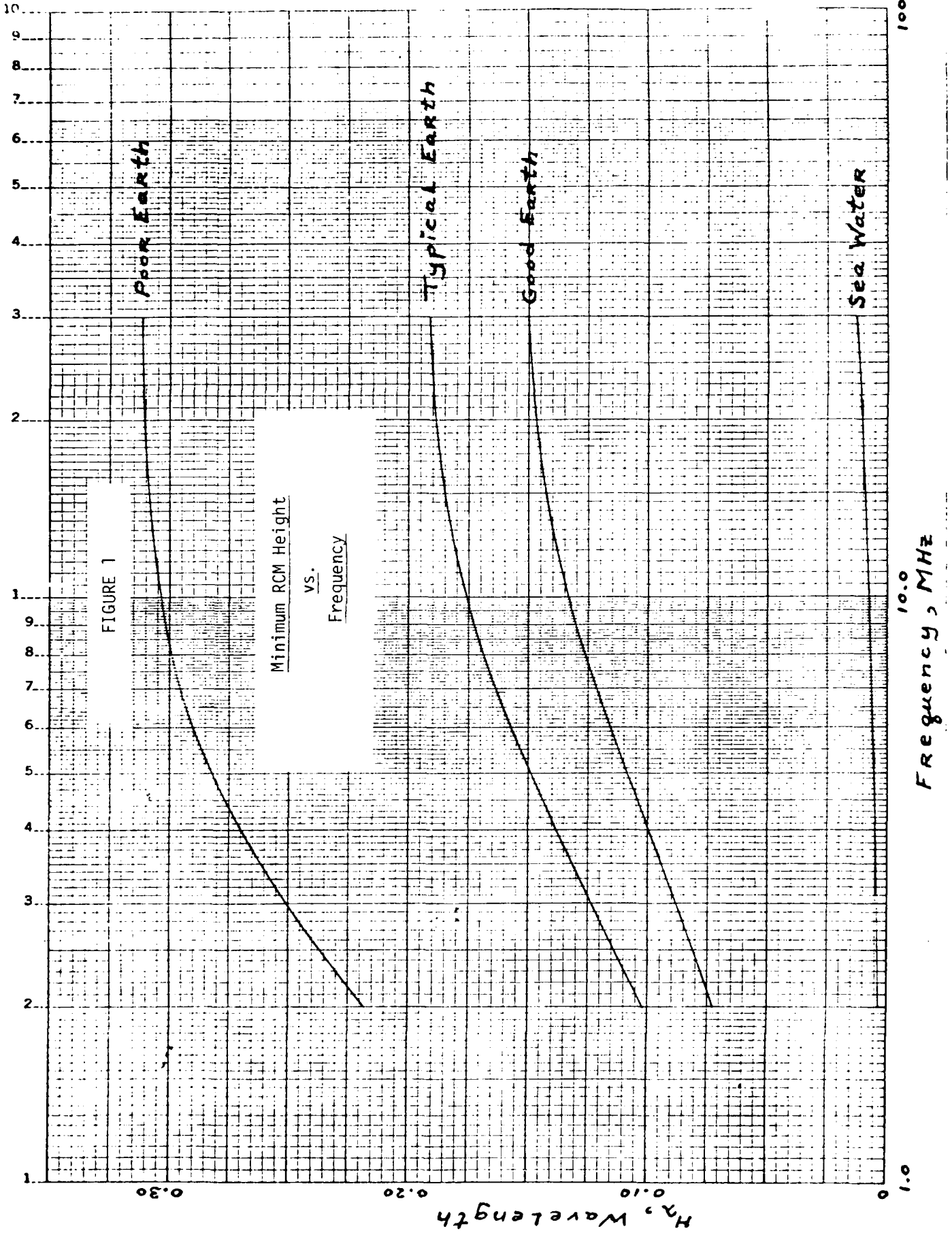
The results plotted on the next 50 graphs are mutual impedance,  $R_{21}$  and  $X_{21}$ , solutions. These solutions were obtained by using NEC to compare the antenna's self (free-space) impedance,  $Z_{11}$ , with the antenna's input impedance,  $Z_{in}$ , when near the earth as follows.<sup>3</sup>

when the antenna is horizontal:

$$Z_{in} = Z_{11} + (-Z_{21})$$

$$Z_{21} = Z_{11} - Z_{in} \quad \text{ohms}_{11} \quad 2$$

NAVY DEPARTMENT  
Semi-Logarithmic Chart  
6th Edition revised  
MAY 1954



0.1

10.0

100.0

$H_m$ , Wavelength

Frequency, MHz

when the antenna is vertical:

$$Z_{in} = Z_{11} + (+ Z_{21})$$

$$Z_{21} = Z_{in} - Z_{11} \quad \text{ohms}_{\perp} \quad 3$$

Since the antenna was pruned to first-resonance,  $Z_{11} = R_{11}$ , and equations 2-3 reduce, respectively, to:

$$Z_{21} = R_{11} - Z_{in} \quad \text{ohms}_{\perp} \quad 4$$

$$Z_{21} = Z_{in} - R_{11} \quad \text{ohms}_{\perp} \quad 5$$

The first-resonant dipole self resistance,  $R_{11}$ , used in equations 4 and 5 can be approximated without having to resort to the computer NEC program. The procedure is to use an estimated relative velocity,  $V_r(e)$ , multiply  $0.5\lambda_0$  by this  $V_r(e)$  to get an actual length,  $L$ , divide  $L$  by the wire diameter,  $D$ , and solve equation 4 of reference 4 for an actual relative velocity,  $V_r(a)$ . The process is repeated (iterated) until  $V_r(a) = V_r(e)$ .

When each  $V_r(a)$  thus obtained is used as the next  $V_r(e)$ , the solution  $V_r(a) = V_r(e)$  is obtained via a relatively few iterations because of rapid convergence. Then, note  $L/D$  when  $V_r(a) = V_r(e)$ , and use this  $L/D$  in equation 9 of reference 4 to obtain  $R_{11}$ . The following is an example solution:

$$V_r(e) = 0.976772 \quad \text{numeric}$$

$$0.5\lambda_0 \doteq 2950.718504 \quad \text{inches at 2.0 MHz}$$

$$L \doteq (0.976772) (2950.718504) \doteq 2882.179215 \quad \text{inches}$$

$$D = 0.08081 \quad \text{inches (\#12 wire)}$$

$$V_r(a) \doteq 1 - [10.541 \log_{10} \left(\frac{L}{D}\right) - 4.933]^{-1}$$

$$\doteq 0.976772 = V_r(e) \quad \text{numeric}$$

$$\begin{aligned} \therefore Z_{11} = R_{11} &\doteq 73.0 - [0.252 \log_{10} \left( \frac{2882.179215}{0.08081} \right) + 0.232]^{-1} \\ &\doteq 72.275 + j 0.0 \qquad \text{ohms} \end{aligned}$$

when these L and D values are used in the computer NEC program, the free-space solution at 2 MHz is

$$Z_{11} \doteq 72.330 - j 0.340 \qquad \text{ohms}$$

Thus, when  $L/D \doteq 35666$ , the above procedure gives a solution that is within 0.06 ohms and 0.27 degrees of that obtained via NEC at 2.0 MHz!

To obtain the effect of frequency upon the results, the 2-30 MHz band was divided into 4 MHz increments. Then, with the exception of solutions over a perfect earth, 8 frequencies are used in this analysis. Where less than 8 curves appear on the imperfect earth graphs, curves are combined when the error is less than plus-minus 1.5 ohms.

To obtain the effect of earth's electrical properties upon the results, 5 defined earths are used. The arbitrary properties are listed in Table I.

TABLE I		
Earth	$\epsilon_r$ (numeric)	$\tau$ (mhos/meter)
Poor	5.0	0.001
Typical	13.0	0.005
Good	21.0	0.010
Sea Water	80.0	5.000
Perfect	1.0	$\infty$

The normalized height arguments,  $H_\lambda$ , shown on the graphs are feed heights over the earth. Thus, the remote end of one arm of a vertical center-fed first-resonant dipole antenna is very close to the earth when  $H_\lambda = 0.25$ .

The curves on the enclosed 54 figures were generated from 9942 calculated data points. Thus, the enormous amount of required computer plus reduction time precludes the inclusion of other antenna types in this report.

## II. HORIZONTALLY-POLARIZED MUTUAL RESISTANCE.

The mutual resistance,  $R_{21}$ , results are plotted on Figures 2-6, 7-11, 12-16, and 17-21 for height,  $H_\lambda$ , intervals of 0.001-0.015, 0.015-0.155, 0.15-0.85, and 0.85-1.55 wavelengths, respectively. Thus, at each height interval, there are 5 graphs, one for each defined earth, and the frequency or frequency range is plotted on each graph.

With the graphs so arranged, some degree of earth interpolation is enhanced. As an example, let the earth's electrical properties be  $\epsilon_r = 10$  and  $\tau = 0.002$  mhos/meter (between poor and typical earth). Using Figures 2 and 3 with  $H = 0.01\lambda_0$  and  $f = 2.0$  MHz, the solution is  $-35.3 < R_{21} < + 3.0$  ohms. The NEC solution is  $-18.8$  ohms.

These figures show that ground (not sea water or perfect earth) mutual resistance is highly negative when this antenna is near an imperfect ground which, from equation 4, increases the antenna resistance drastically. This conclusion is supported by field measurements.<sup>5,6,7,8</sup>

The results shown on Figure 5 appear to be highly frequency sensitive when this antenna is near sea water. The loss tangent of sea water does not exhibit a relatively strong displacement current until the frequency is above 1.0 MHz. The great difference in  $R_{21}$  solutions between 26 and 30 MHz was not expected, and the reason for this is given in the Summary.

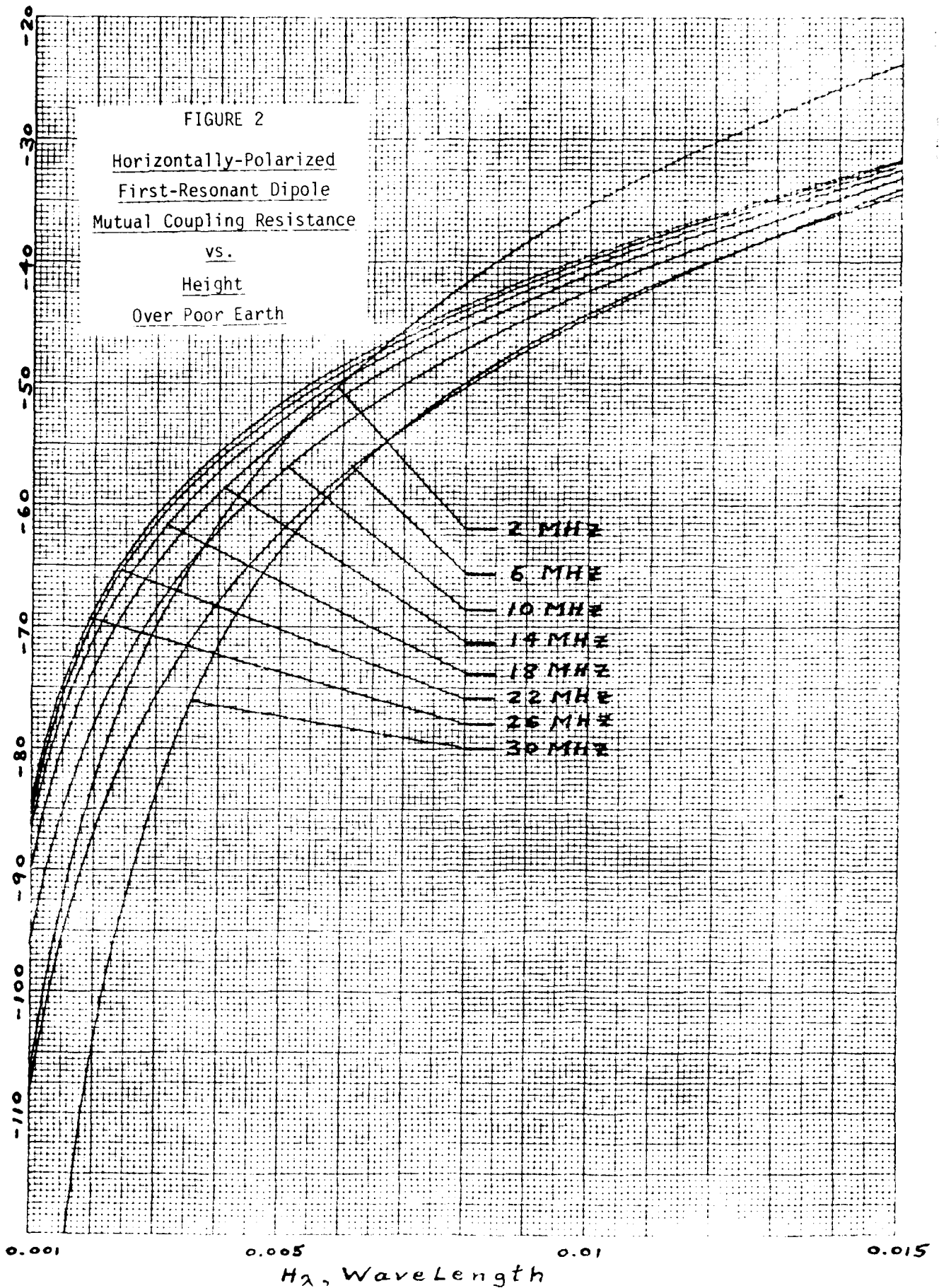
The results shown on Figure 6 are what one would expect. The mutual resistance,  $R_{21}$ , approaches the dipole self resistance,  $R_{11}$ , when the height,  $H_\lambda$ , approaches the dipole radius, and the dipole self resistance,  $R_{11}$ , is a function of  $L/D$ . For practical reasons, number 12 wire (diameter = 0.08081 inches) was used at all frequencies except 30 MHz

46 1323

K-Σ 10 X 10 TC 3 INCH 7 X 10 INCHES  
KEUFFEL & ESSER CO. MADE IN U.S.A.

$R_{21}$ , Ohms

FIGURE 2  
Horizontally-Polarized  
First-Resonant Dipole  
Mutual Coupling Resistance  
vs.  
Height  
Over Poor Earth



46 1323

K-E 10 X 10 TO 1/4 INCH 7 X 10 INCHES  
RUFFEL & SMITH CO. MADE IN U.S.A.

$R_{21}$ , Ohms

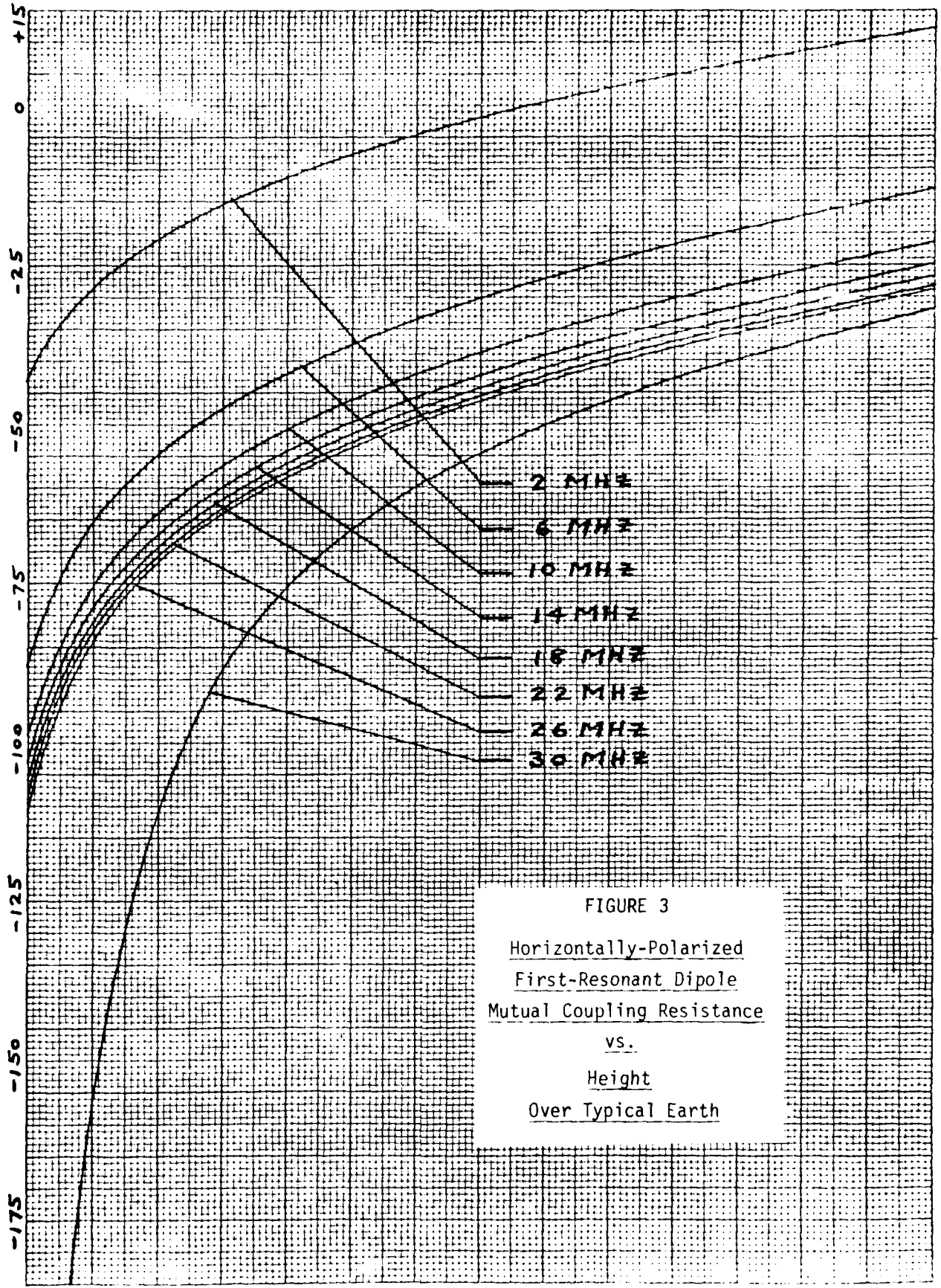


FIGURE 3  
 Horizontally-Polarized  
 First-Resonant Dipole  
 Mutual Coupling Resistance  
 vs.  
 Height  
 Over Typical Earth

0.001                      0.005                      0.01                      0.015  
 $H_2$ , WaveLength

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K&E 10 X 10 TO 1/2 INCH 7 X 10 INCHES  
KEUFFEL & ESSER CO. MADE IN U.S.A.

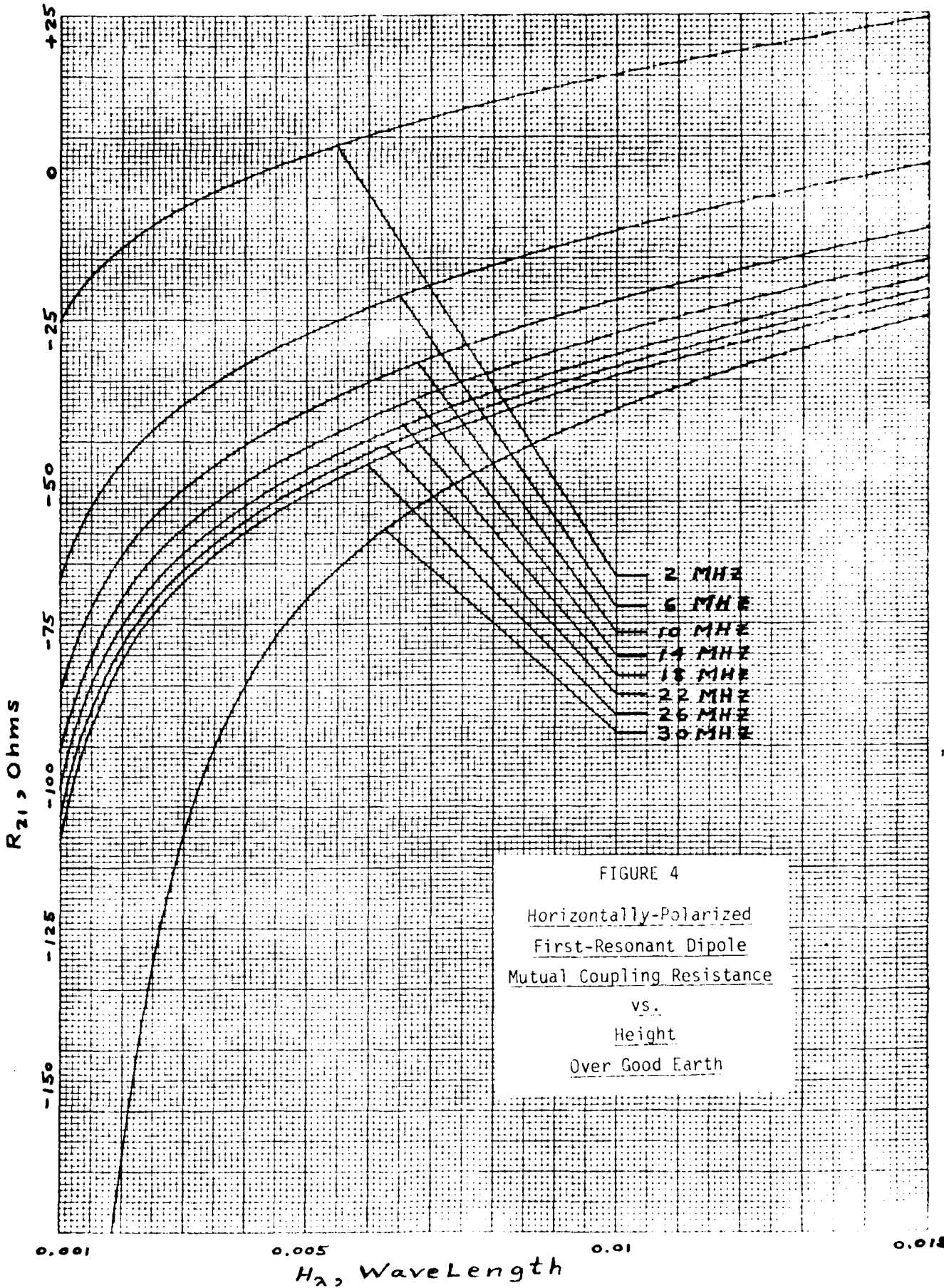


FIGURE 4  
 Horizontally-Polarized  
 First-Resonant Dipole  
 Mutual Coupling Resistance  
 vs.  
 Height  
 Over Good Earth

$H_\lambda$ , WaveLength

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K $\sigma$ E 10 X 10 TO 1/4 INCH 7 X 10 INCHES  
KEUFFEL & ESSER CO. MADE IN U.S.A.

$R_{21}$ , Ohms

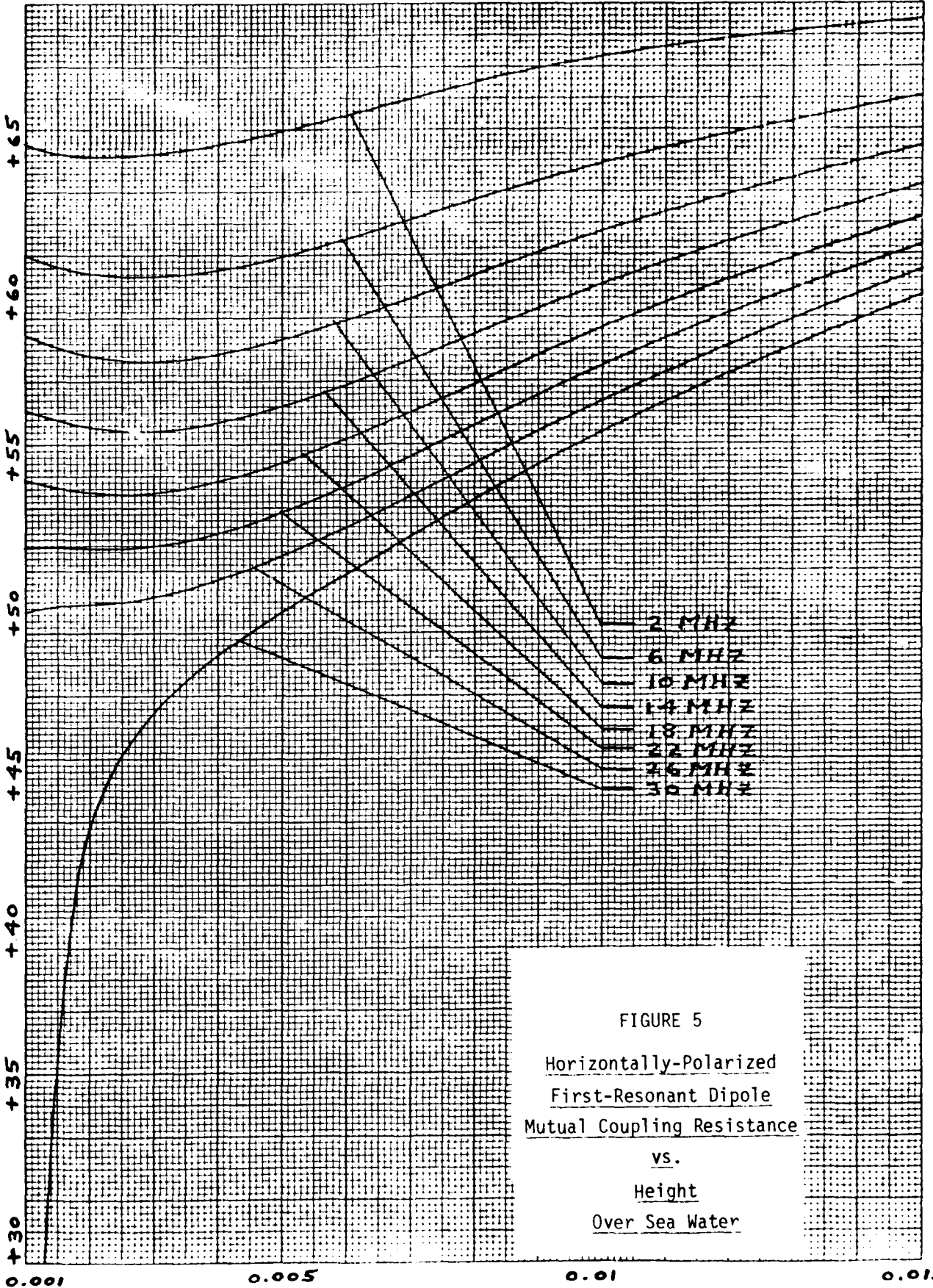


FIGURE 5  
Horizontally-Polarized  
First-Resonant Dipole  
Mutual Coupling Resistance  
vs.  
Height  
Over Sea Water

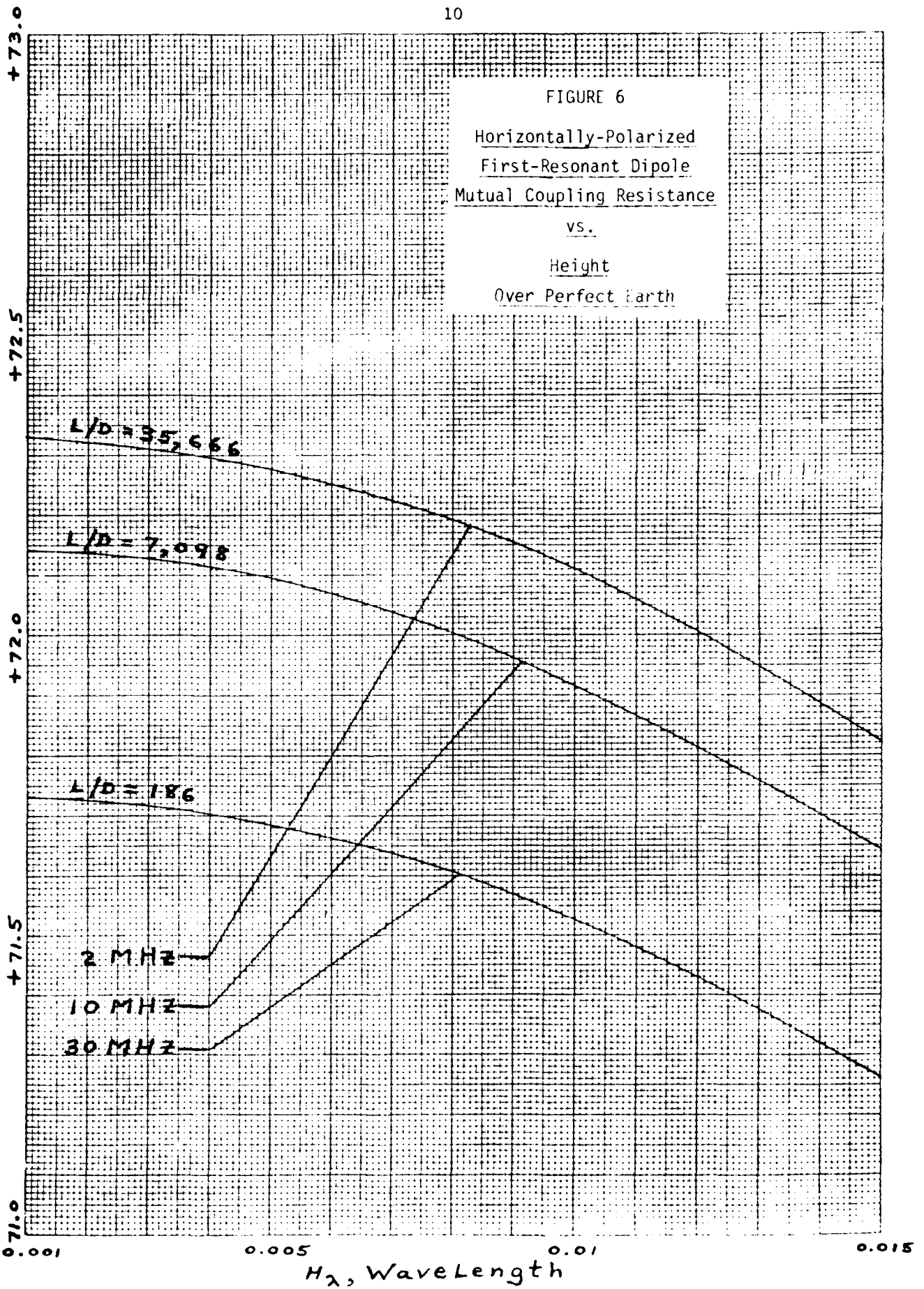
$H_\lambda$ , WaveLength

0.015

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K·S  
10 X 10 TO 1/4 INCH  
KLOFFEL & FABER CO. MADE IN F.R.G.

$R_{21}$ , Ohms



46 1323

KOE 10 X 10 TO 1/4 INCH 7 X 10 INCHES  
KEUFFEL & ESSER CO. MADE IN U.S.A.

$R_{21}$ , Ohms

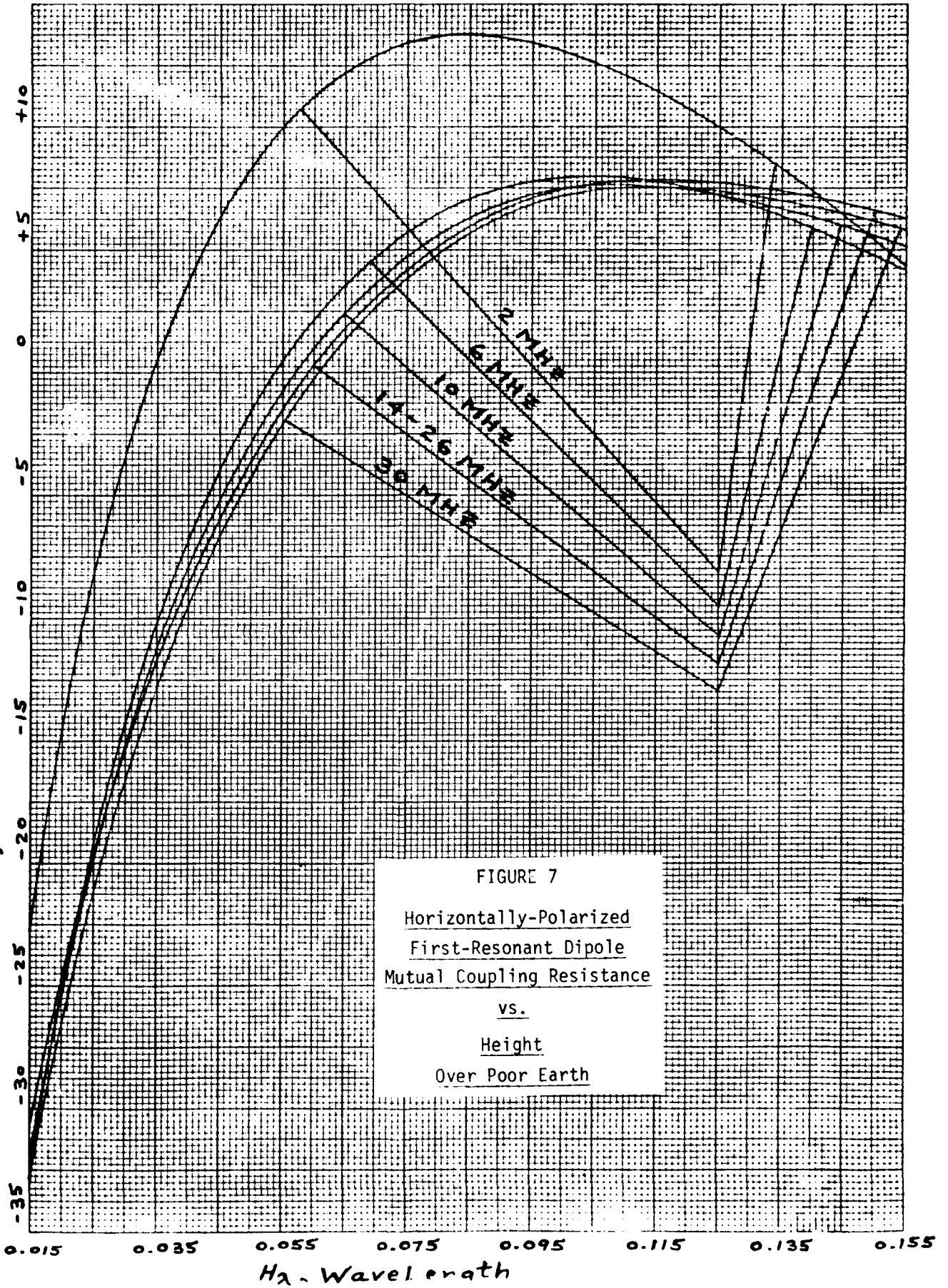


FIGURE 7  
 Horizontally-Polarized  
 First-Resonant Dipole  
 Mutual Coupling Resistance  
 vs.  
 Height  
 Over Poor Earth

$H\lambda$  - Wavelength

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K·E 10 X 10 TO 1/4 INCH 7 X 10 INCHES  
KEUFFEL & ESSER CO. MADE IN U.S.A.

$R_{21}$ , Ohms

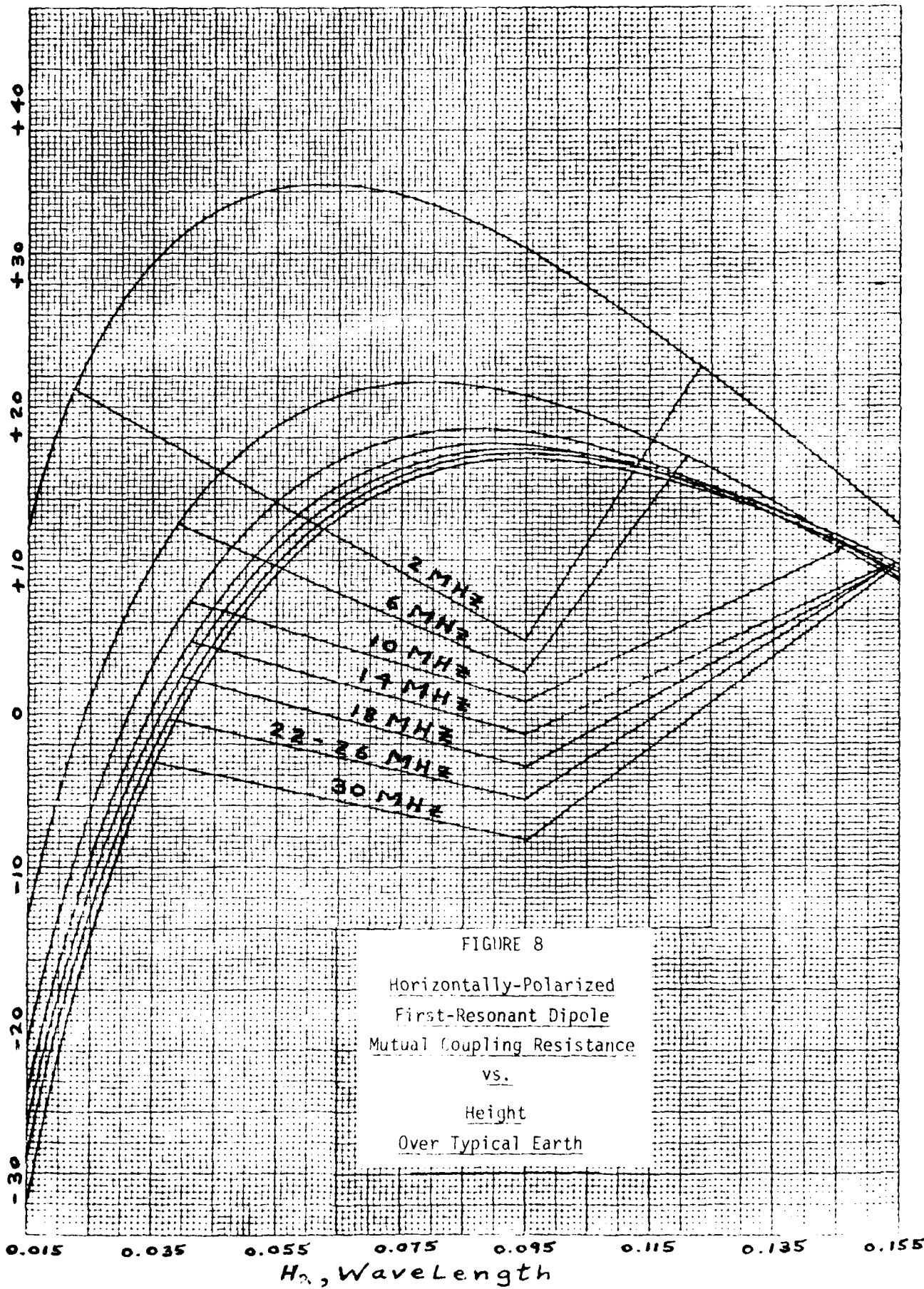


FIGURE 8  
Horizontally-Polarized  
First-Resonant Dipole  
Mutual Coupling Resistance  
vs.  
Height  
Over Typical Earth

46 1323

K·E 10 X 10 TO 1/4 INCH 7 X 10 INCHES  
KEUFFEL & ESSER CO. MADE IN U.S.A.

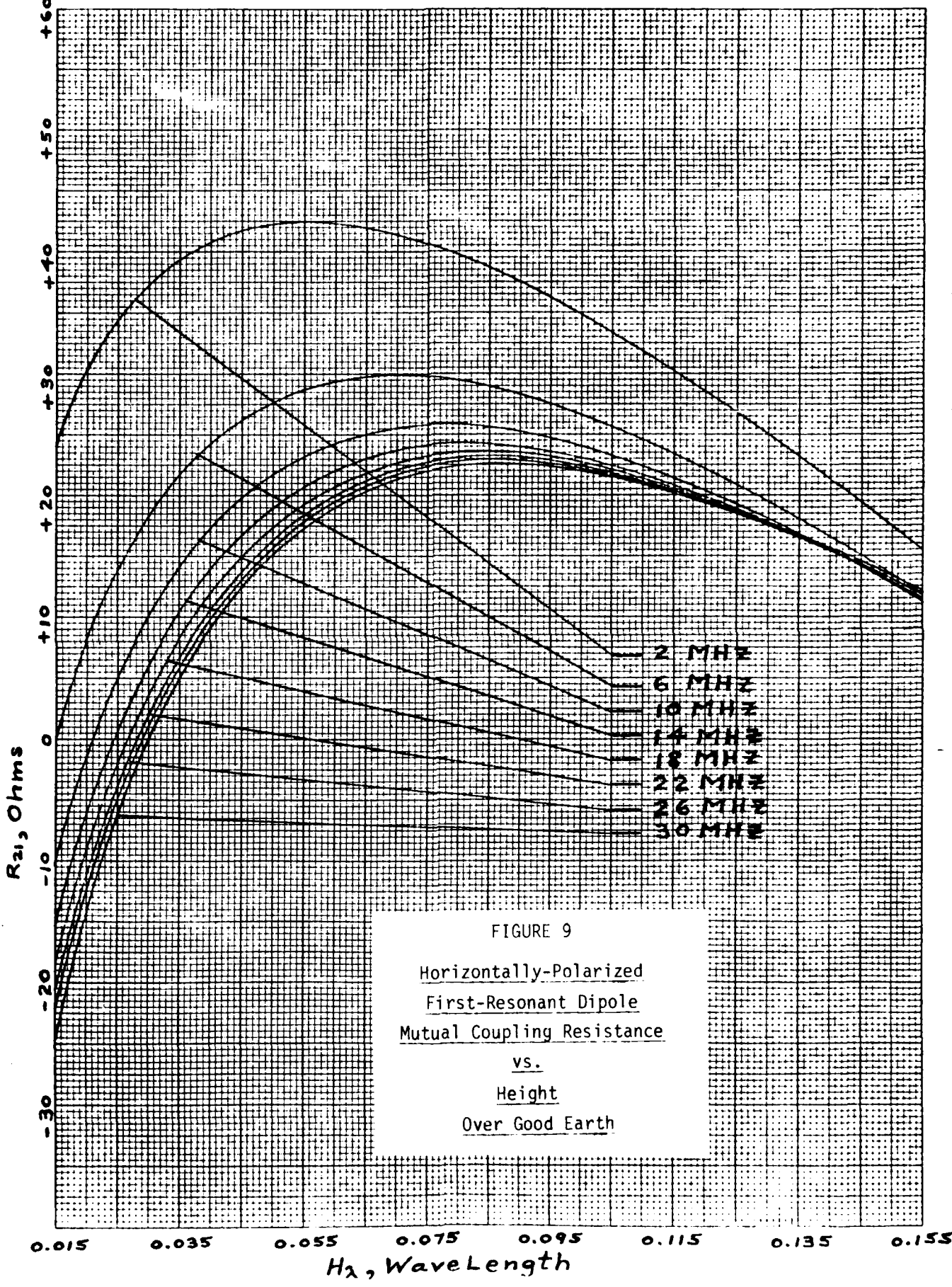


FIGURE 9  
 Horizontally-Polarized  
 First-Resonant Dipole  
 Mutual Coupling Resistance  
 vs.  
 Height  
 Over Good Earth

46 1323

K·E 10 X 10 TO 14 INCH 7 X 10 INCHES  
KEUFFEL & ESSER CO. MADE IN U.S.A.

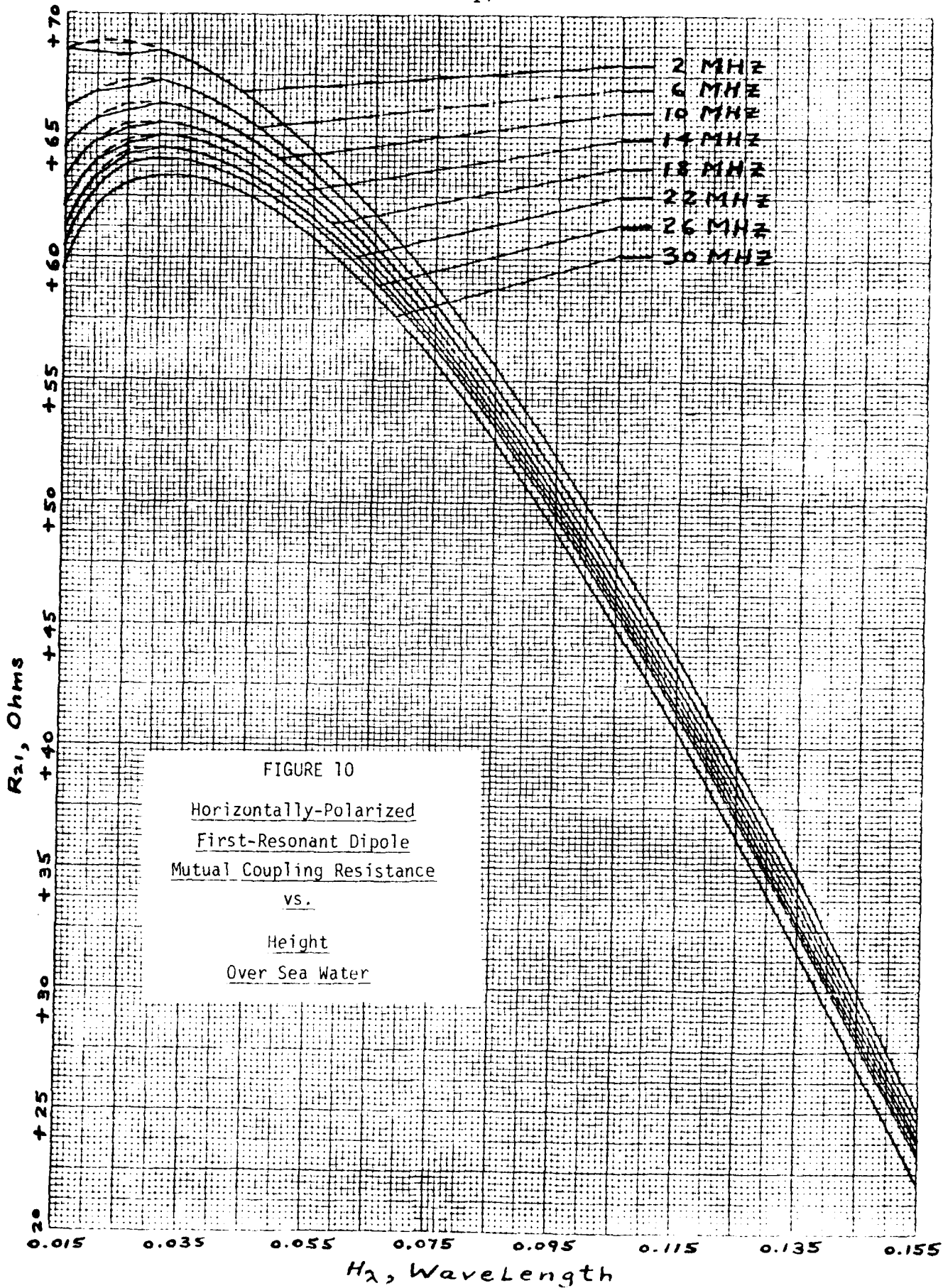
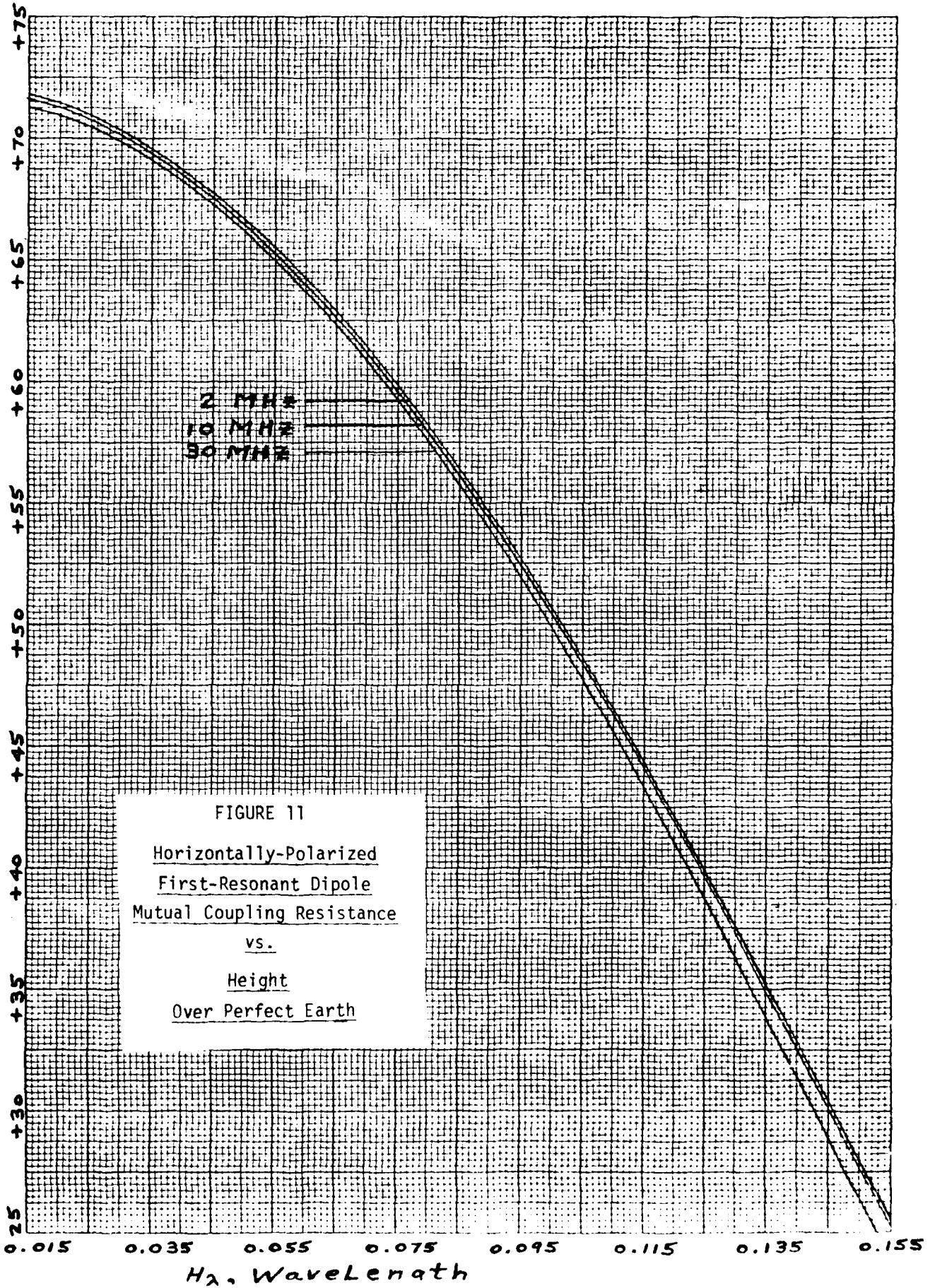


FIGURE 10  
Horizontally-Polarized  
First-Resonant Dipole  
Mutual Coupling Resistance  
 vs.  
Height  
Over Sea Water

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K-E 10 X 10 TO 1/4 INCH 7 X 10 INCHES  
KEUFFEL & ESSNER CO. MADE IN U.S.A.

$R_{21}$ , Ohms



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K&E 10 X 0 TO 1/4 INCH 7 X 10 INCHES  
KEUFFEL & ESSER CO. MADE IN U.S.A.

$R_{21}$ , Ohms

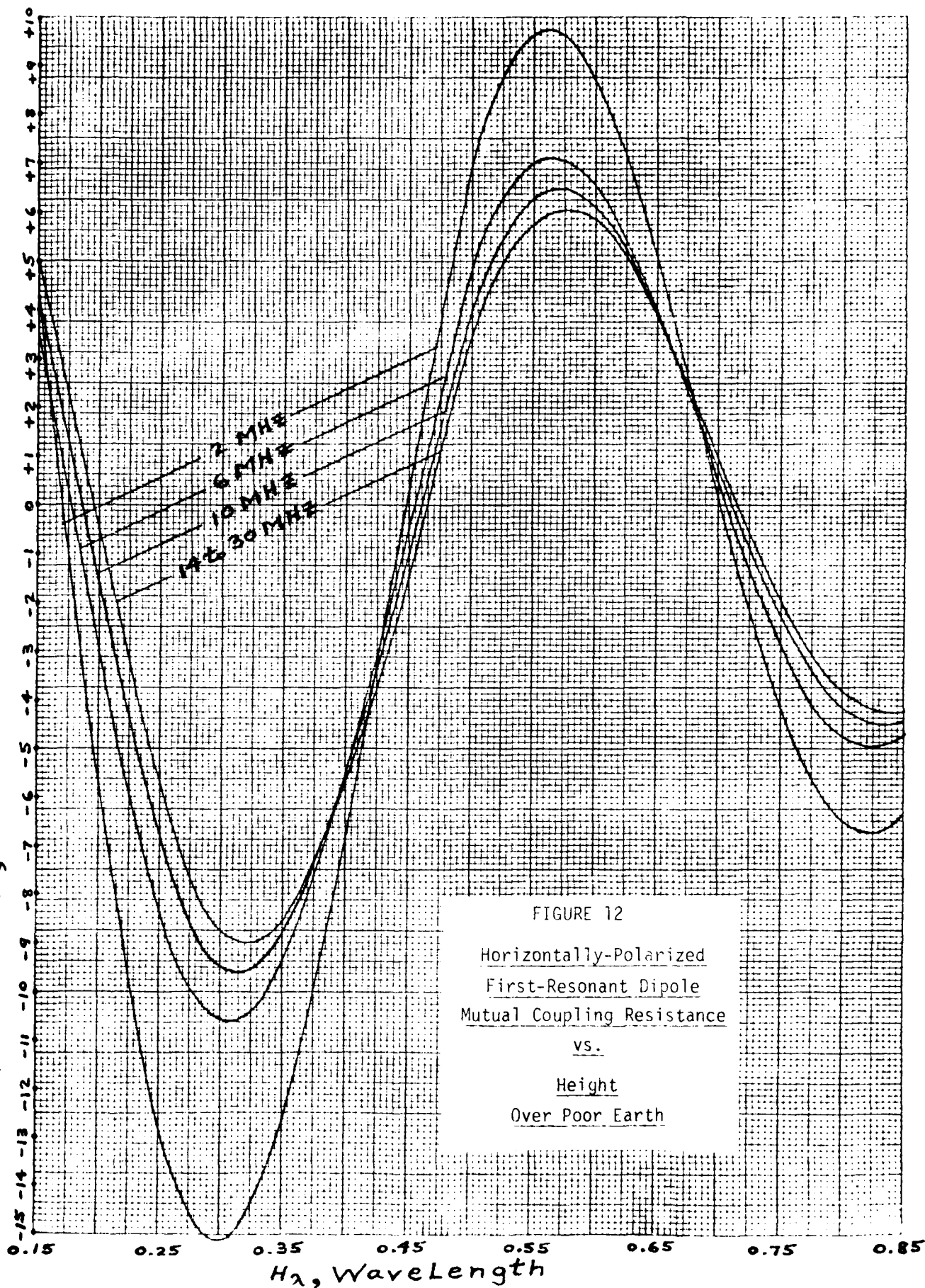


FIGURE 12  
Horizontally-Polarized  
First-Resonant Dipole  
Mutual Coupling Resistance  
vs.  
Height  
Over Poor Earth

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K·E 10 X 10 TO 1/4 INCH 7 X 10 INCHES  
KEUFFEL & ESSER CO. MANUFACTURERS

$R_{21}$ , Ohms

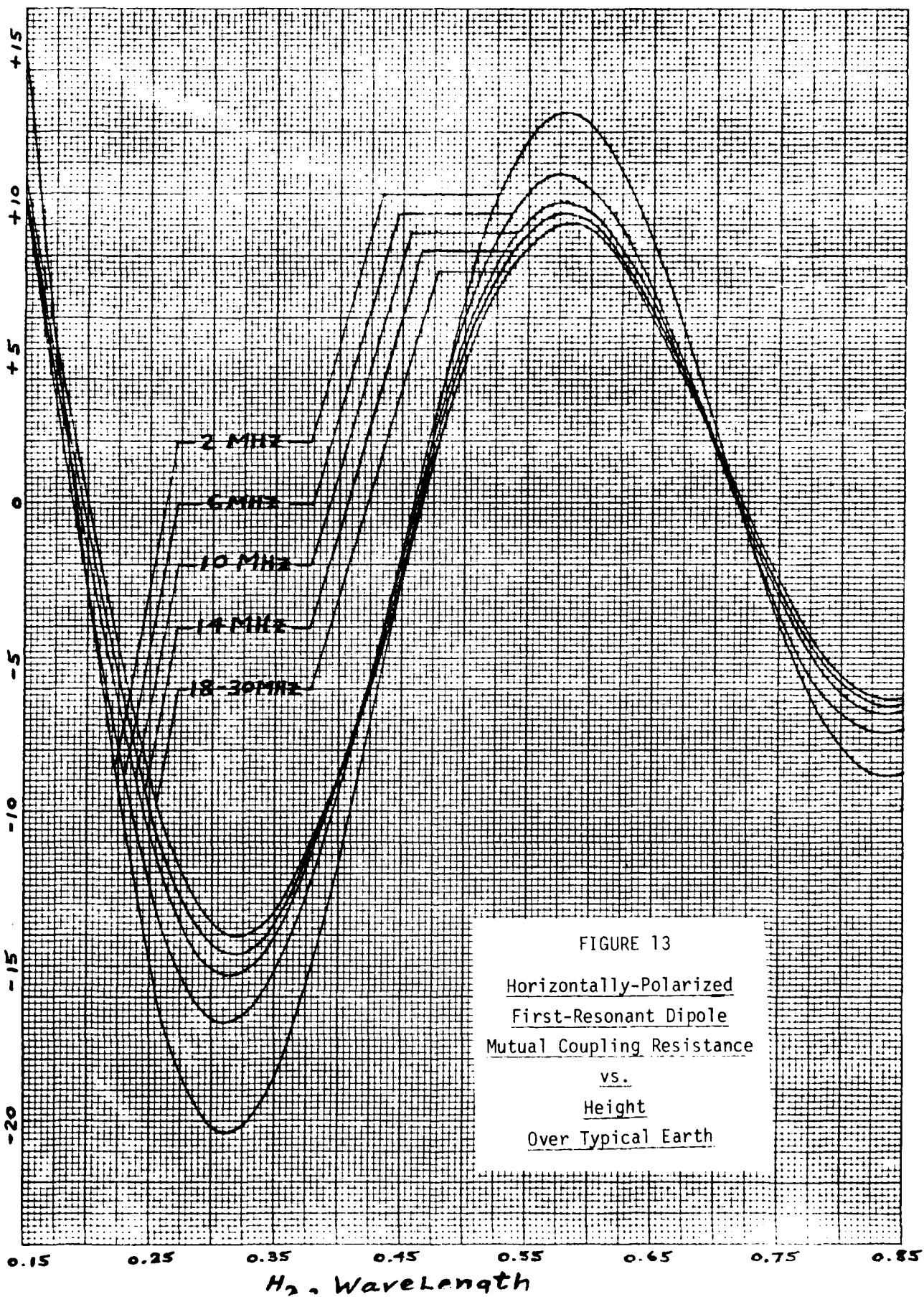
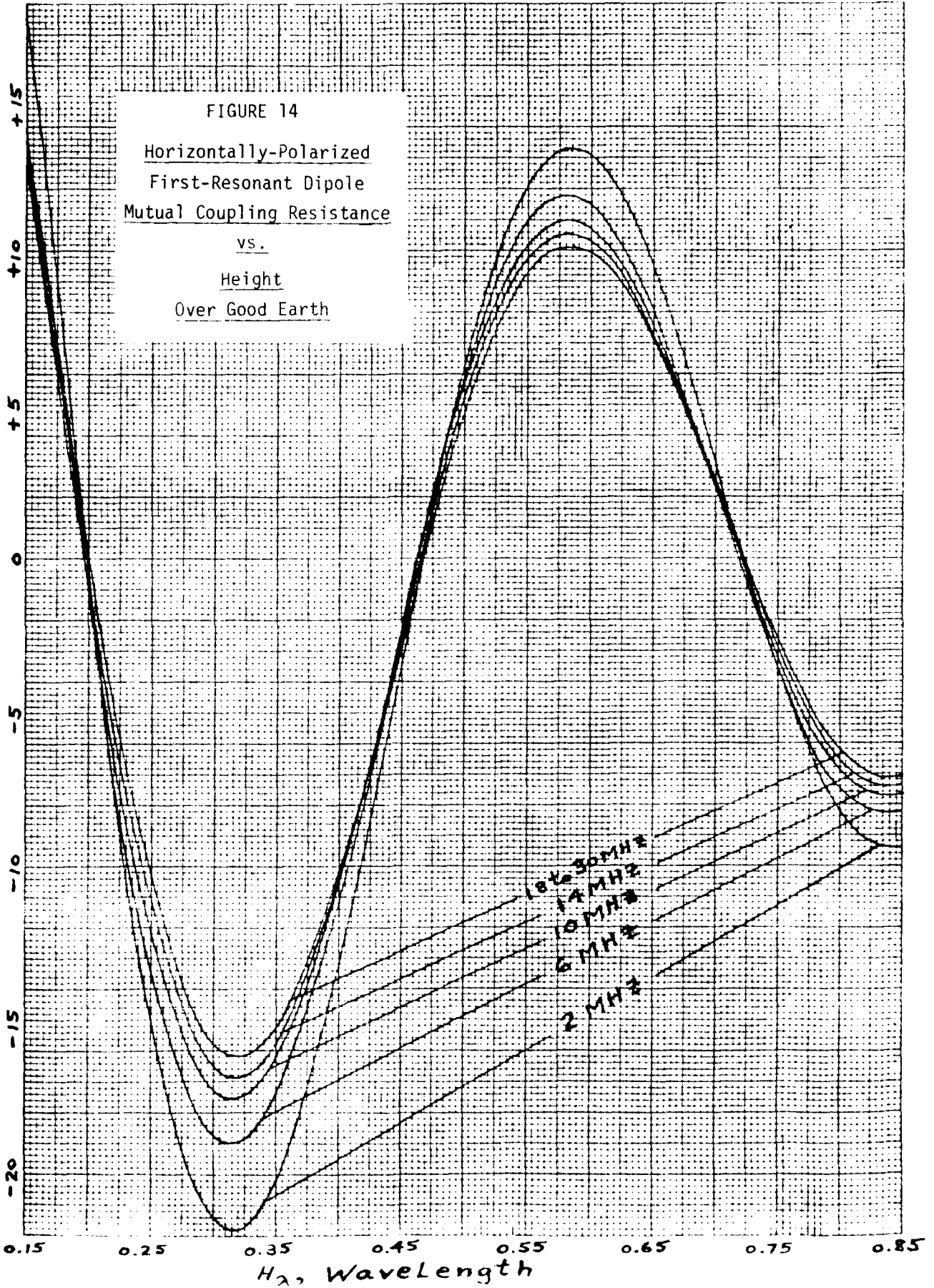


FIGURE 13  
Horizontally-Polarized  
First-Resonant Dipole  
Mutual Coupling Resistance  
vs.  
Height  
Over Typical Earth

46 1323

K-Σ 10 X 10 TO 1/8 INCH 7 X 10 INCHES  
NEUFEL & ESSER CO. MAX. U.S.A.

$R_{21}$ , Ohms



46 1323

K-E 10 X 10 TO 1/4 INCH 7 X 10 INCHES  
KLUFFEL & ESSER CO. MADE IN U.S.A.

$R_{21}$ , Ohms

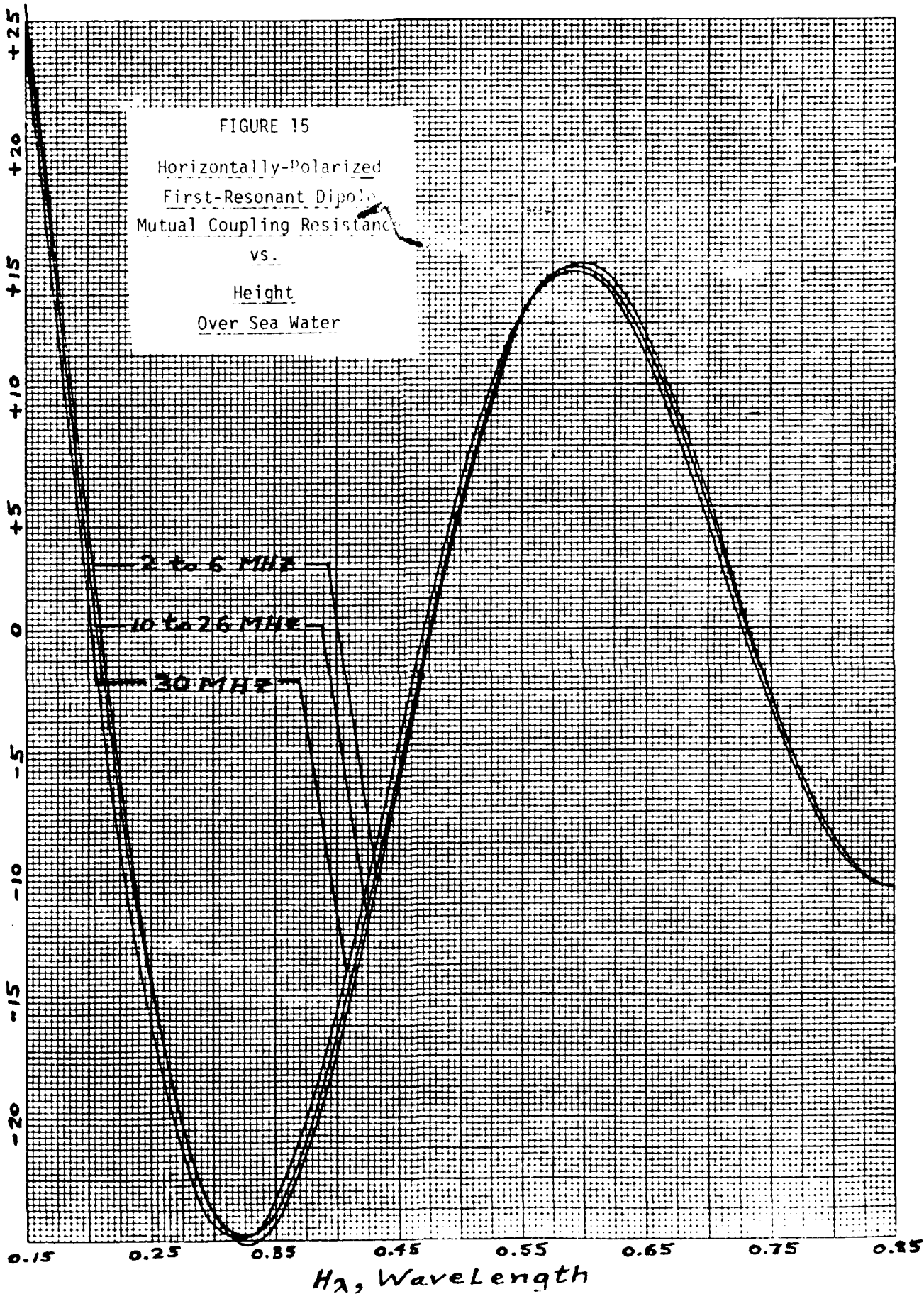


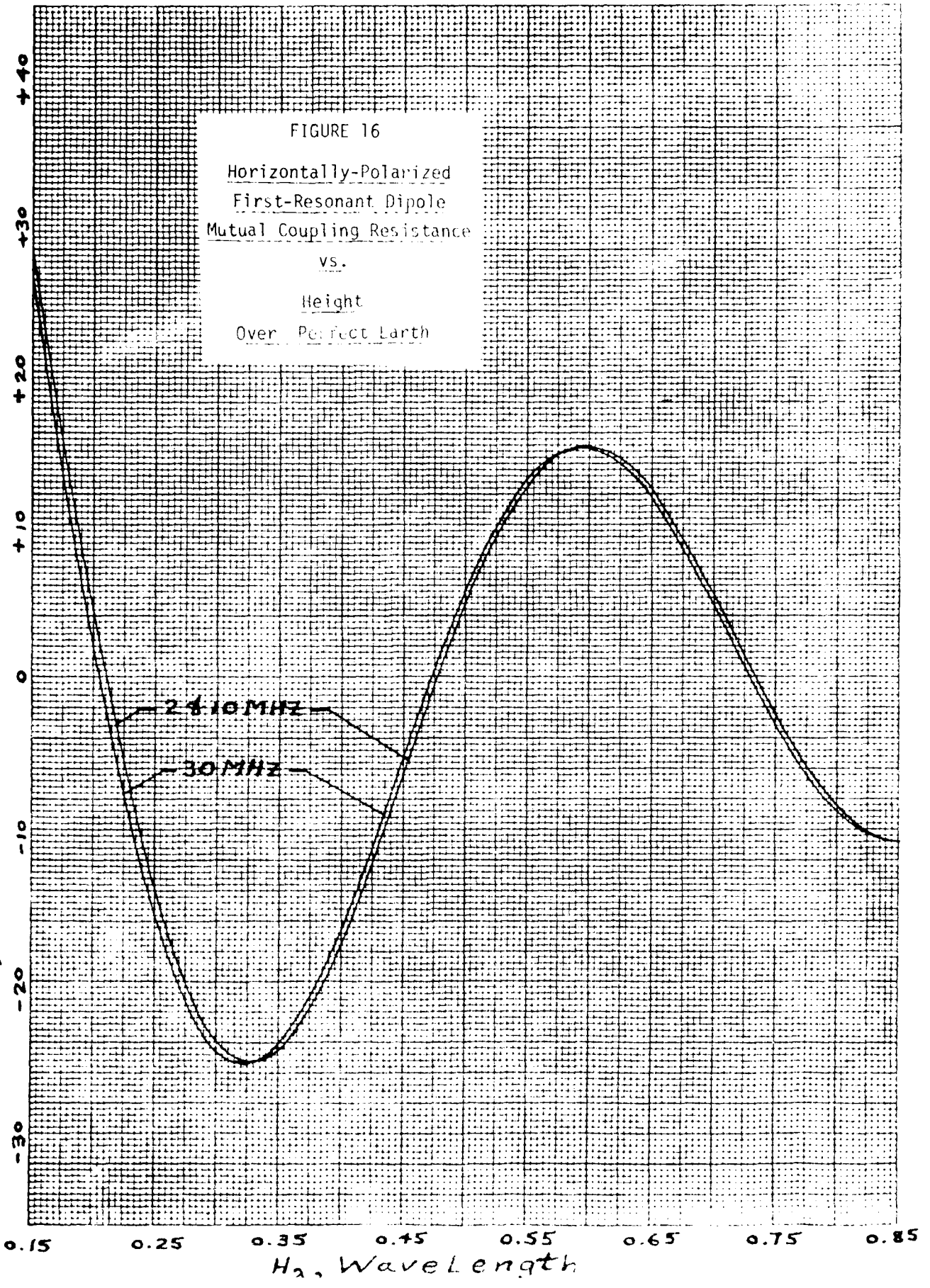
FIGURE 15  
 Horizontally-Polarized  
 First-Resonant Dipole  
 Mutual Coupling Resistance  
 vs.  
 Height  
 Over Sea Water

$H\lambda$ , WaveLength

46 1323

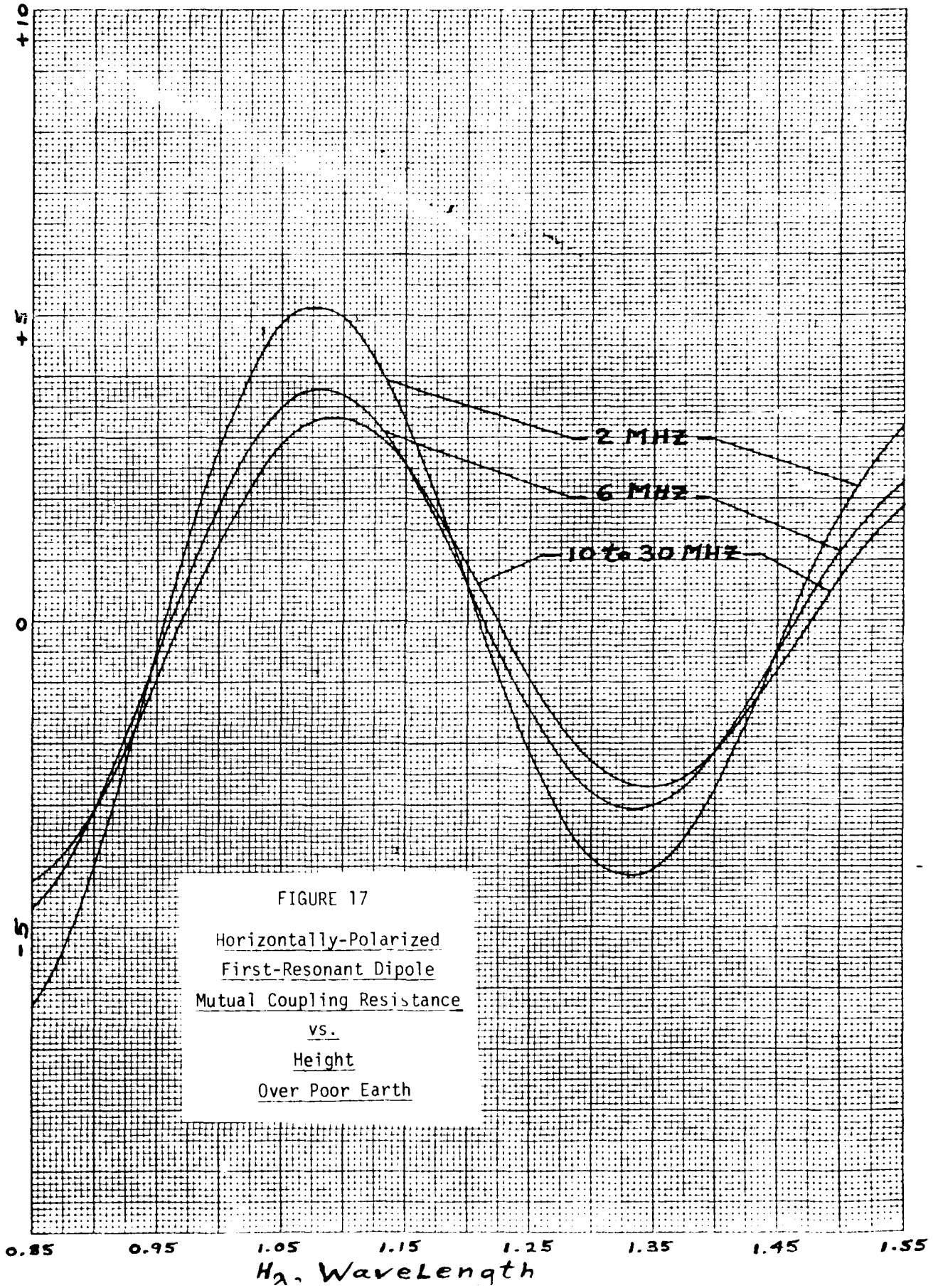
K&E 10 X 13 TO 1/2 INCH 7 X 10 INCHES  
KEUFFEL & ESSER CO. MADE IN U.S.A.

$R_{21}$ , Ohms



$H_2$ , Wavelength

46 1323

K·E  
10 X 10 TO 1/4 INCH 7 X 10 INCHES  
KEUFFEL & ESSER CO. MADE IN U.S.A. $R_{21}$ , Ohms

K-E 10 X 10 TO 1/2 INCH 7 X 10 INCHES  
KELVIN-ELL & ESSER CO. MADE IN U.S.A.

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$R_{21}$ , Ohms

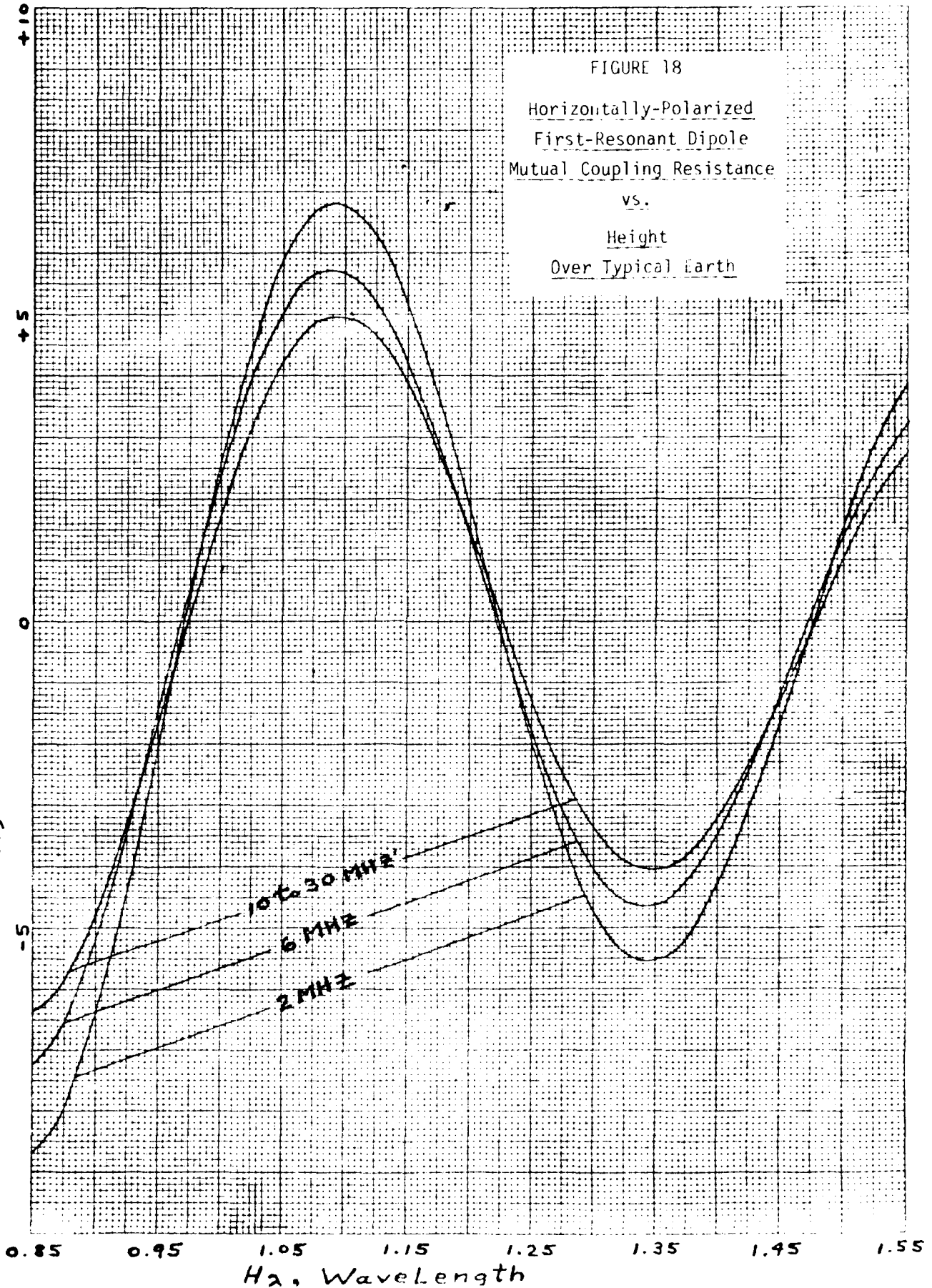


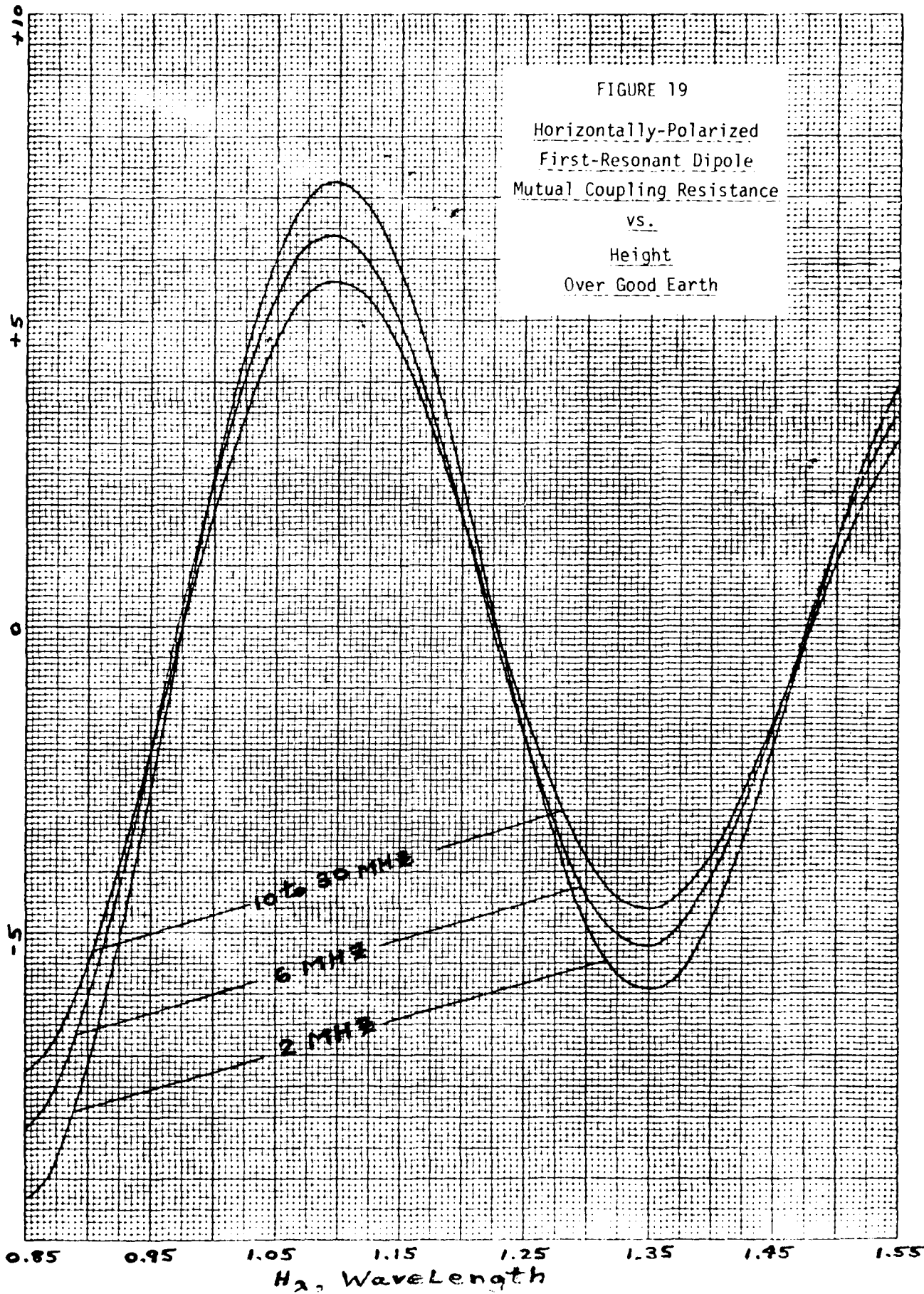
FIGURE 18  
 Horizontally-Polarized  
 First-Resonant Dipole  
 Mutual Coupling Resistance  
 vs.  
 Height  
 Over Typical Earth

$H\lambda$ , Wavelength

46 1323

K·E 10 X 10 TO 4 INCH 7 X 10 INCHES  
KEUFEL & ESSER CO. MADE IN U.S.A.

$R_{21}$ , Ohms



46 1323

K-E 10 X 10 TO 1/2 INCH 7 X 10 INCHES  
NEUFEL & ESSEMER CO. MADE IN U.S.A.

$R_{21}$ , Ohms

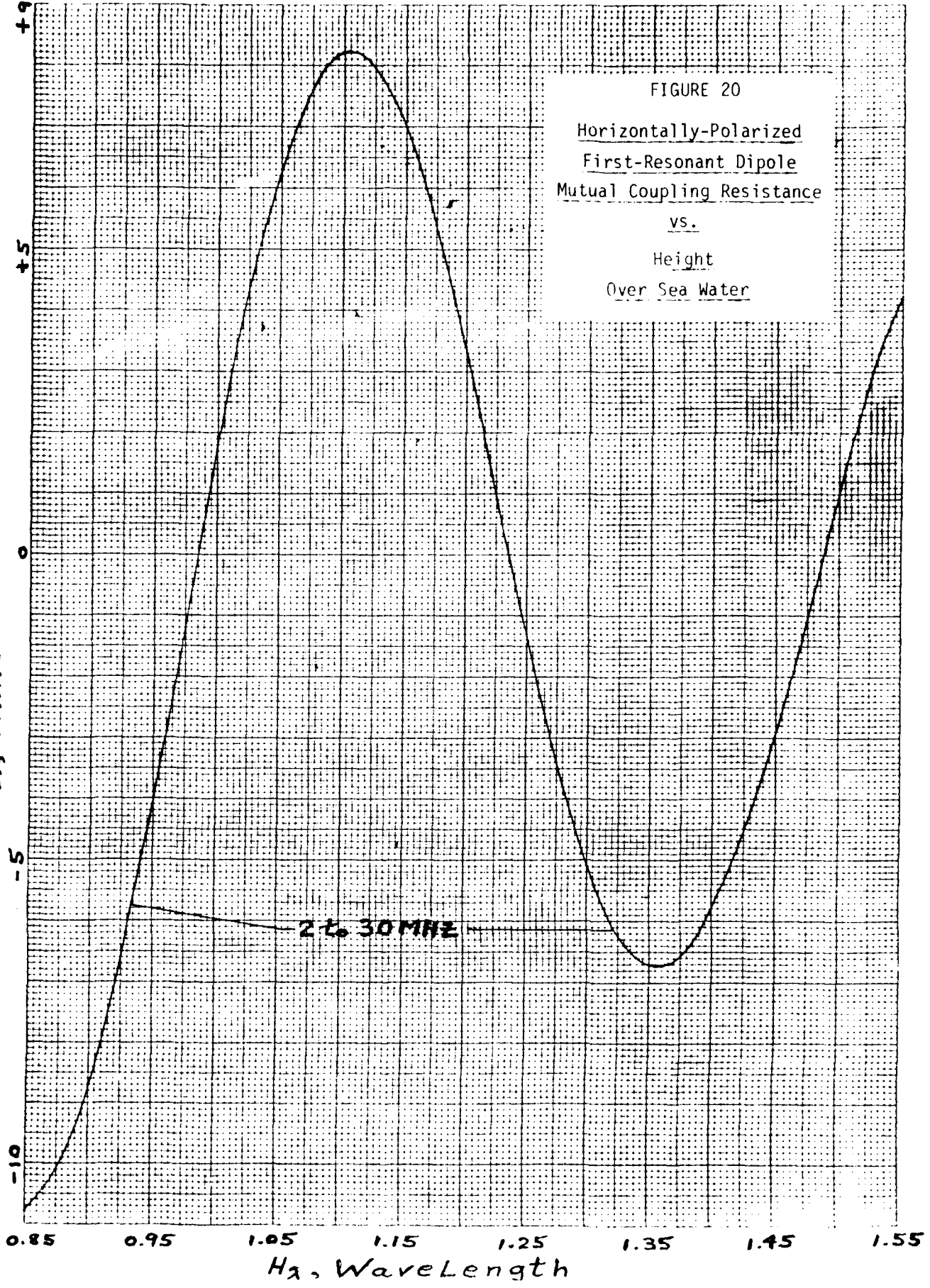


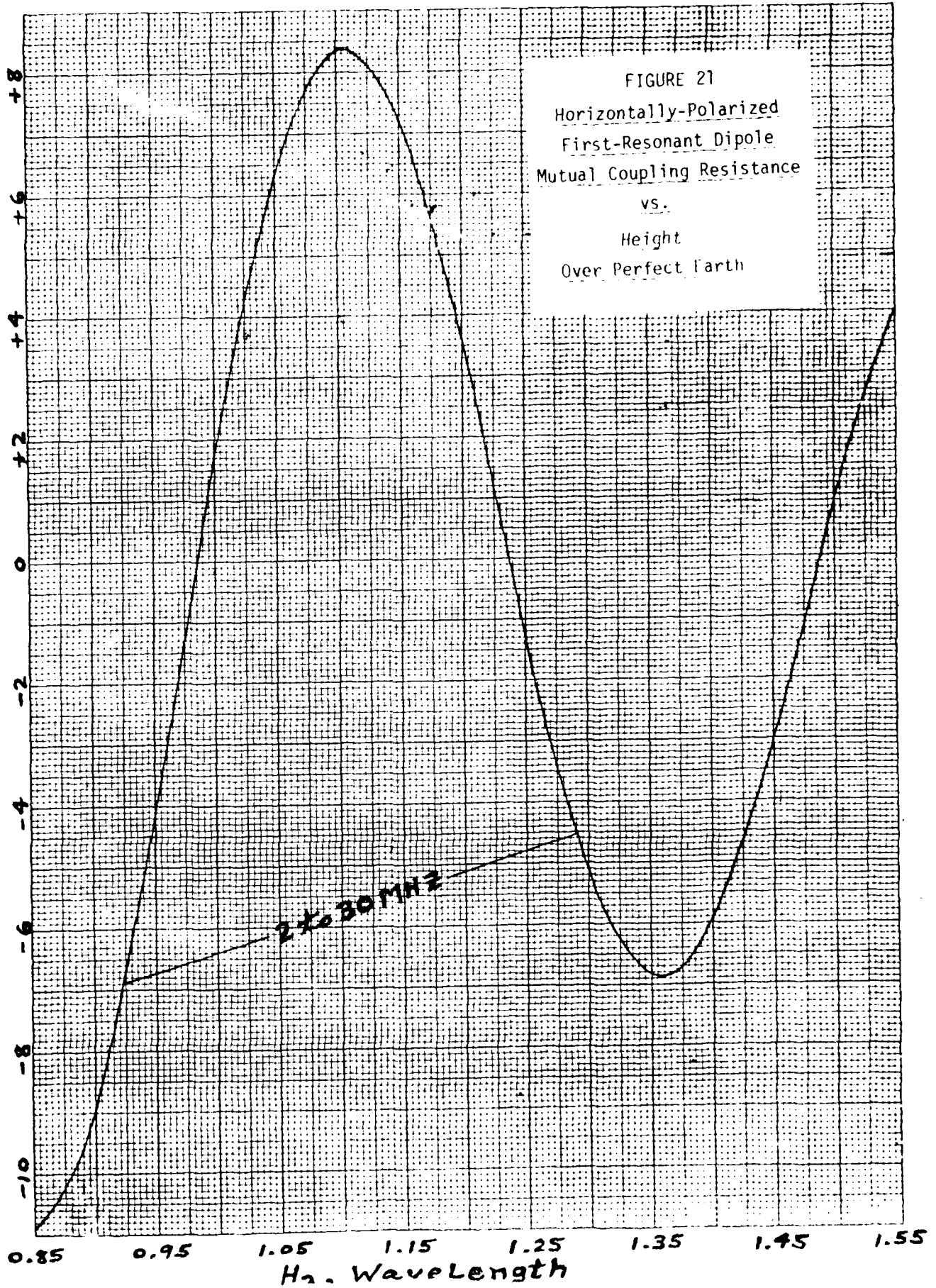
FIGURE 20  
Horizontally-Polarized  
First-Resonant Dipole  
Mutual Coupling Resistance  
vs.  
Height  
Over Sea Water

2 to 30 MHz

46 1323

K·E 10 X 10 TO 1/4 INCH  
7 X 10 INCHES  
KUPFFEL & ESSER CO. MAN. IN U.S.A.

$R_{21}$ , Ohms



where a tubing diameter of 1.0 inch was used. Equation 4 of reference 4 was used, as discussed in the introduction, to obtain first resonant L/D ratios which are plotted on Figure 52 in Summary section, and shown on Figure 6 at 2, 10, and 30 MHz.

When the L/D ratios shown on Figure 6 are used in equation 9 of reference 4, solutions for  $R_{11}$  are 0.06 ohms less than NEC solutions at 2.0 MHz, 0.03 ohms greater than NEC solutions at 10.0 MHz, and 0.03 ohms greater than NEC solutions at 30.0 MHz. The difference between the NEC solution curves shown on Figure 6 is a function of dipole first-resonant lengths of  $0.488386\lambda_0$  at 2.0 MHz,  $0.485980\lambda_0$  at 10.0 MHz, and  $0.473683\lambda_0$  at 30.0 MHz.

The results plotted on Figure 10 show that NEC solutions are not correct when the dipole height is  $0.015 \leq H_\lambda \leq 0.03$  wavelength over sea water and the frequency is below 26 MHz. Surprisingly, this height range is well within the RCM limit discussed in the Introduction leading to equation 1 and Figure 1. Since the subroutine gives reasonable solutions when other combinations of earth electrical properties, frequency, and height are used, the error appears to be philosophical.

### III. HORIZONTALLY-POLARIZED MUTUAL REACTANCE.

The mutual reactance,  $X_{21}$ , results are plotted on Figures 22-26, 27-31, 32-36, and 37-41 for height,  $H_\lambda$ , intervals of 0.001-0.015, 0.015-0.155, 0.15-0.85, and 0.85-1.55 wavelengths, respectively. Thus, at each height interval there are 5 graphs, one for each defined earth, and the frequency or frequency range is plotted on each graph.

With the graphs so arranged, some degree of earth interpolation is enhanced. As an example, let the earth's electrical properties be  $\epsilon_r = 10$  and  $\tau = 0.002$  mhos/meter (between poor and typical earth). Using Figures 22 and 23 with  $H = 0.01\lambda_0$  and  $f = 2.0$  MHz, the solution is  $-90.8 < X_{21} < -64.6$  ohms. The NEC solution is -80.7 ohms.

46 1323

K&E 10 X 10 TO 1/2 INCH KEUFFEL & ESSER CO. MADE IN U.S.A.

$X_{21}$ , Ohms

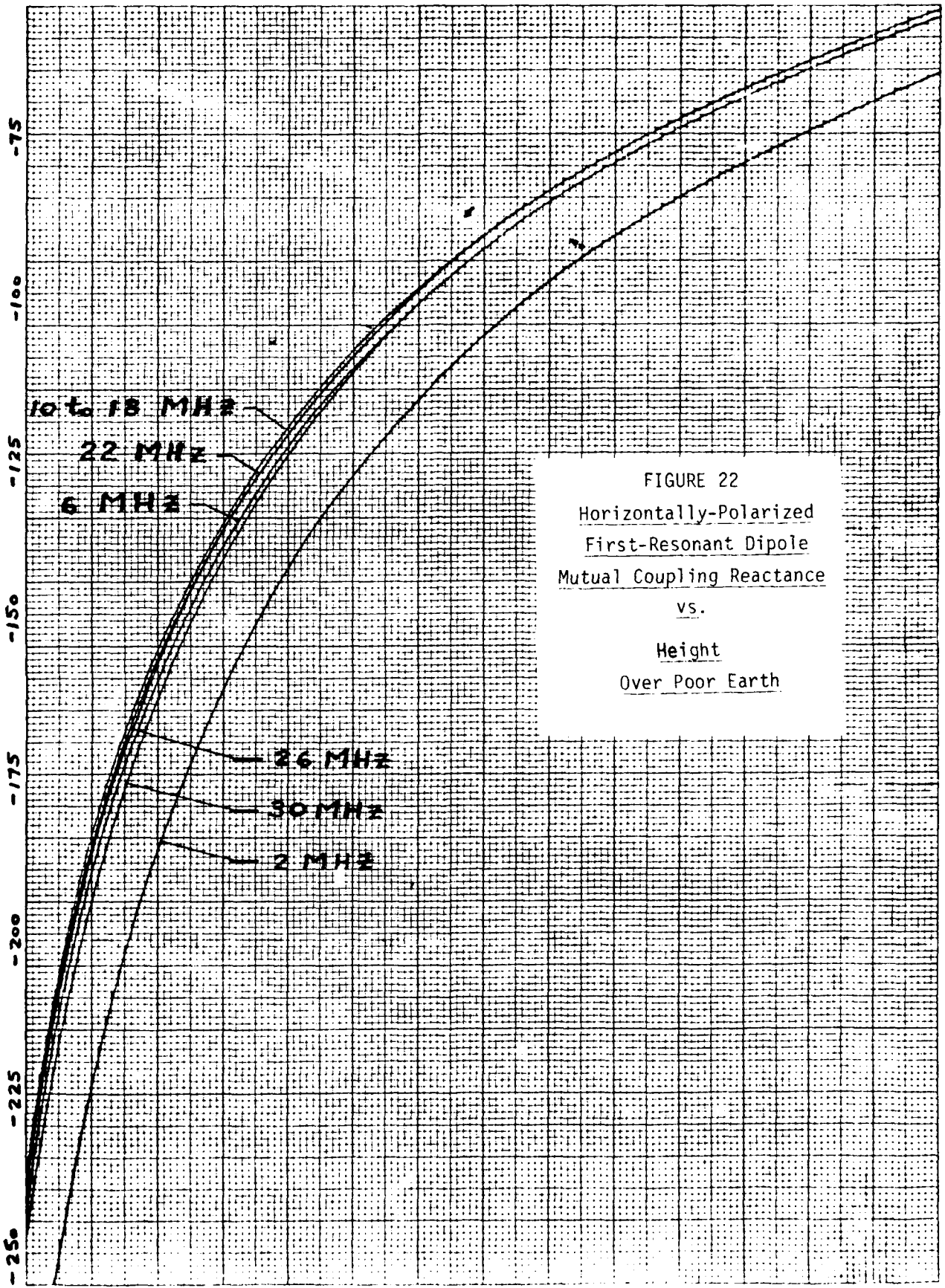


FIGURE 22  
 Horizontally-Polarized  
 First-Resonant Dipole  
 Mutual Coupling Reactance  
 vs.  
 Height  
 Over Poor Earth

$H_2$ , Wavelength

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K-E 10 X 10 TO 1/4 INCH 7 X 10 INCHES  
KEUFFEL & ESSER CO. MADE IN U.S.A.

$X_{21}$ , Ohms

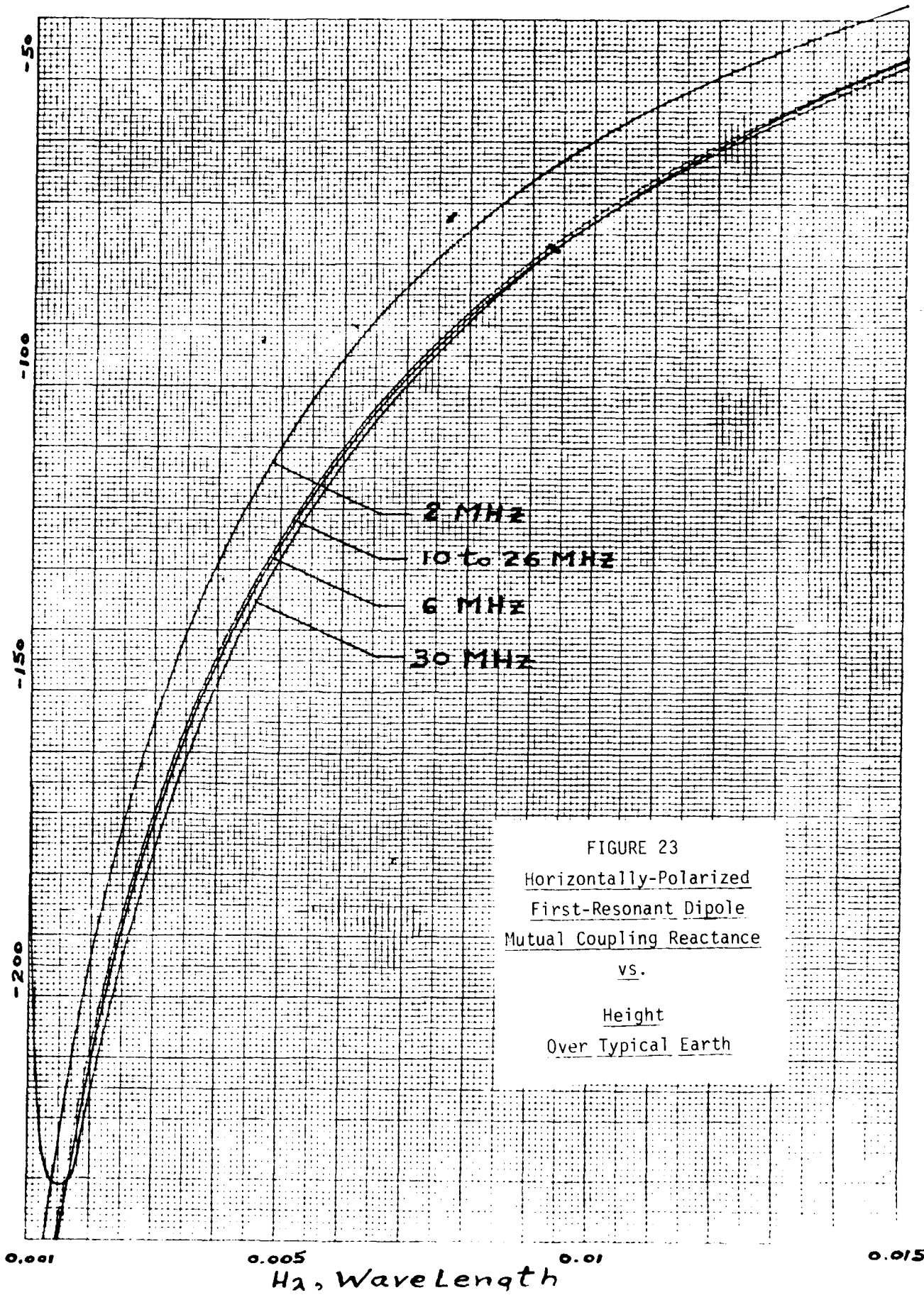


FIGURE 23  
 Horizontally-Polarized  
 First-Resonant Dipole  
 Mutual Coupling Reactance  
 vs.  
 Height  
 Over Typical Earth

$\lambda_2$ , WaveLength

0.015

46 1323

K&E 10 X 10 TO 1/4 INCH 7 X 10 INCHES  
KEUFFEL & ESSER CO. MADE IN U.S.A.

$X_{21}$ , Ohms

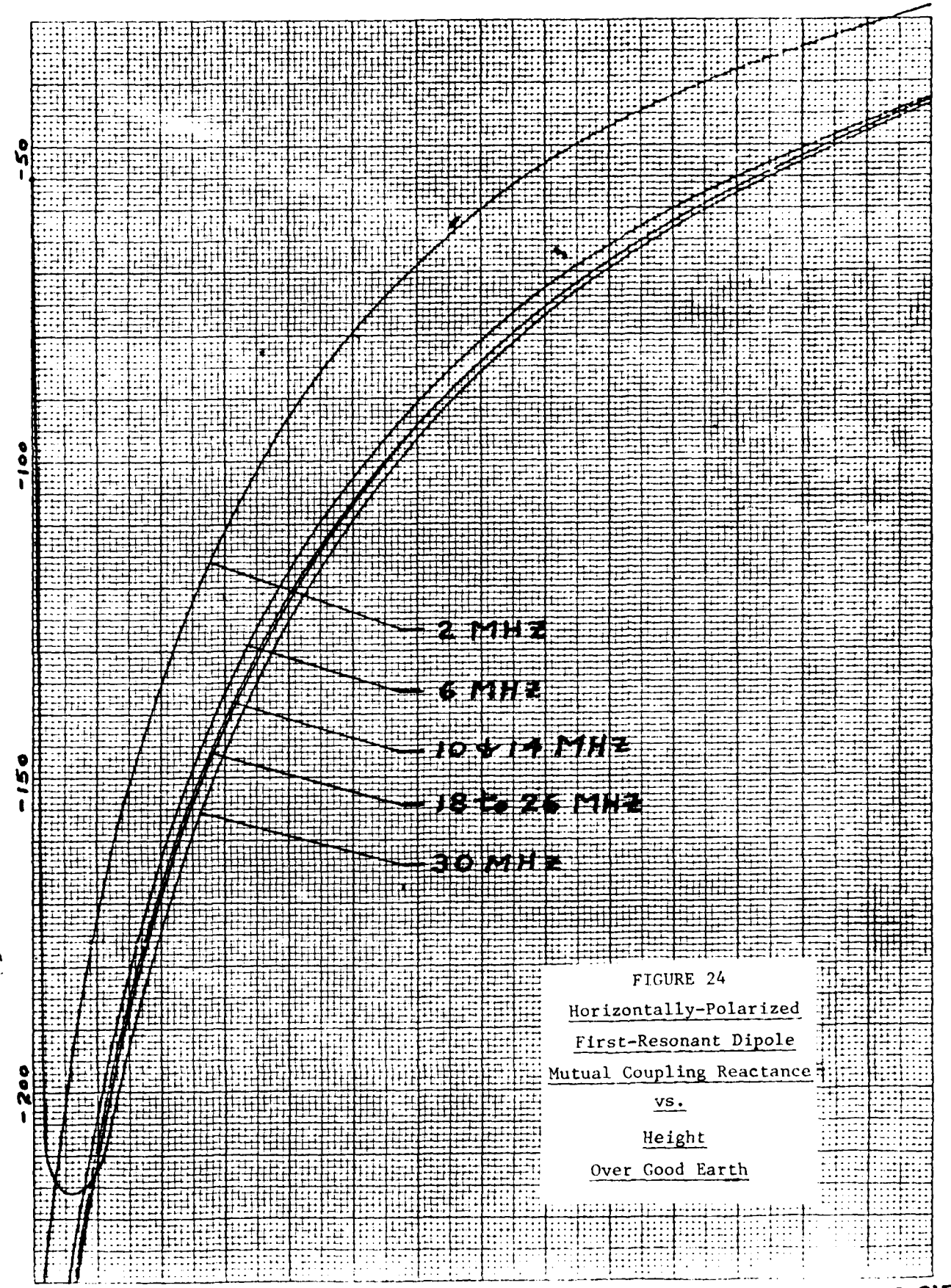


FIGURE 24  
Horizontally-Polarized  
First-Resonant Dipole  
Mutual Coupling Reactance  
 vs.  
Height  
Over Good Earth

0.001

0.005

0.01

0.015

$H_2$ . Wavelength

46 1323

K&E  
10 X 10 TO 1/2 INCH 7 X 10 INCHES  
KEUFFEL & ESSER CO. MADE IN U.S.A.

$X_{21}$ , Ohms

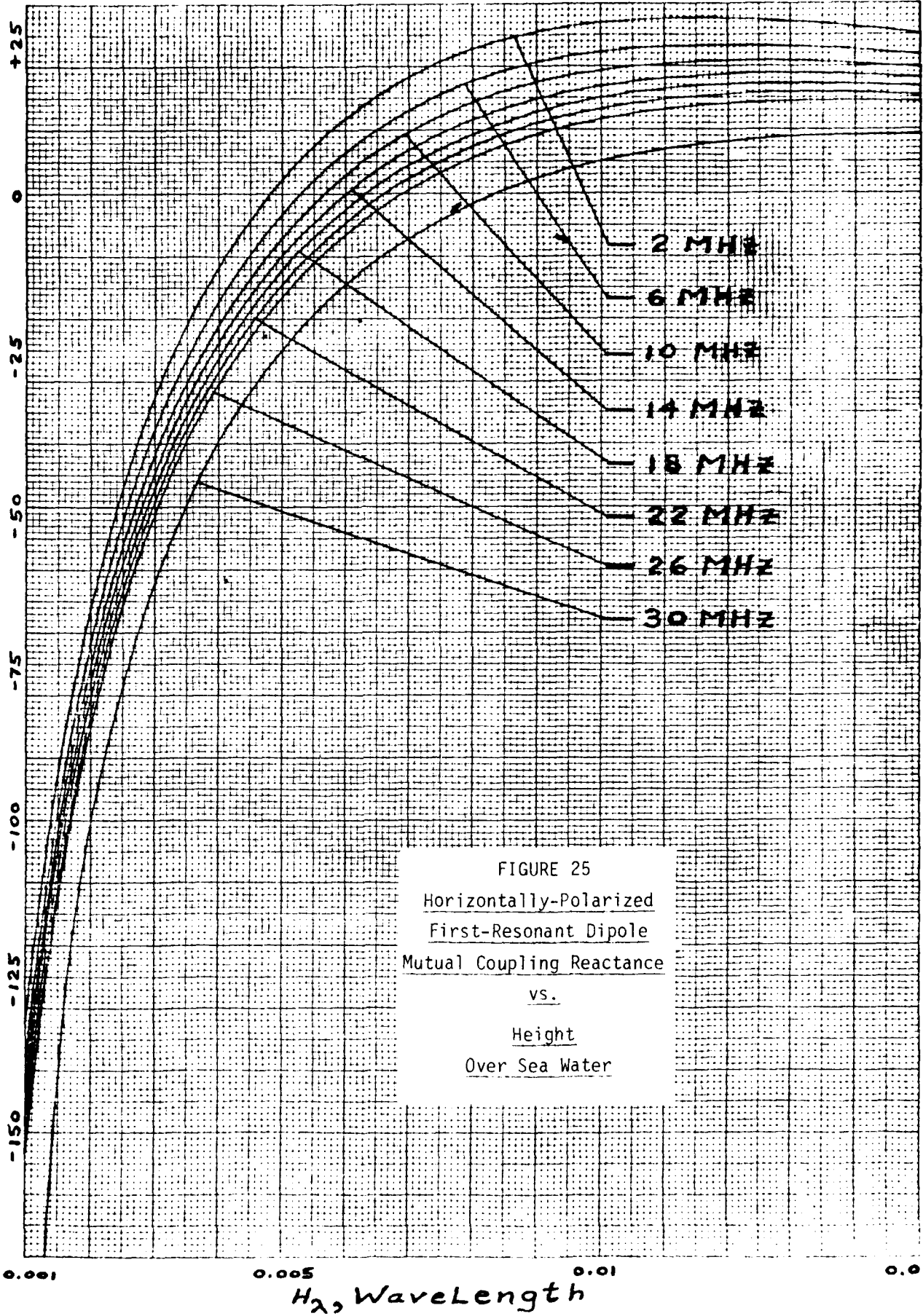


FIGURE 25  
 Horizontally-Polarized  
 First-Resonant Dipole  
 Mutual Coupling Reactance  
 vs.  
 Height  
 Over Sea Water

0.001

0.005

0.01

0.015

$\lambda$ , WaveLength

46 1323

K&E 10 X 10 TO 1/4 INCH 7 X 10 INCHES KEUFFEL & ESSER CO. MADE IN U.S.A.

$X_{21}$ , Ohms

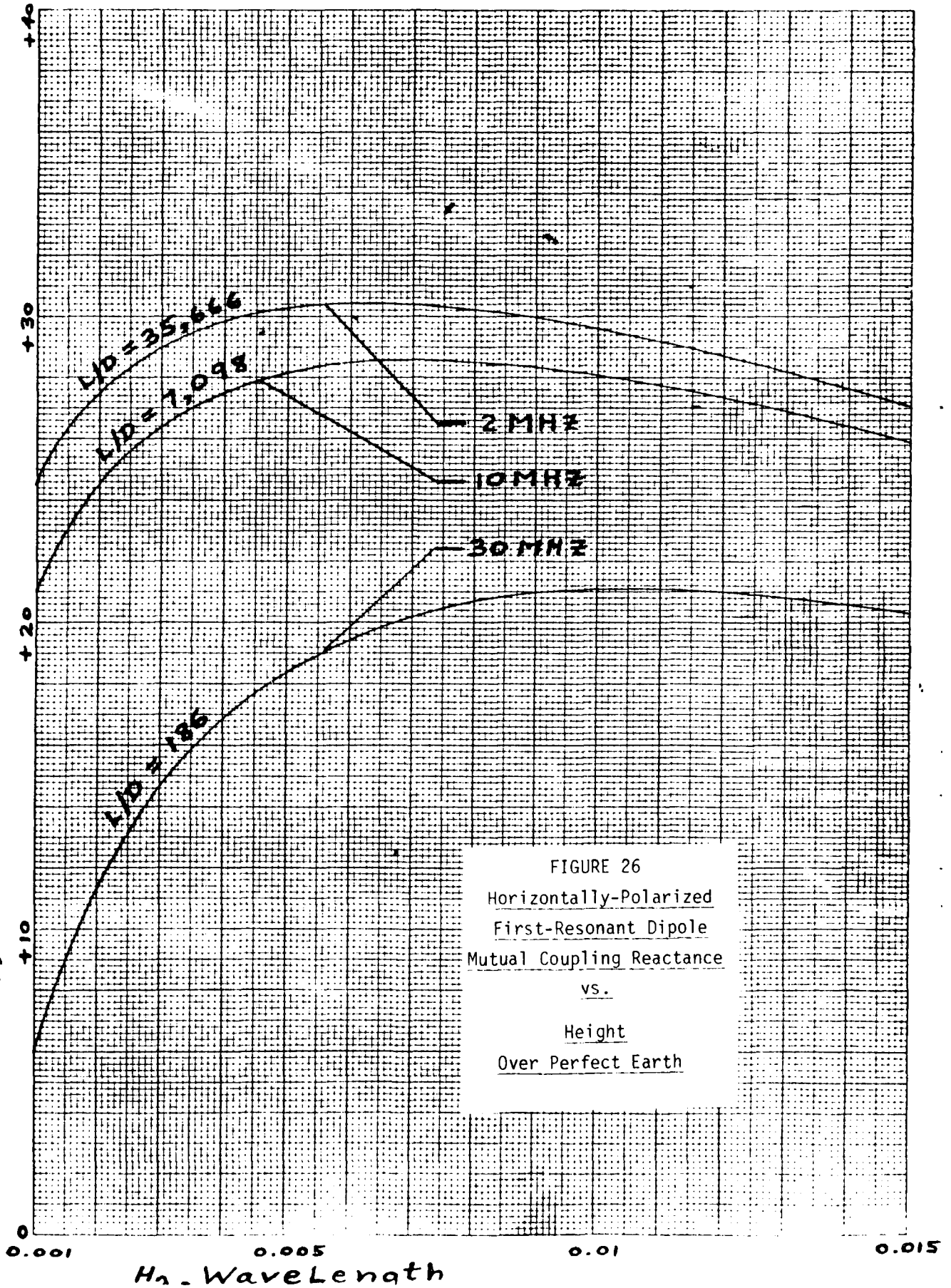


FIGURE 26  
 Horizontally-Polarized  
 First-Resonant Dipole  
 Mutual Coupling Reactance  
 vs.  
 Height  
 Over Perfect Earth

46 1323

K-E 10 X 10 TO 1/4 INCH 7 X 10 INCHES  
KEUFEL & ESSER CO. MAN. IN U.S.A.

$X_{21}$ , Ohms

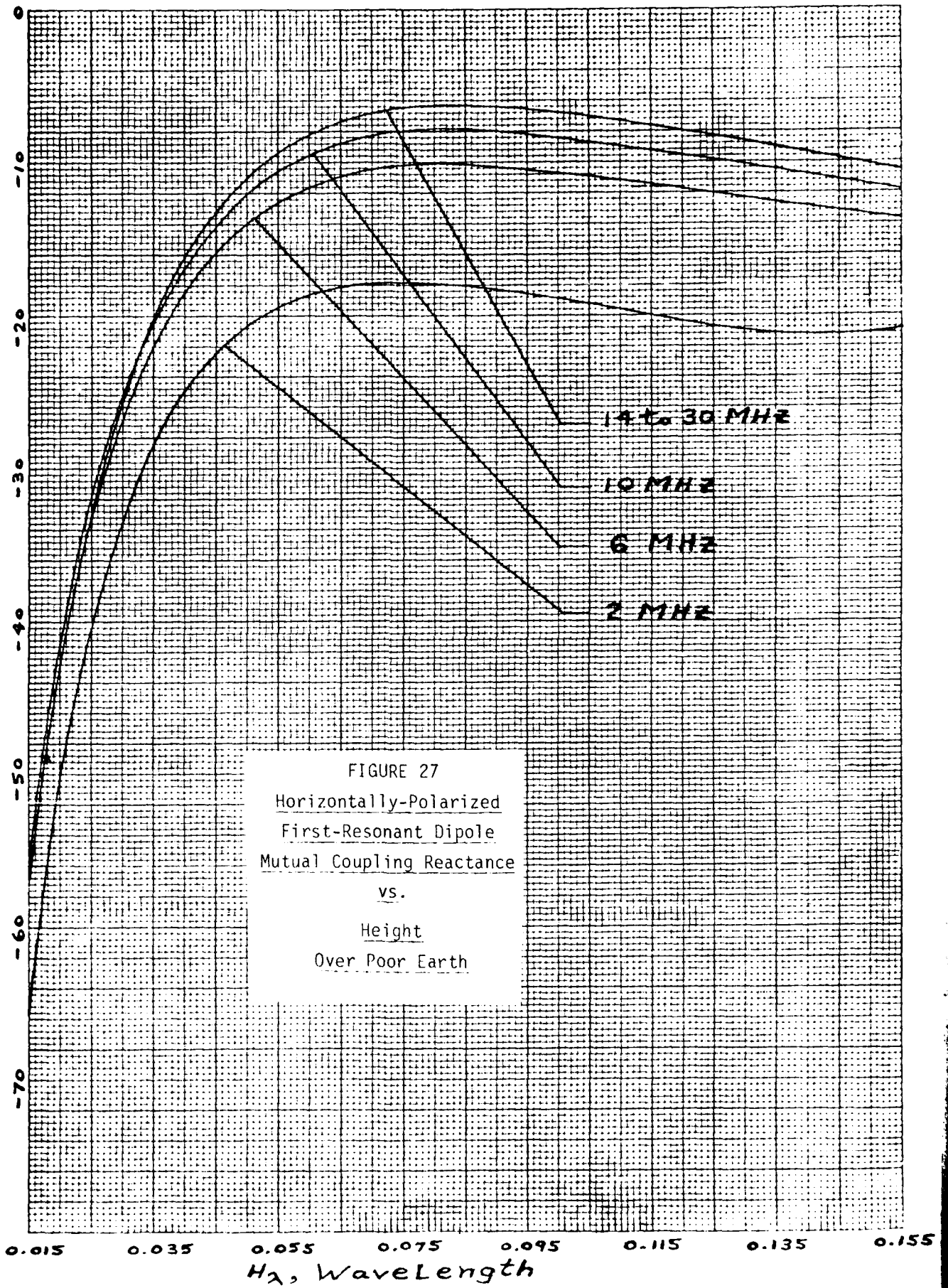


FIGURE 27  
Horizontally-Polarized  
First-Resonant Dipole  
Mutual Coupling Reactance  
vs.  
Height  
Over Poor Earth

46 1323

K&E 10 X 10 TO 1/4 INCH 7 X 10 INCHES  
KEUFFEL & ESSER CO. MADE IN U.S.A.

$X_{21}$ , Ohms

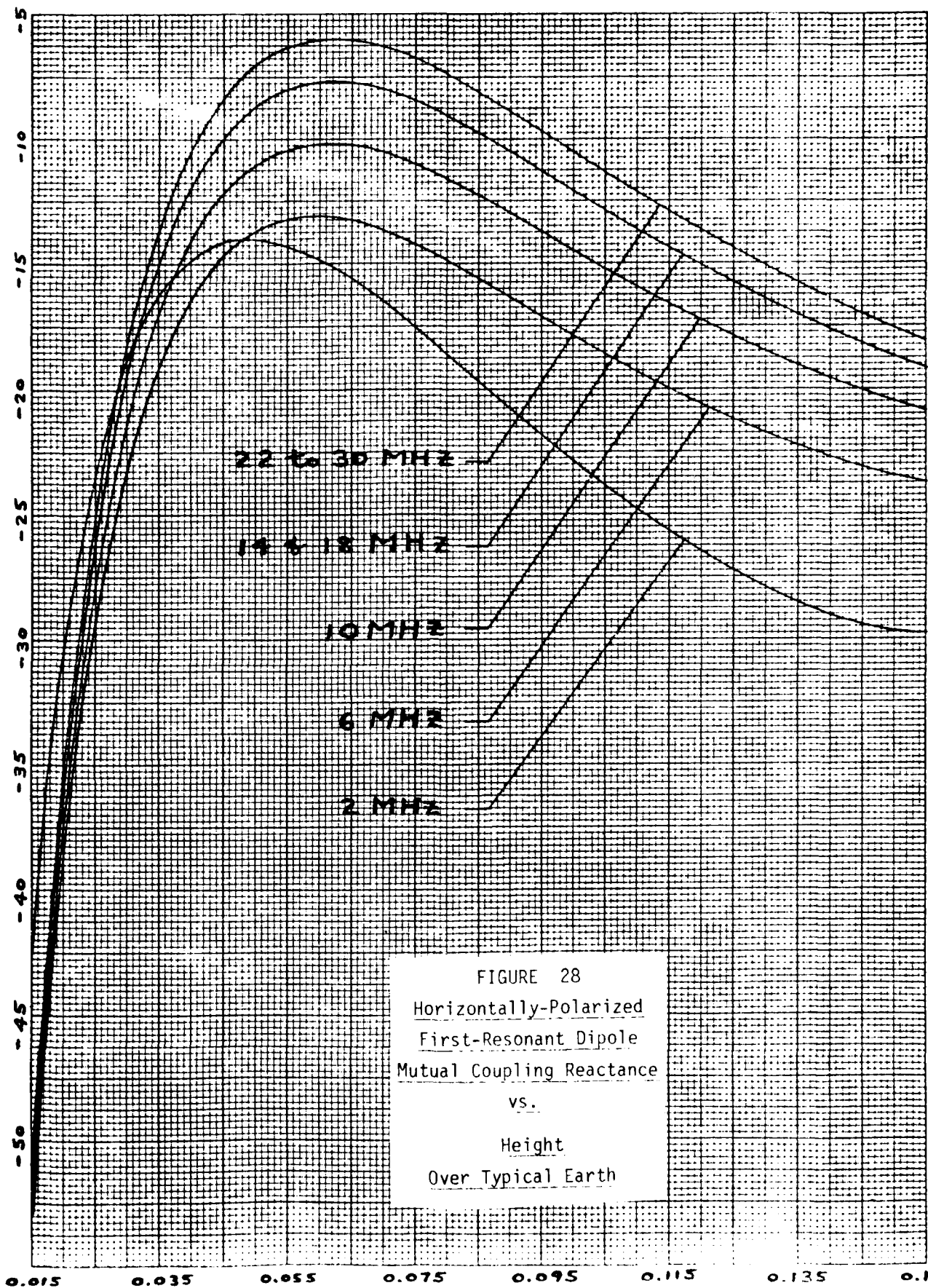


FIGURE 28  
 Horizontally-Polarized  
 First-Resonant Dipole  
 Mutual Coupling Reactance  
 vs.  
 Height  
 Over Typical Earth

$H_2$ , Wavelength

46 1323

K·E 10 X 10 TO 1/8 INCH 7 X 10 INCHES  
KEUFFEL & ESSER CO. MADE IN U.S.A.

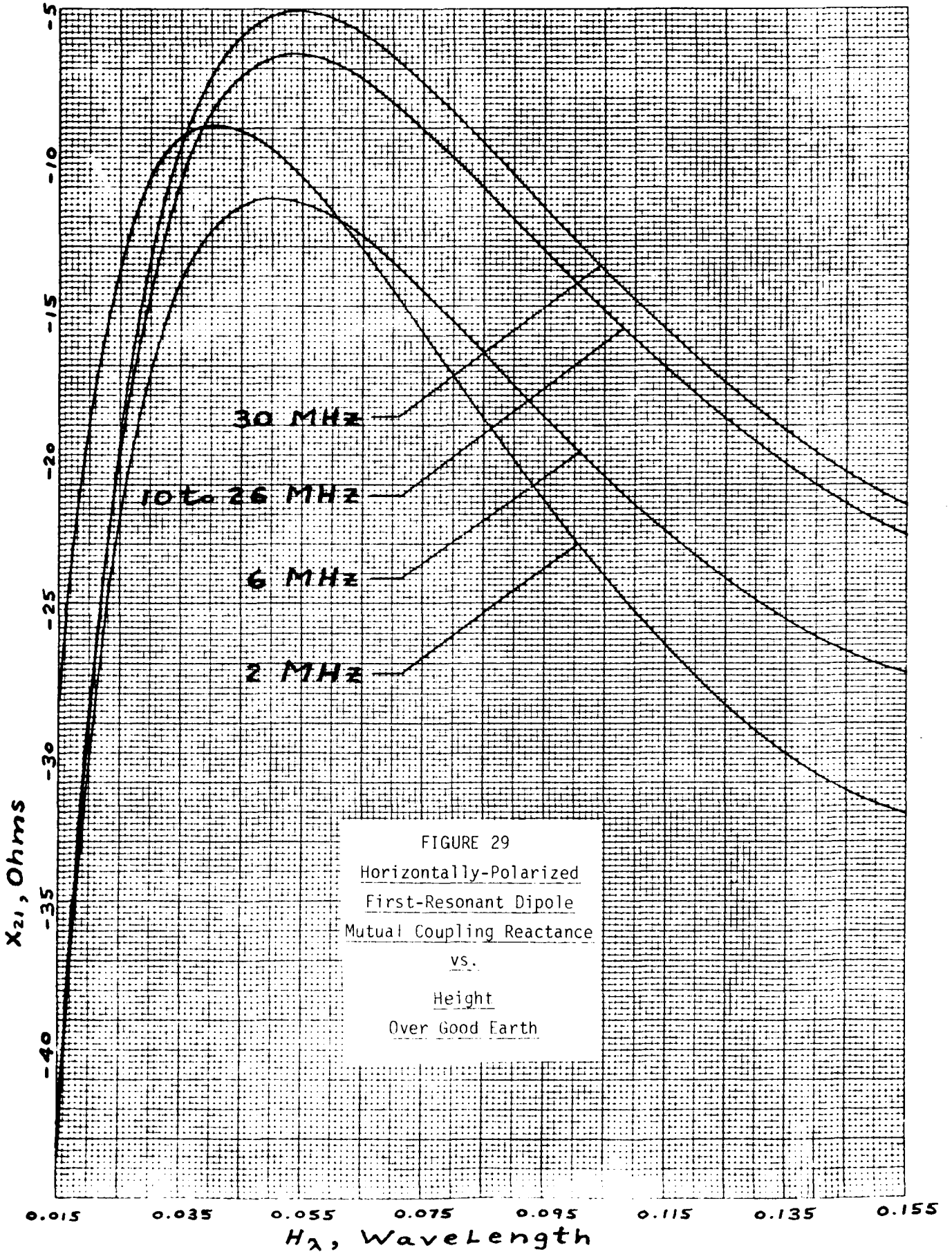


FIGURE 29  
Horizontally-Polarized  
First-Resonant Dipole  
Mutual Coupling Reactance  
vs.  
Height  
Over Good Earth

46 1323

K·E 10 X 10 TO 41 INCH 7 X 10 INCHES  
KEUFFEL & ESSER CO. MADE IN U.S.A.

$X_{21}$ , Ohms

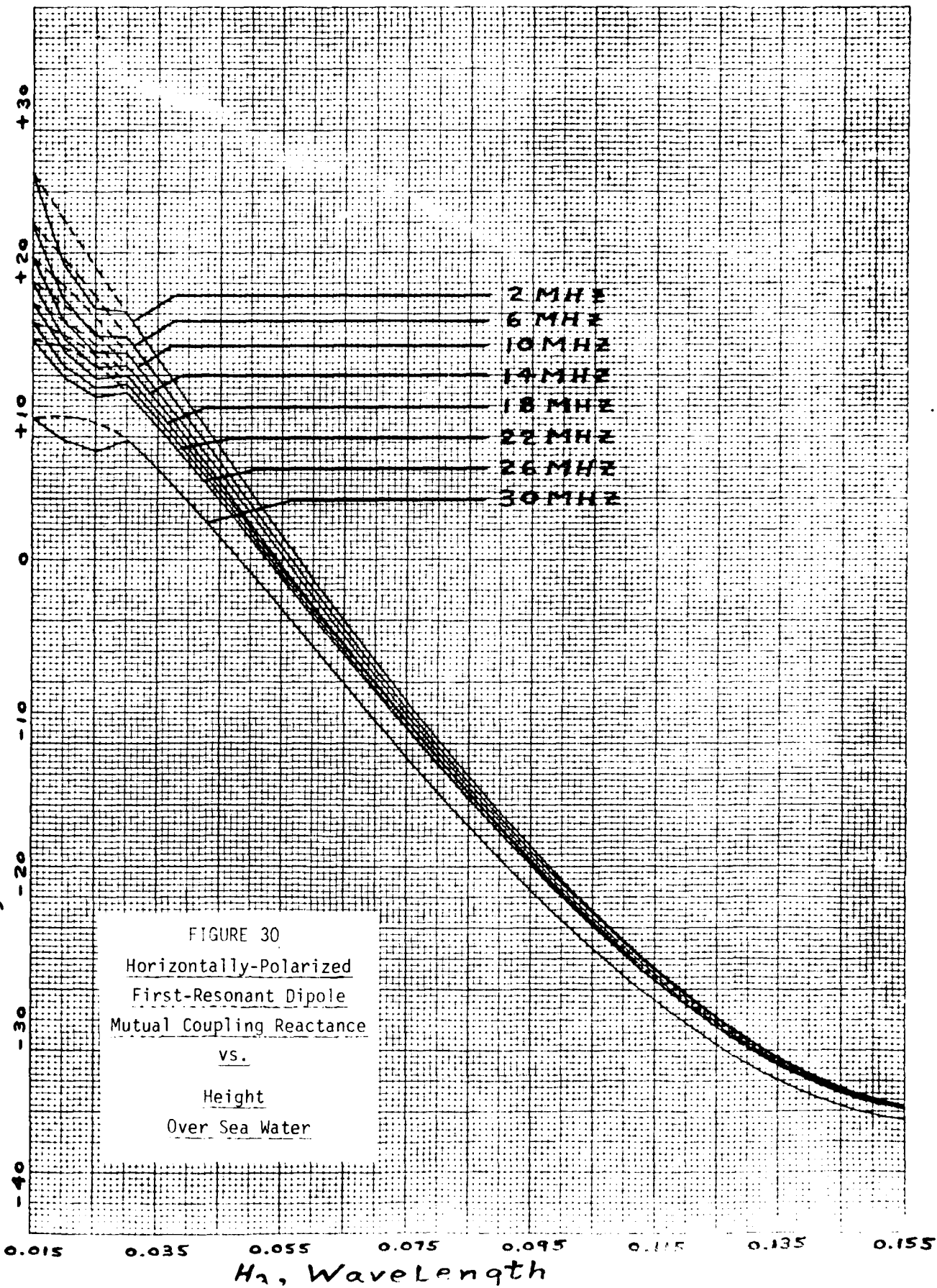


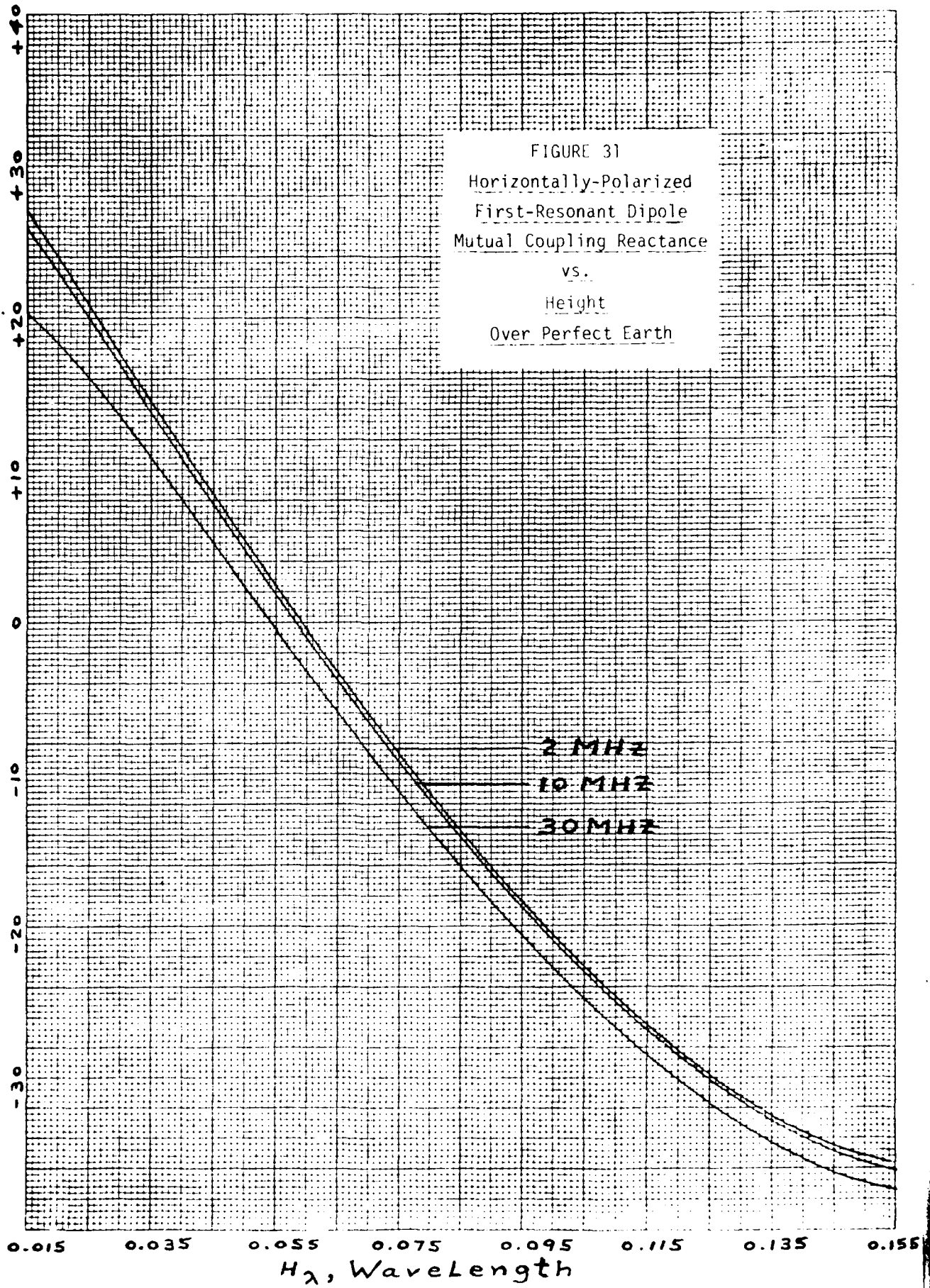
FIGURE 30  
 Horizontally-Polarized  
 First-Resonant Dipole  
 Mutual Coupling Reactance  
 vs.  
 Height  
 Over Sea Water

$H_2$ , Wavelength

46 1323

K&E 10 X 10 TO 1/8 INCH 7 X 10 INCHES  
KEUFFEL & ESSER CO. MADE IN U.S.A.

$X_{21}$ , Ohms



46 1323

K&E 10 X 10 TO 1/4 INCH 7 X 10 INCHES  
KEUFFEL & ESSER CO. MADE IN U.S.A.

$X_{21}$ , Ohms

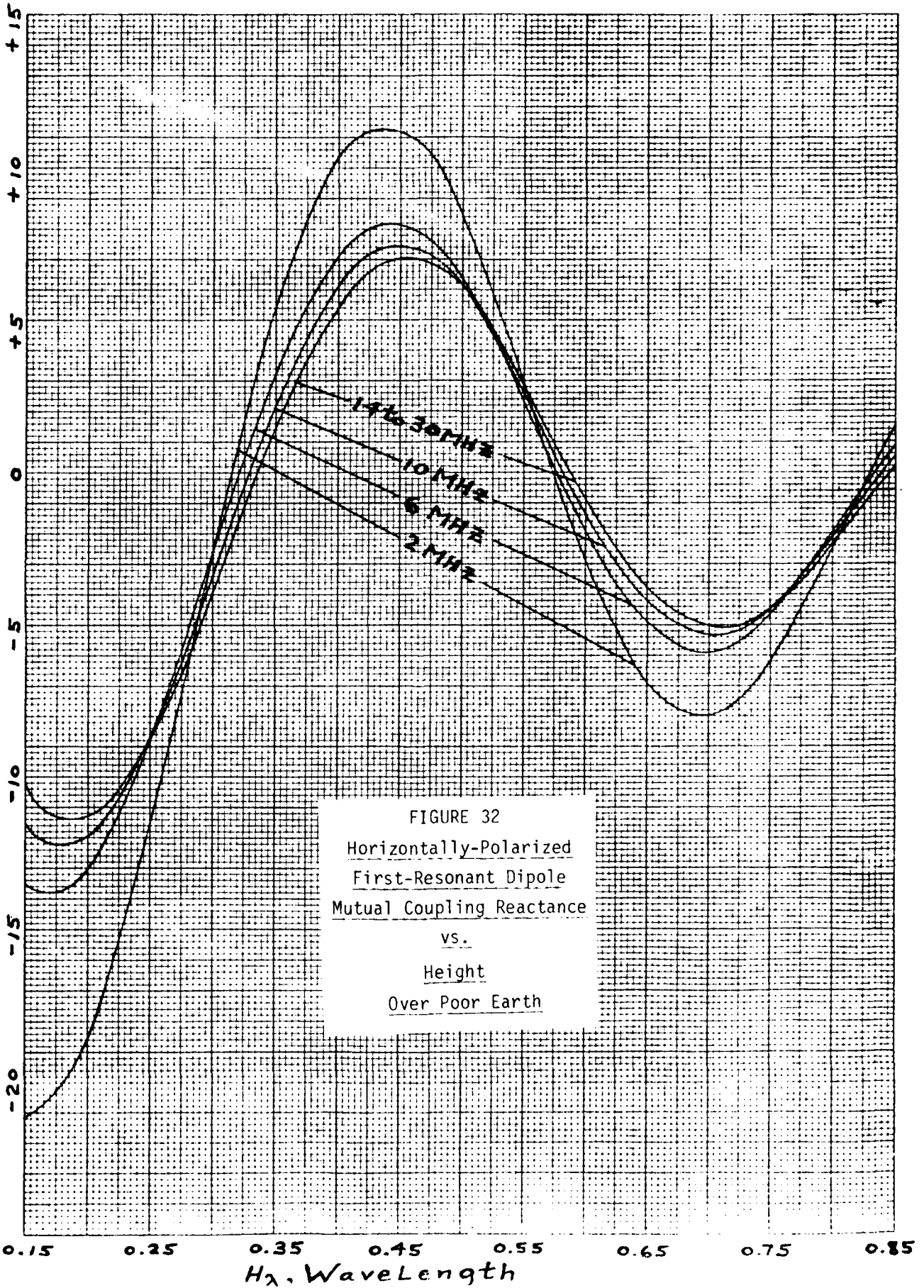


FIGURE 32  
 Horizontally-Polarized  
 First-Resonant Dipole  
 Mutual Coupling Reactance  
 vs.  
 Height  
 Over Poor Earth

46 1323

K·E 10 X 10 TO 14 INCH. 7 X 10 INCHES  
 HEUFFEL & ESSER CO. MADE IN U.S.A.

$X_{21}$ , Ohms

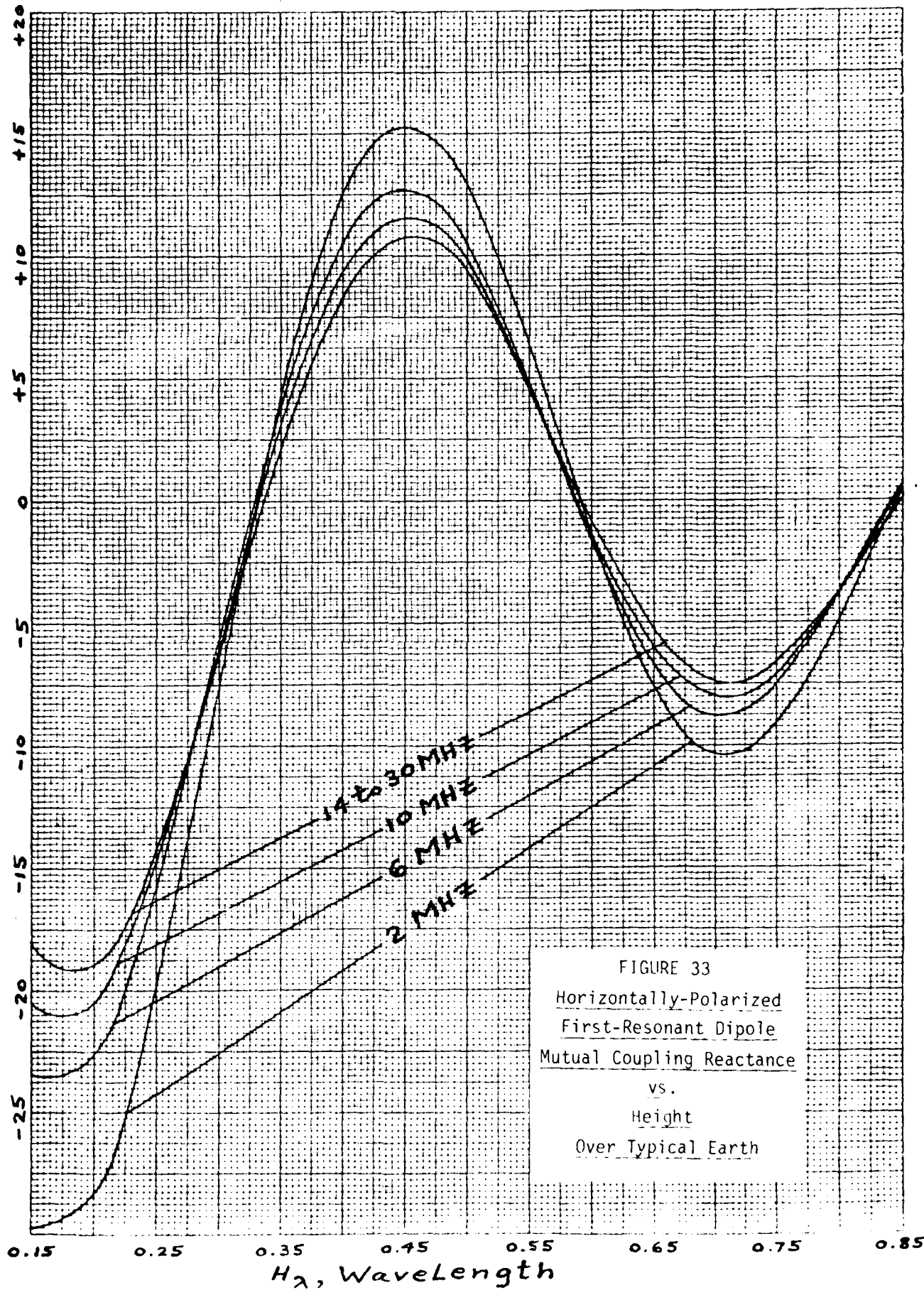


FIGURE 33  
 Horizontally-Polarized  
 First-Resonant Dipole  
 Mutual Coupling Reactance  
 vs.  
 Height  
 Over Typical Earth

46 1323

K&E 10 X 10 TO 1/4 INCH 7 X 10 INCHES  
KEUFFEL & ESSNER CO. MADE IN U.S.A.

$X_{21}$ , Ohms

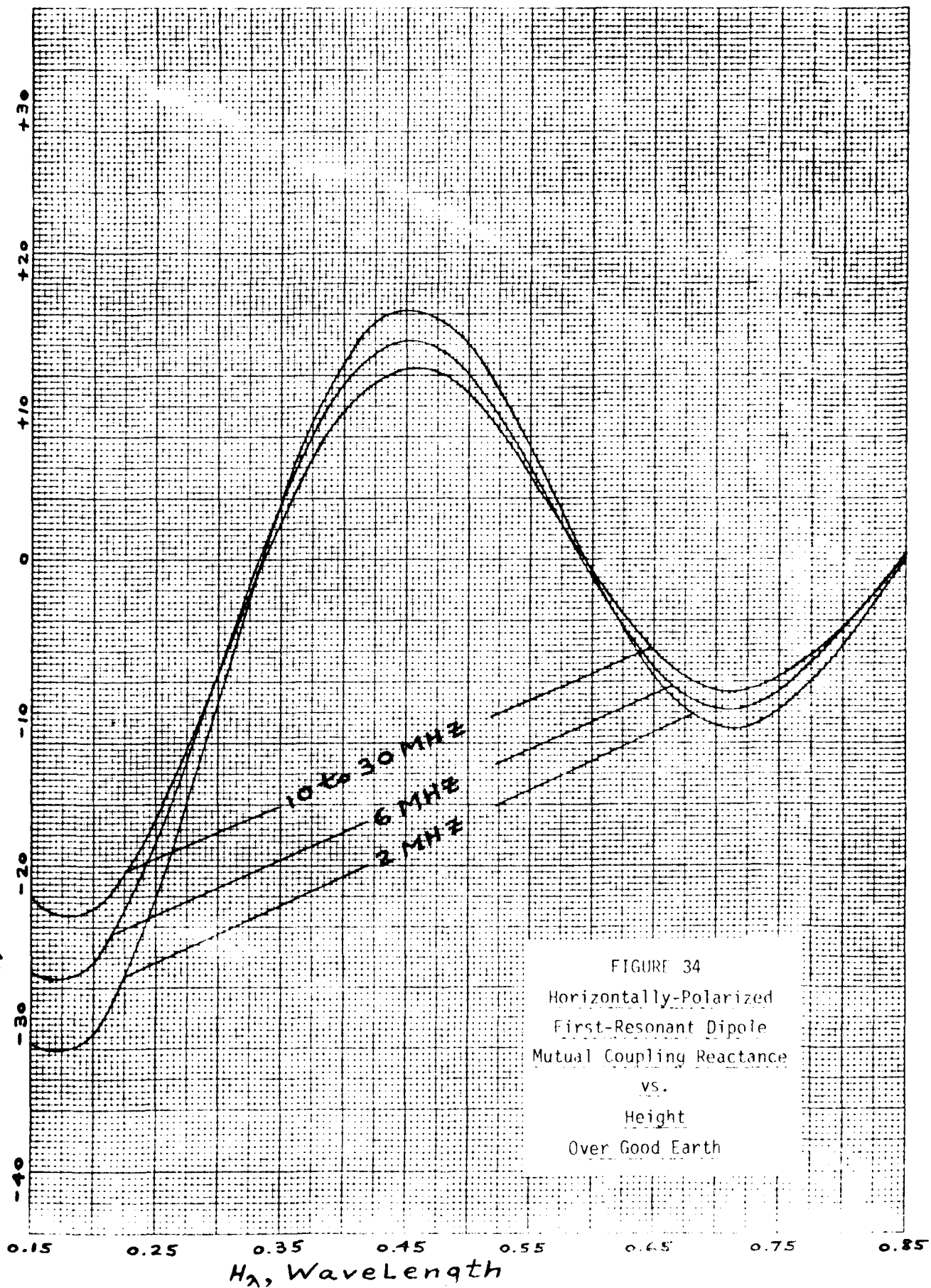


FIGURE 34  
Horizontally-Polarized  
First-Resonant Dipole  
Mutual Coupling Reactance  
vs.  
Height  
Over Good Earth

46 1323

K·E 10 X 10 TO 1/2 INCH 7 X 10 INCHES  
KEUFFEL & ESSER CO. MADE IN U.S.A.

$X_{21}$ , Ohms

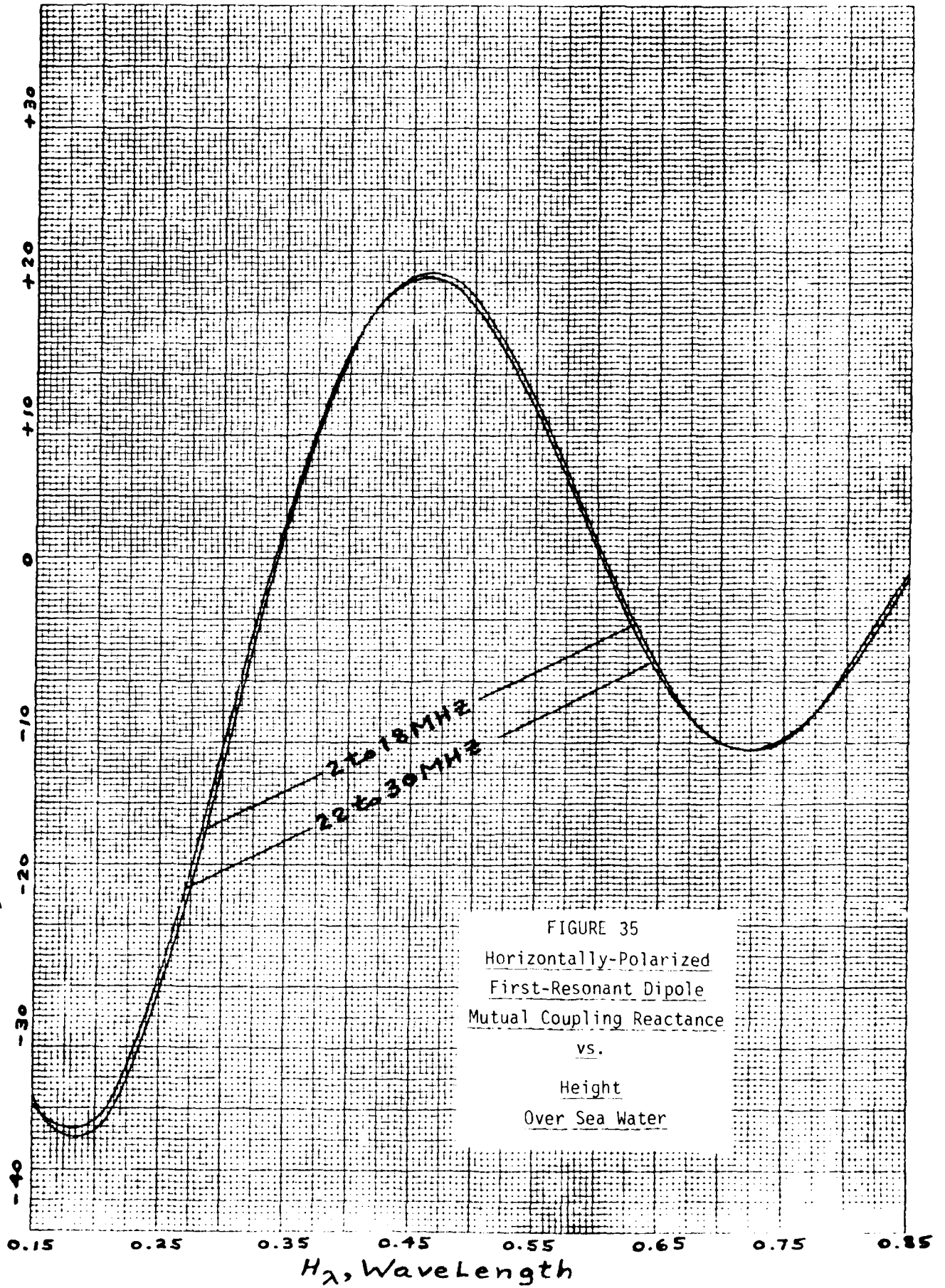


FIGURE 35  
Horizontally-Polarized  
First-Resonant Dipole  
Mutual Coupling Reactance  
vs.  
Height  
Over Sea Water

46 1323

K·E 10 X 10 TO 1/4 INCH 7 X 10 INCHES  
KEUFFEL & ESSER CO. MADE IN U.S.A.

$X_{21}$ , Ohms

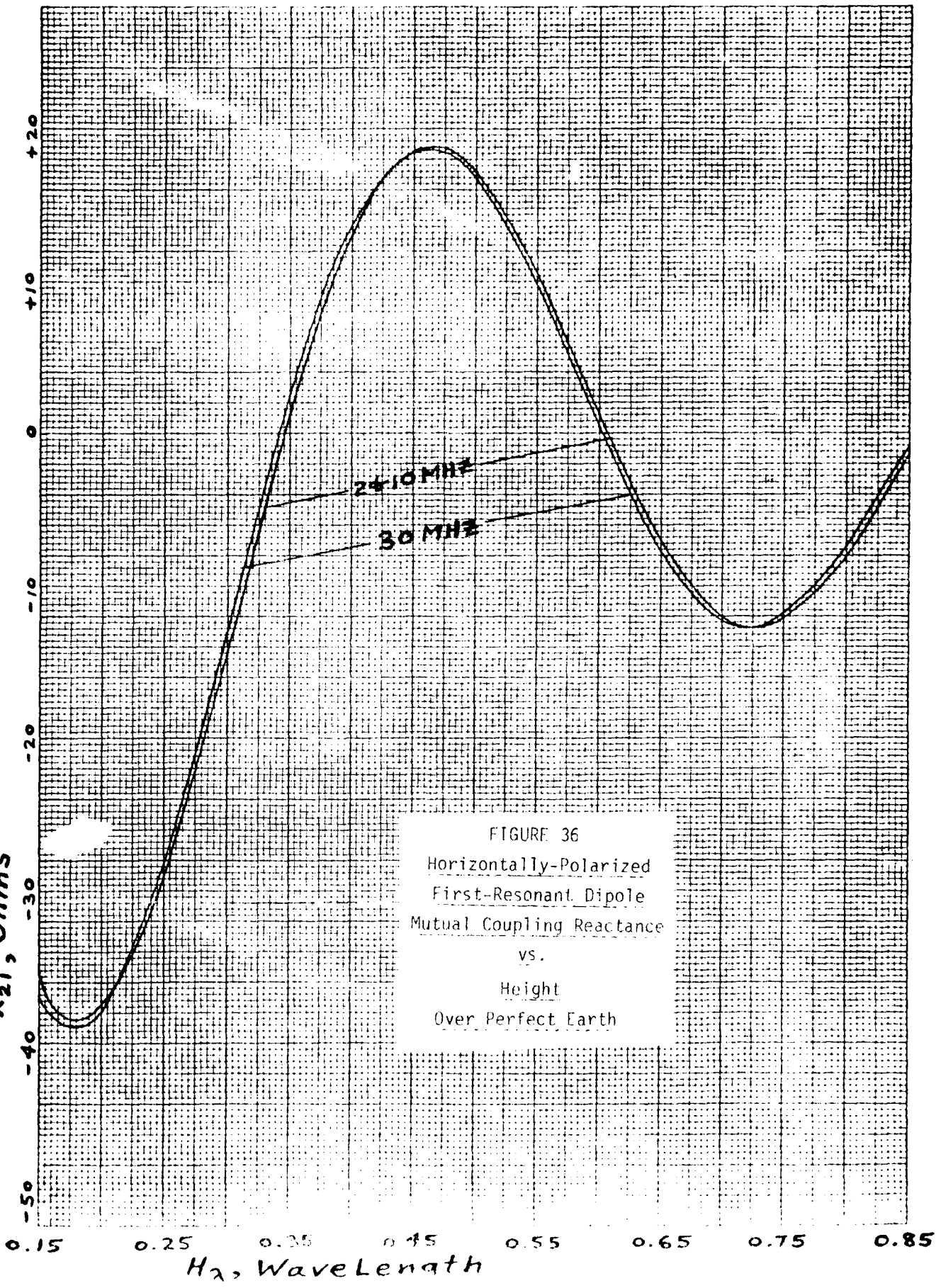
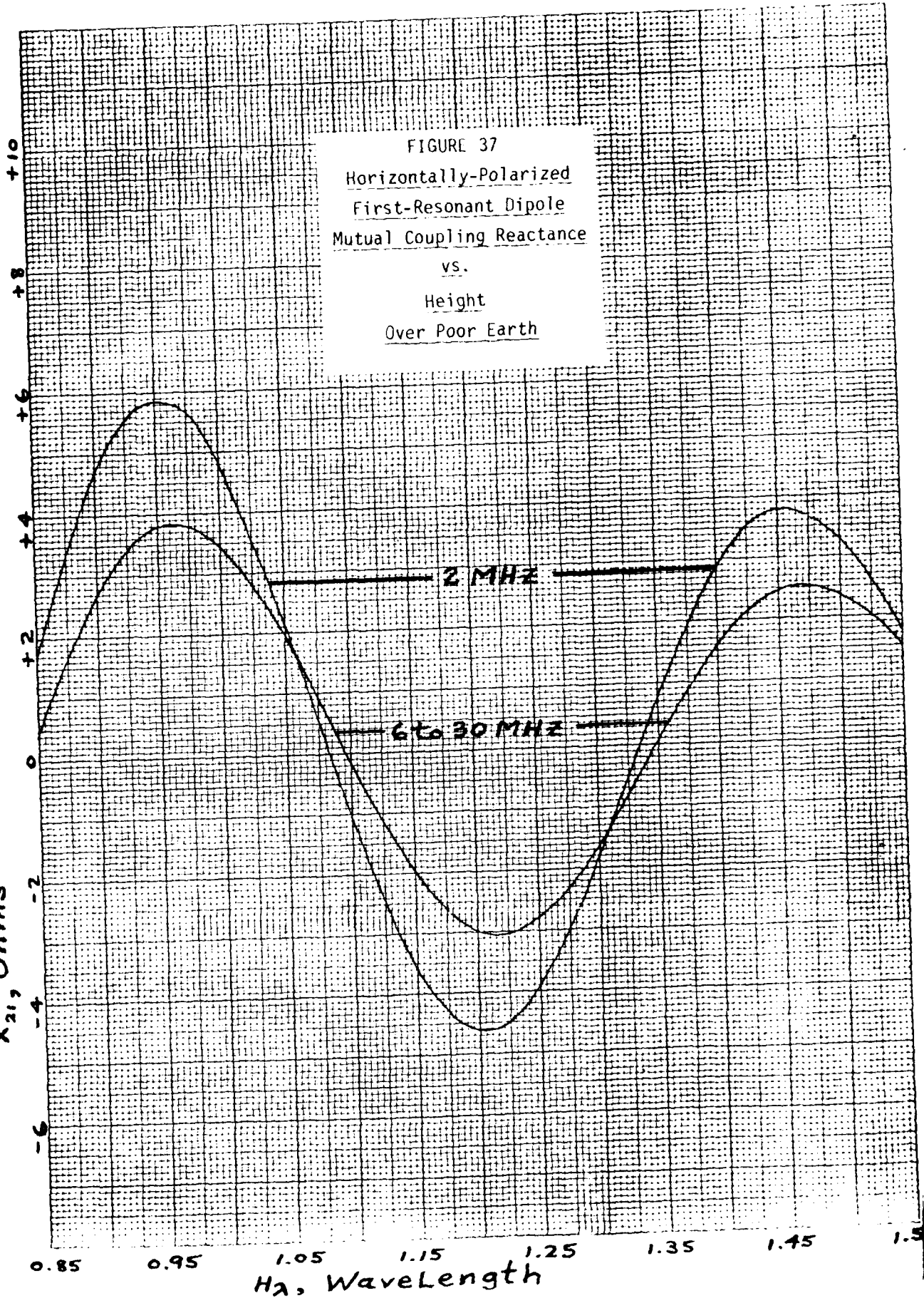


FIGURE 36  
 Horizontally-Polarized  
 First-Resonant Dipole  
 Mutual Coupling Reactance  
 vs.  
 Height  
 Over Perfect Earth

46 1323

K-E 10 X 10 TO 1/4 INCH 7 X 10 INCHES  
KEUFFEL & ESSER CO. MADE IN U.S.A.

$X_{21}$ , Ohms



$\lambda$ , WaveLength

K-E 10 X 10 TO 1/4 INCH 7 X 10 INCHES  
KEUFFEL & ESSER CO. MADE IN U.S.A.

46 1323

$X_{21}$ , Ohms

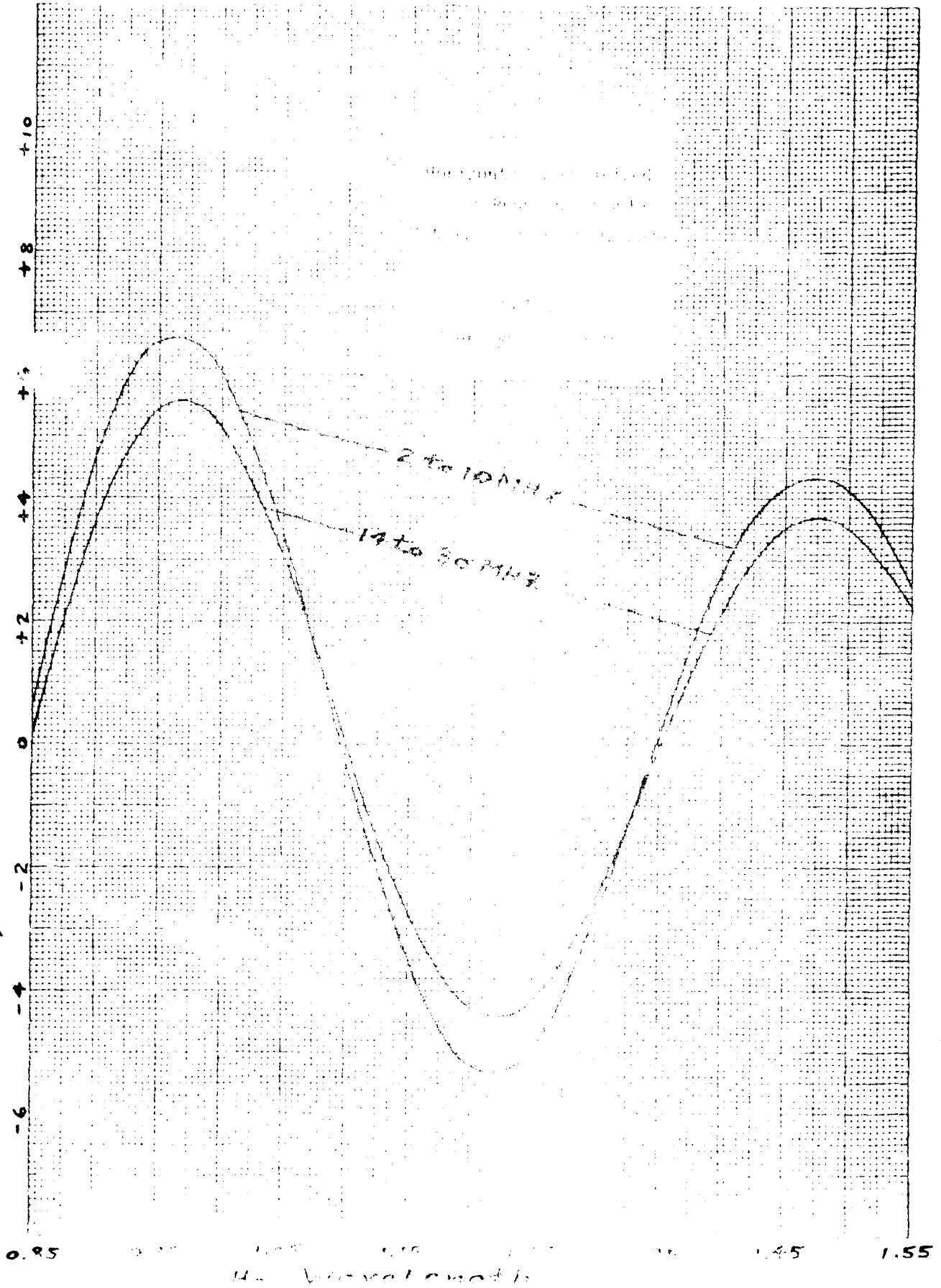
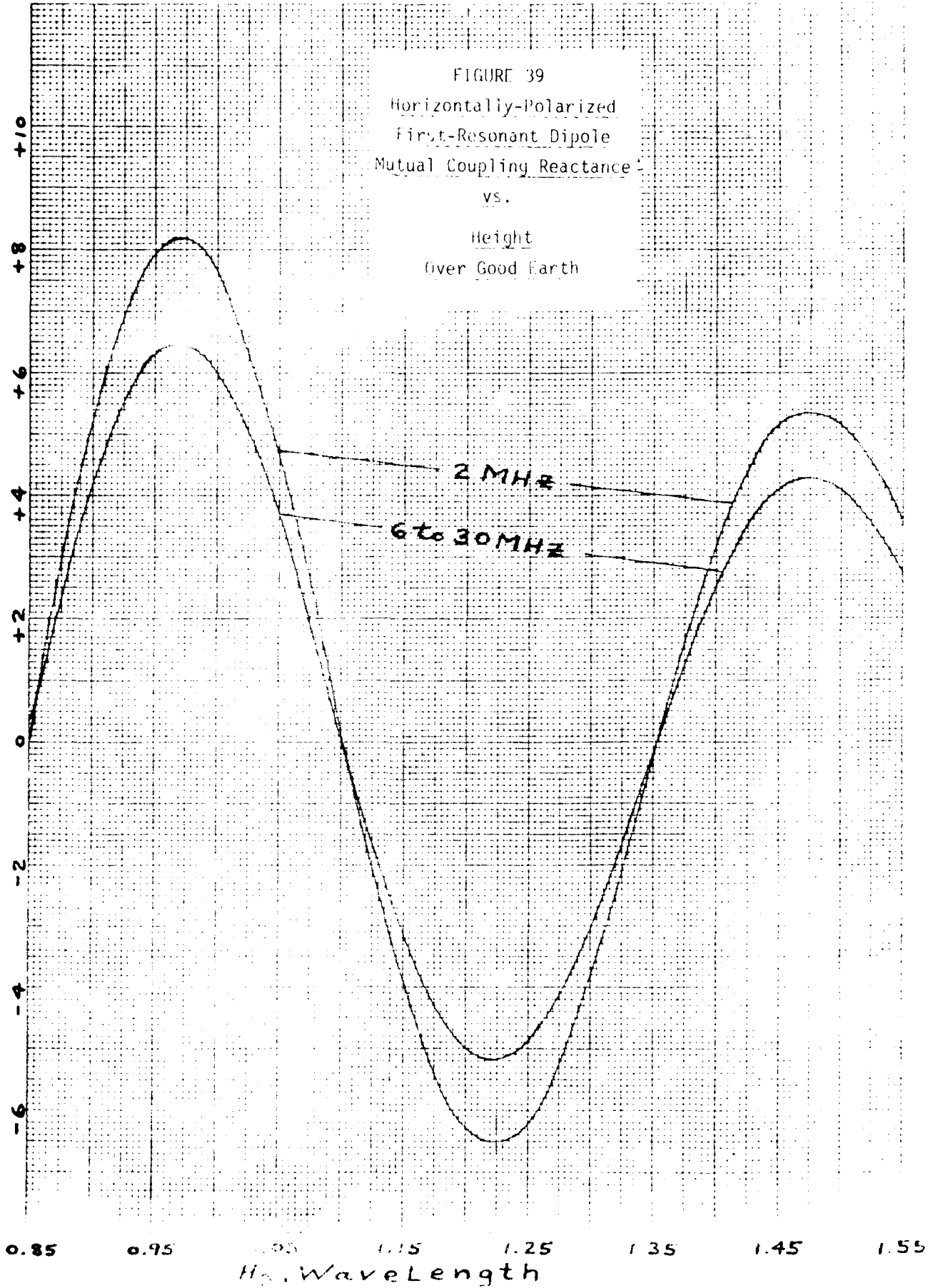


FIGURE 39  
Horizontally-Polarized  
First-Resonant Dipole  
Mutual Coupling Reactance  
vs.  
Height  
Over Good Earth

46 1325

REPRODUCED FROM THE PROCEEDINGS OF THE IRE, NOVEMBER 1958, VOL. 46, NO. 11, P. 1325

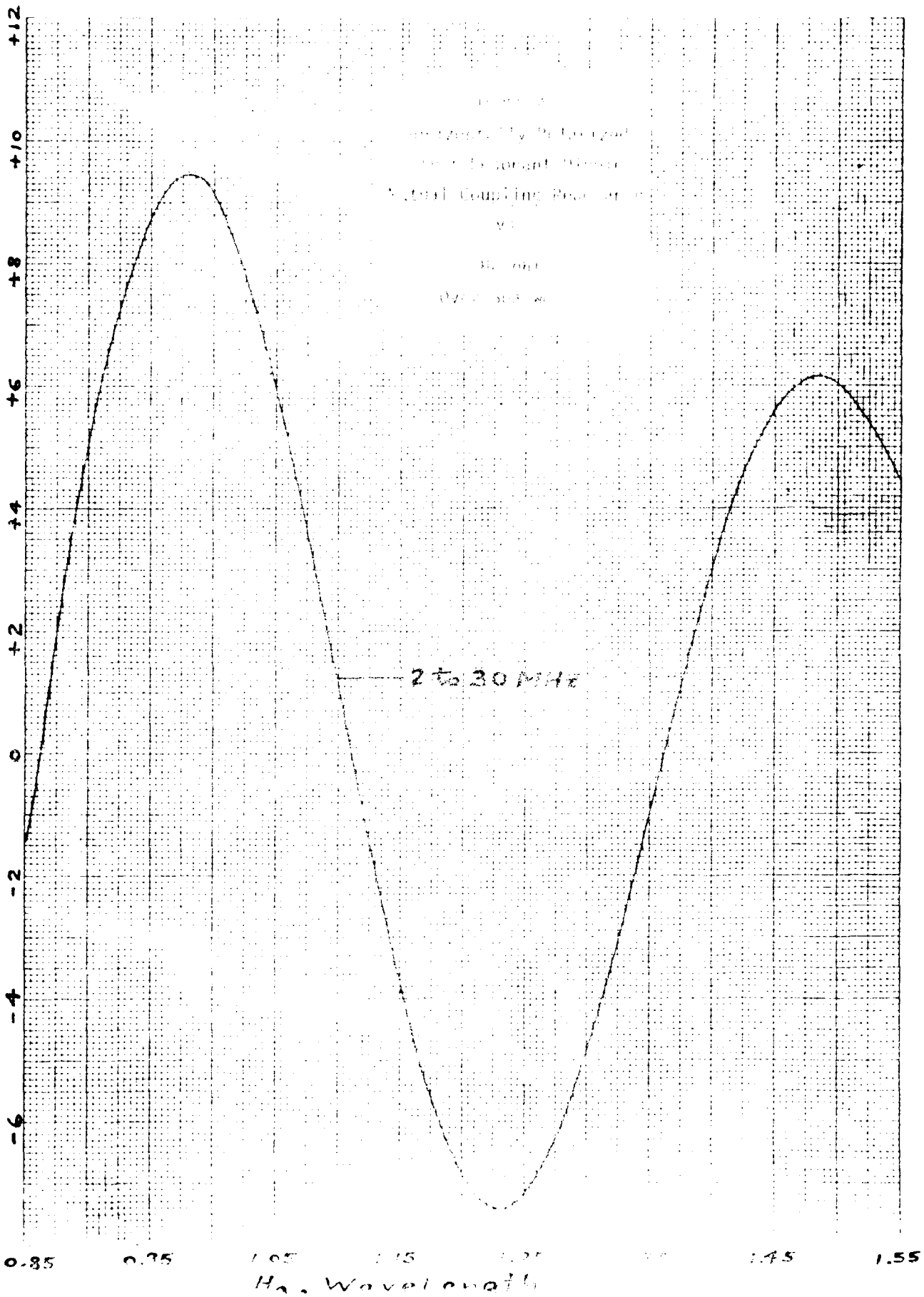
$X_{21}$ , Ohms



46 1323

K-E 10 X 10 TO 1/4 INCH  
KEUFFEL & ESSER CO. MADE IN U.S.A.

$X_{21}$ , Ohms



46 1323

K·S·E. LIAISON BUREAU 2 A. PARIS  
MICRO-RESSOURCES

$X_{21}$ , Ohms

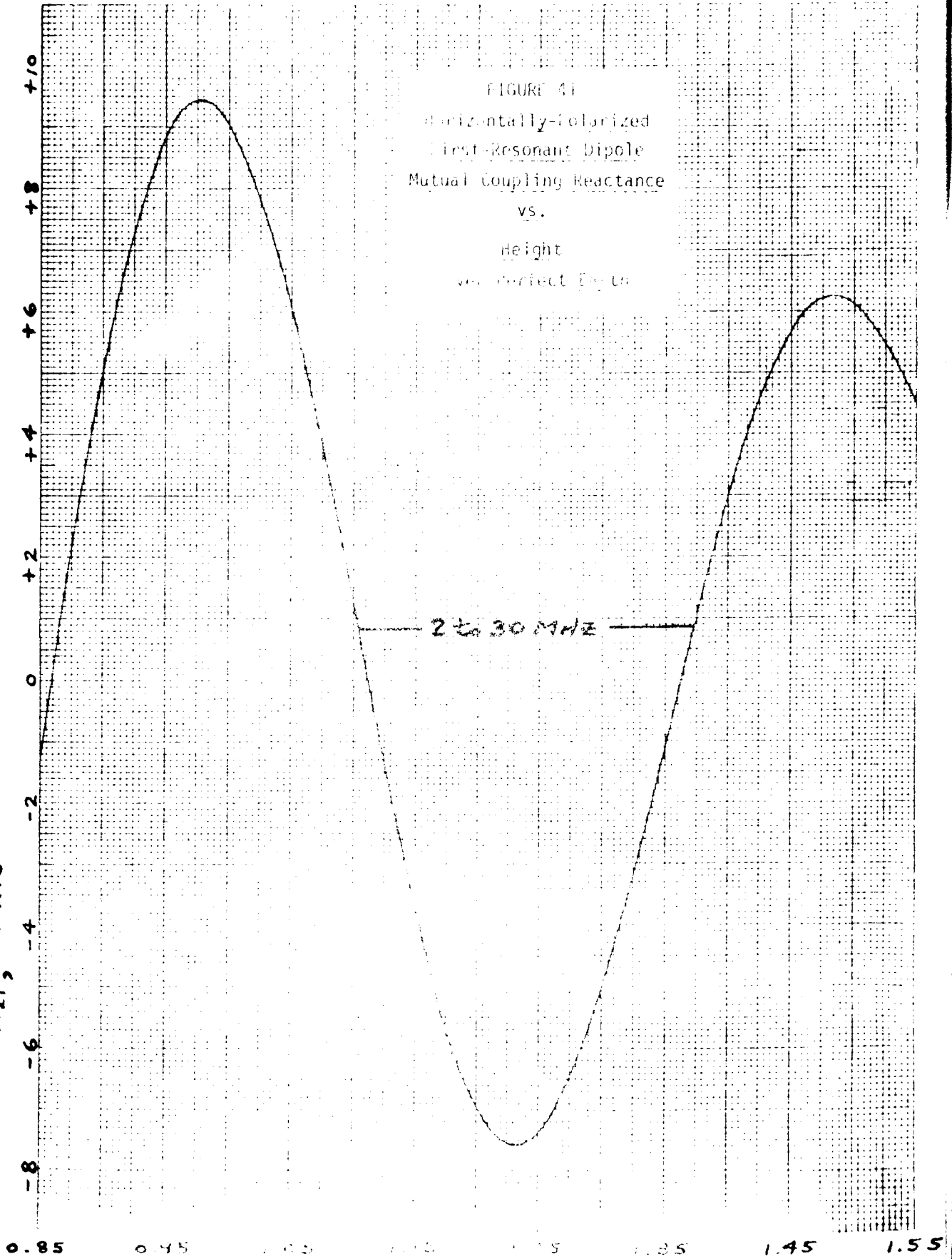


FIGURE 41  
 horizontally-polarized  
 first-resonant dipole  
 Mutual Coupling Reactance  
 vs.  
 Height  
 vs. Perfect Dipole

2 to 30 MHz



The results plotted on Figure 30 show that NEC solutions are not correct when the dipole height is  $0.015 \leq h_{\lambda} \leq 0.03$  wavelength over sea water. This is consistent with the results obtained in Section II, and indicates that NEC - with its existing equations - is not valid over sea water at HF when  $h_{\lambda}$  is in this region.

#### IV. VERTICALLY-POLARIZED MUTUAL RESISTANCE.

The mutual resistance,  $R_{21}$ , results are plotted on Figures 42-46 for  $0.25 \leq h_{\lambda} \leq 0.95$  wavelengths. That is, there are 5 graphs over this range of  $h_{\lambda}$ , one for each different  $\epsilon_{\text{eff}}$ , and the frequency or frequency range is plotted on each graph.

These figures show that mutual resistance is highly positive when this antenna is near ground. At the same time, this mutual resistance is not highly sensitive to changes in frequency or earth electrical properties at HF.

These figures appear to be highly accurate, and vertically-polarized mutual resistance is not very significant at HF when  $h_{\lambda} \geq 0.6$  wavelength over ground with the assumed electrical properties.

#### V. VERTICALLY-POLARIZED MUTUAL REACTANCE.

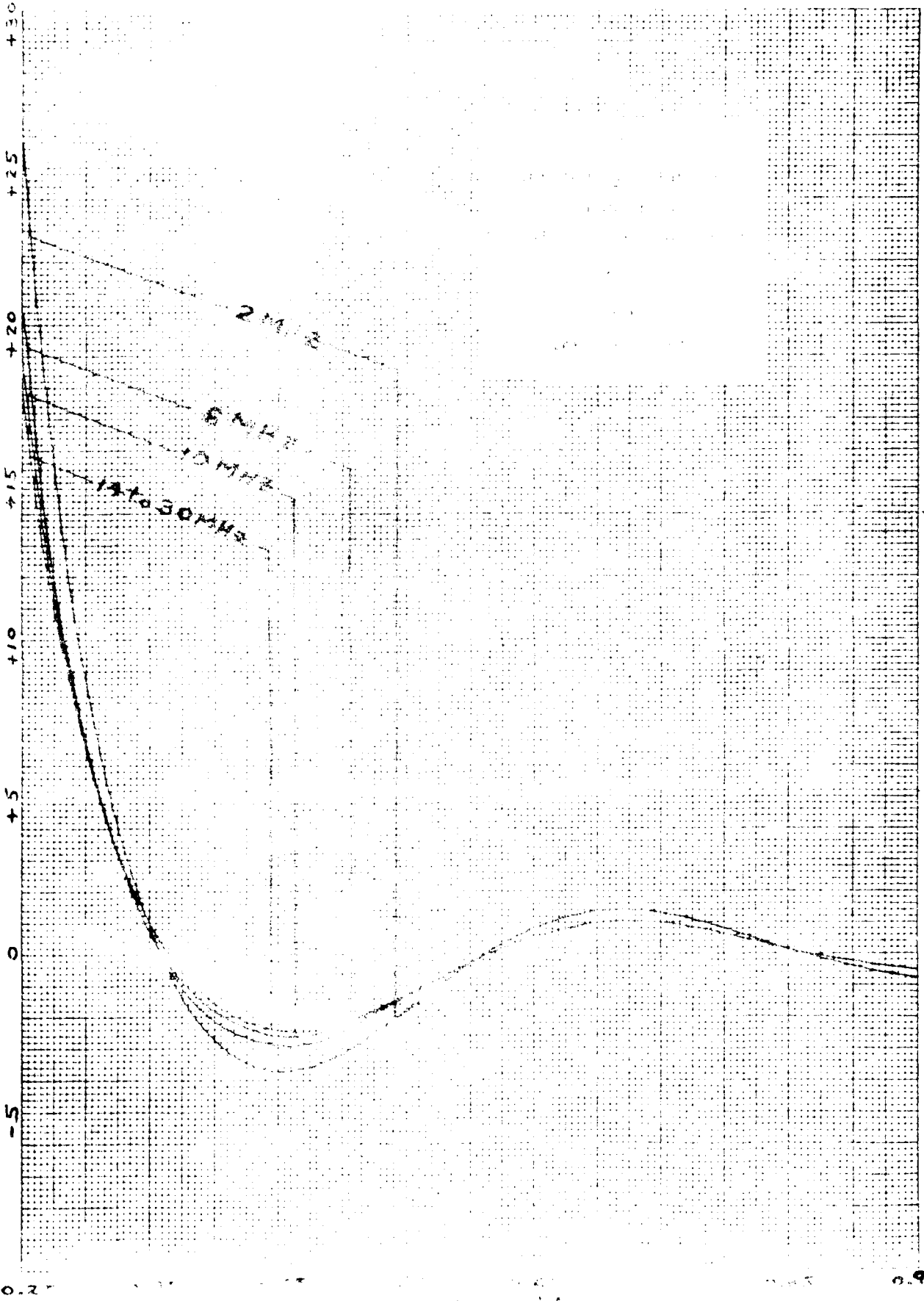
The mutual reactance,  $X_{21}$ , results are plotted on Figures 47-51 for  $0.25 \leq h_{\lambda} \leq 0.95$  wavelengths. That is, there are 5 graphs over this range of  $h_{\lambda}$ , one for each different  $\epsilon_{\text{eff}}$ , and the frequency or frequency range is plotted on each graph.

These figures show that mutual reactance is always positive when this antenna is near ground. This mutual reactance is not highly sensitive to changes in frequency or earth electrical properties at HF. The apparent sensitivity to frequency in results is sensitivity to dipole length at first resonance (a term of  $L/\lambda$ ).

K-E 10 X 10 TO 1/4 INCH 1 X 10 INCHES  
KENTON & EDISON CO. MADE IN U.S.A.

46 1323

$R_{21}$ , Ohms



$R_{21}$  vs.  $f$  (MHz)

46 1323

K·E  
10.3 TO 10.5 INCH 2 X 10 INCHES  
KUPFL & ESSLER CO. MADE IN U.S.A.

$R_{21}$ , Ohms

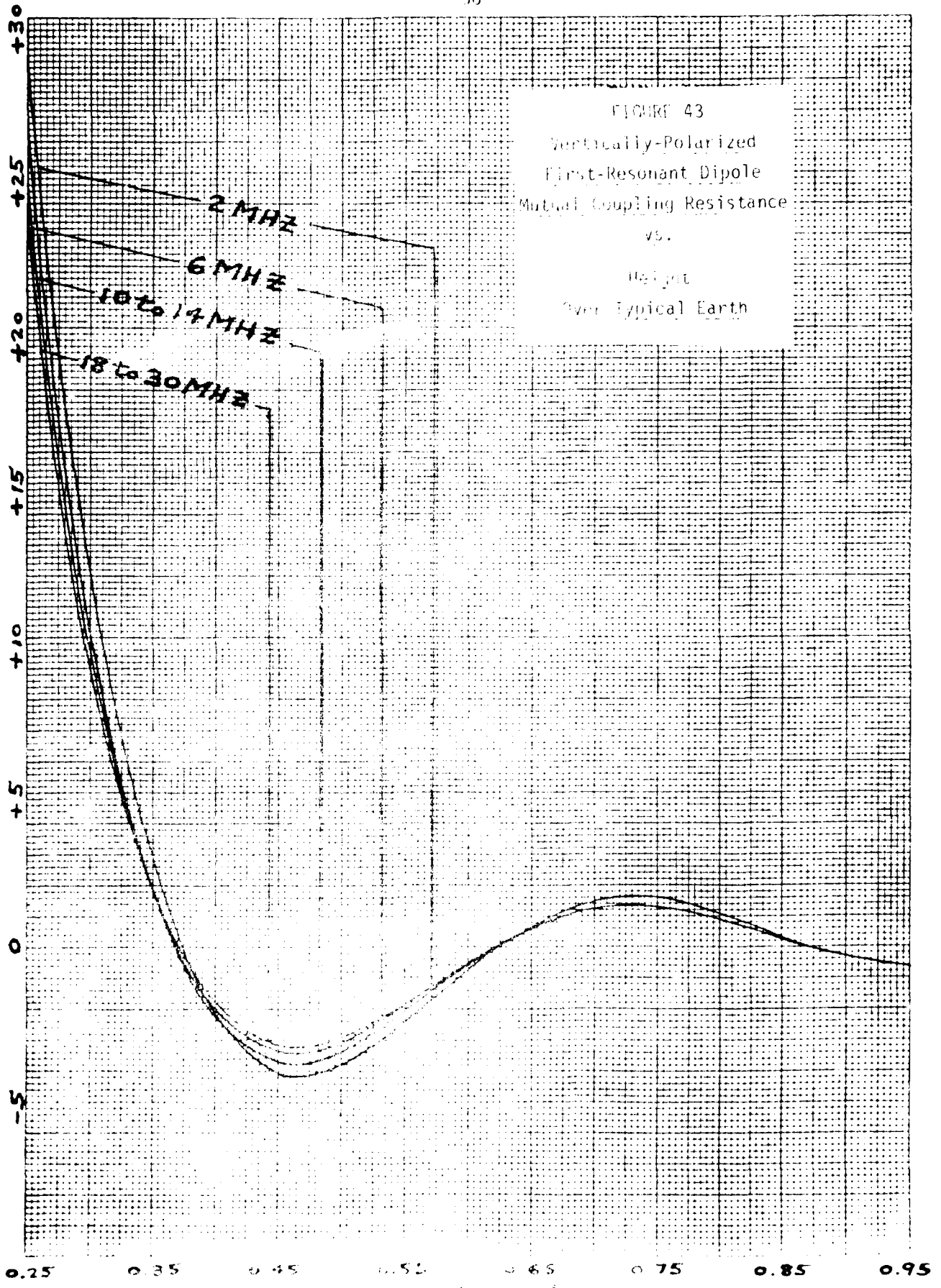
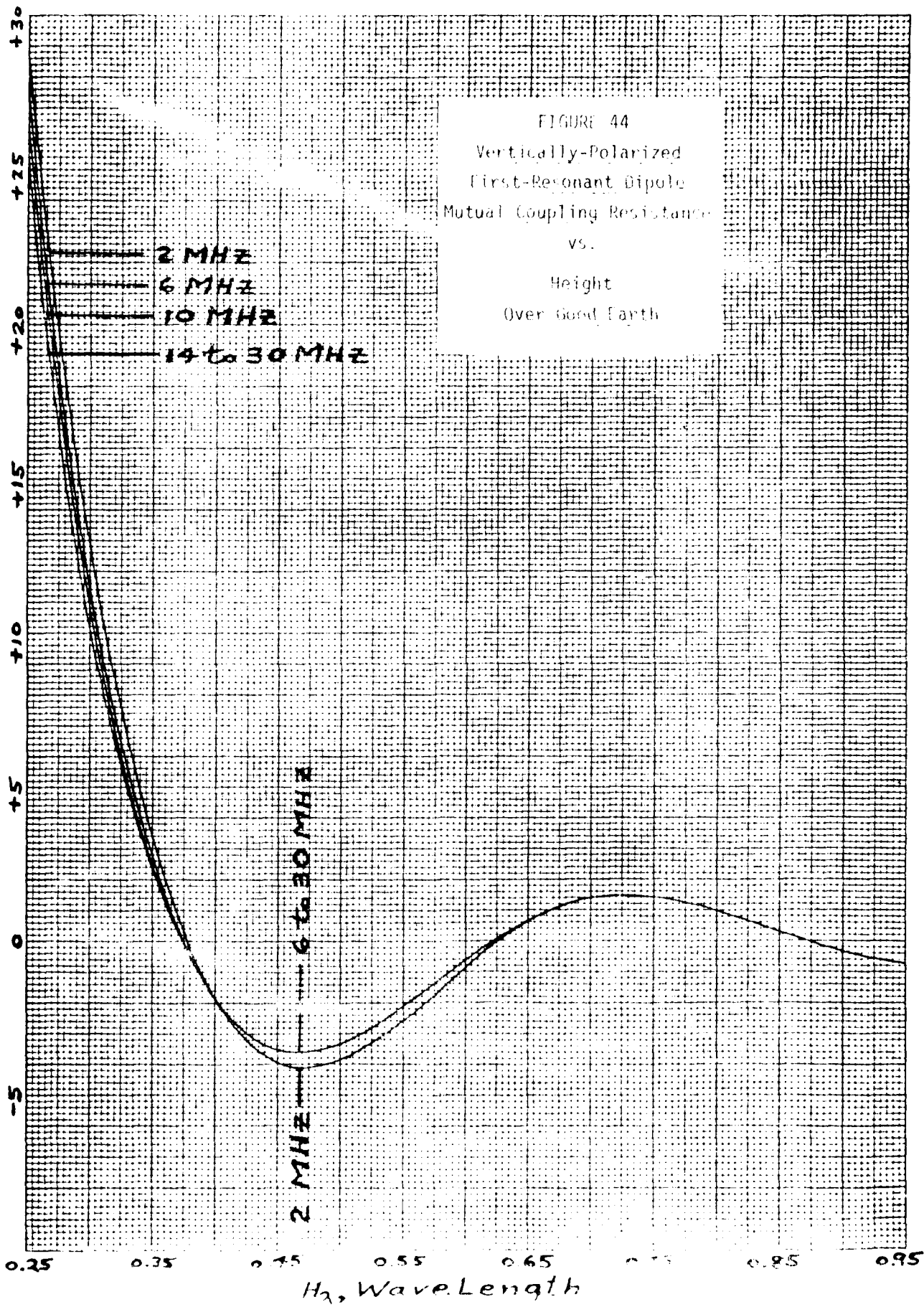


FIGURE 43  
Vertically-Polarized  
First-Resonant Dipole  
Mutual Coupling Resistance  
vs.  
Height  
Over Typical Earth

46 1323

K·E 10 X 10 TO 1/4 INCH 7 X 10 INCHES  
KLEPPEL & EBER CO. MADE IN U.S.A.

$R_{21}$ , Ohms



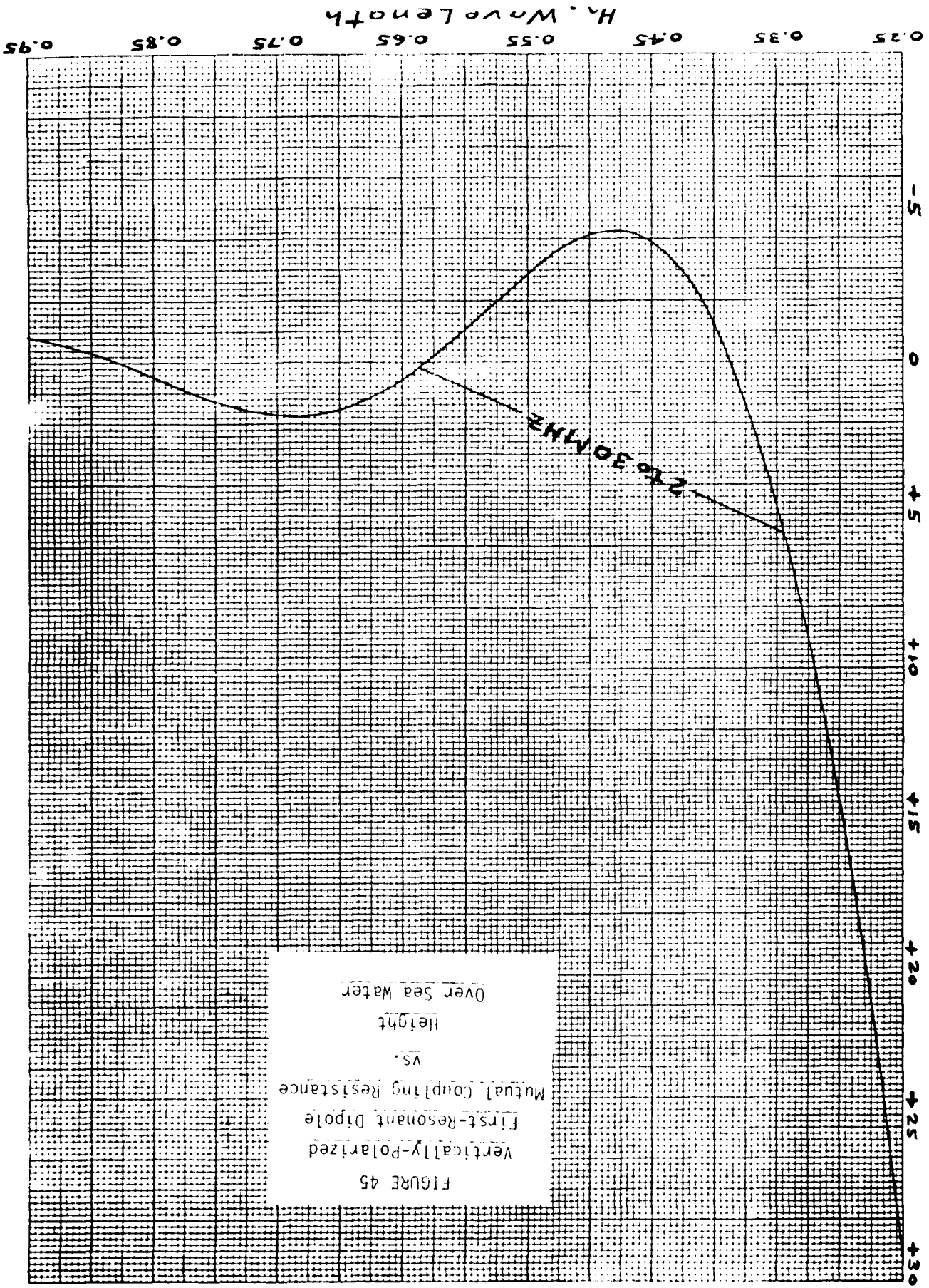


FIGURE 45  
Vertically-Polarized  
First-Resonant Dipole  
vs.  
Height  
Over Sea Water

46 1323

K·E 10 X 10 TO 1/4 INCH 7 X 10 INCHES  
KEUFFEL & ESSER CO. MADE U.S.A.

$R_{21}$ , Ohms

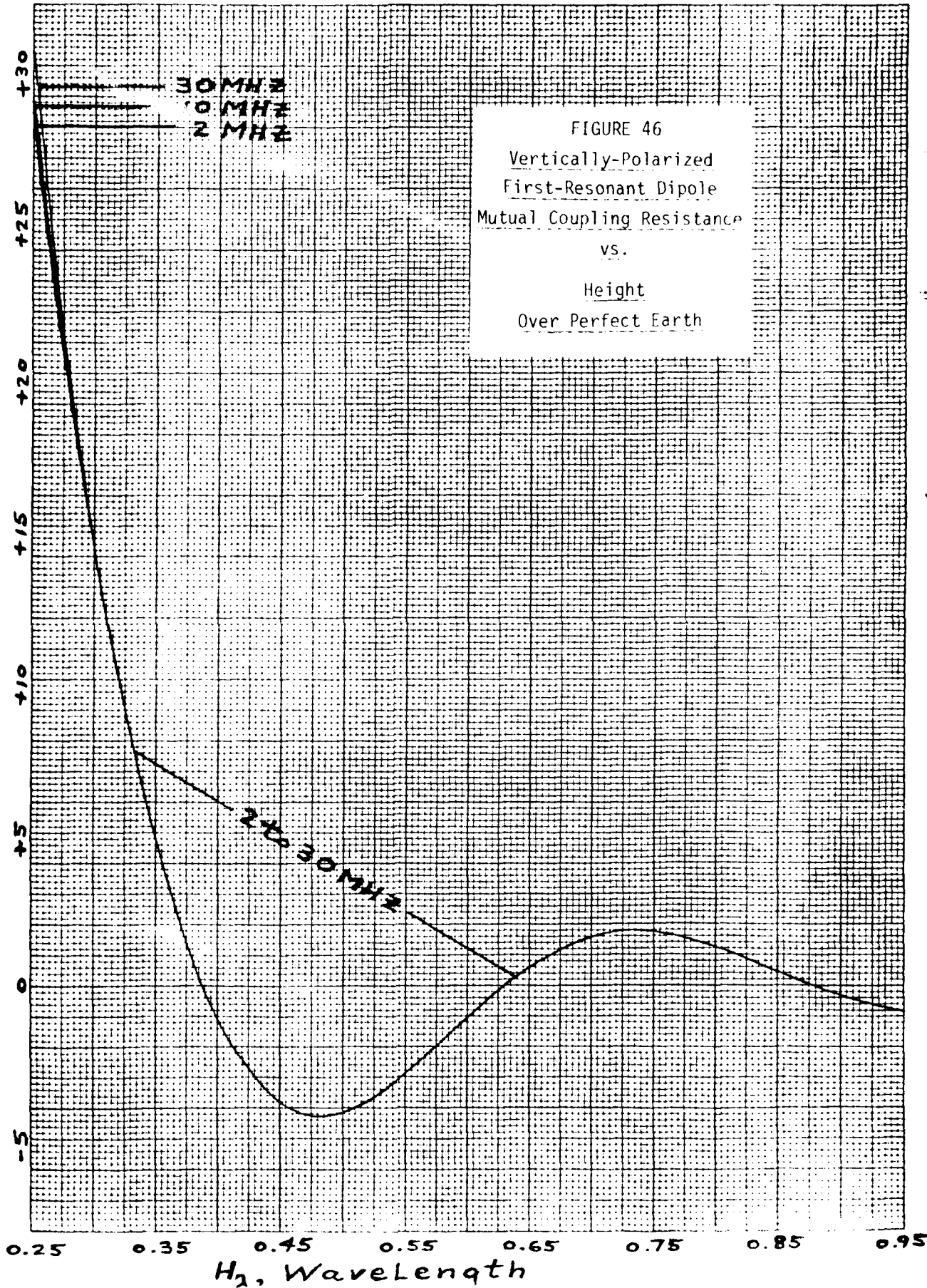


FIGURE 46  
Vertically-Polarized  
First-Resonant Dipole  
Mutual Coupling Resistance  
vs.  
Height  
Over Perfect Earth

46 1323

K·E 10 X 10 TO 1/4 INCH 7 X 10 INCHES  
NEUFFEL & ESSLER CO. MADE IN U.S.A.

$X_{21}$ , Ohms

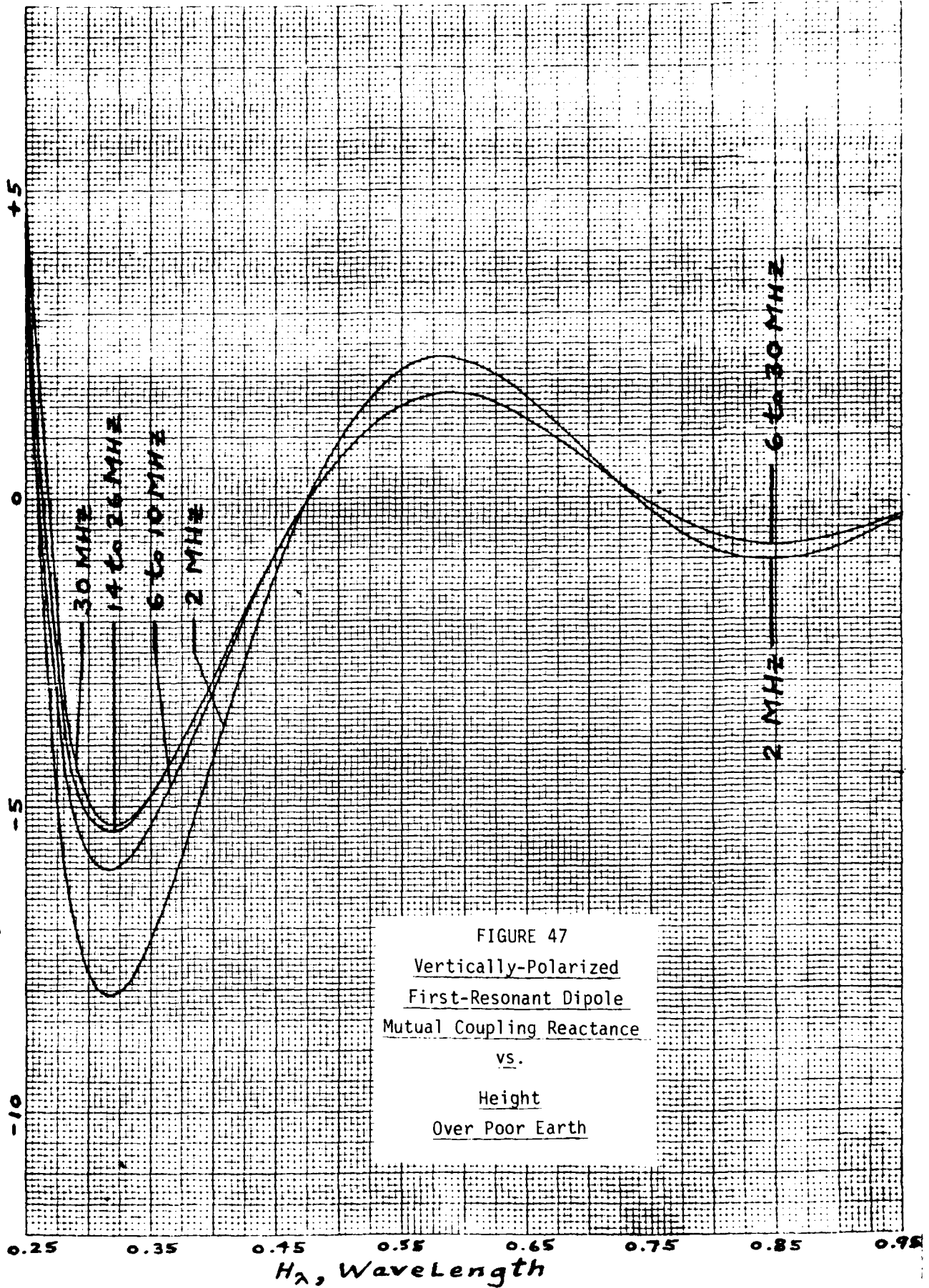


FIGURE 47  
Vertically-Polarized  
First-Resonant Dipole  
Mutual Coupling Reactance  
vs.  
Height  
Over Poor Earth

$X_{21}$ , Ohms

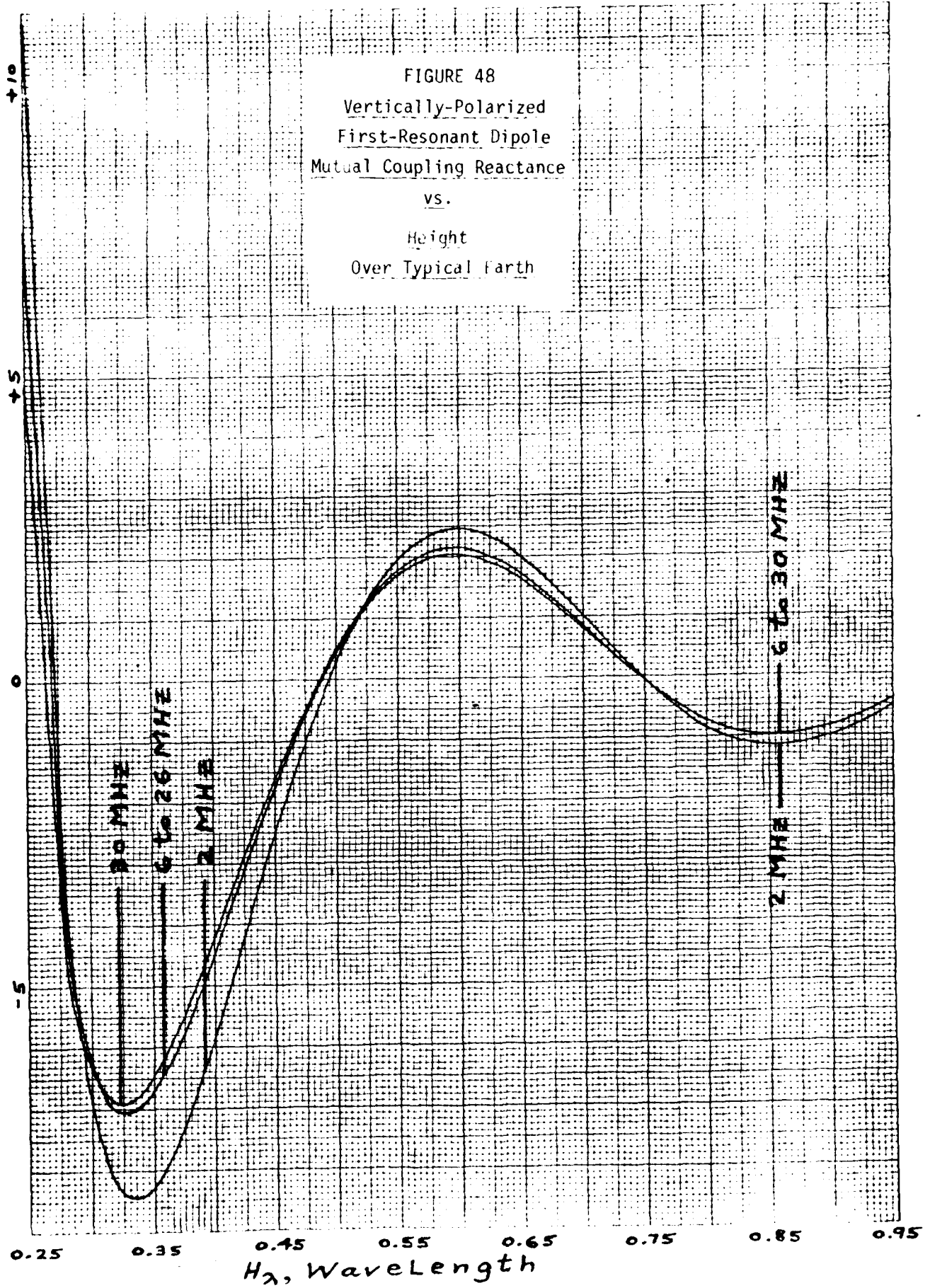


FIGURE 48  
Vertically-Polarized  
First-Resonant Dipole  
Mutual Coupling Reactance  
vs.  
Height  
Over Typical Earth

46 1323

K·E 10 X 10 TO 1/4 INCH 7 X 10 INCHES  
KEUFFEL & ESSER CO. MADE IN U.S.A.

$X_{21}$ , Ohms

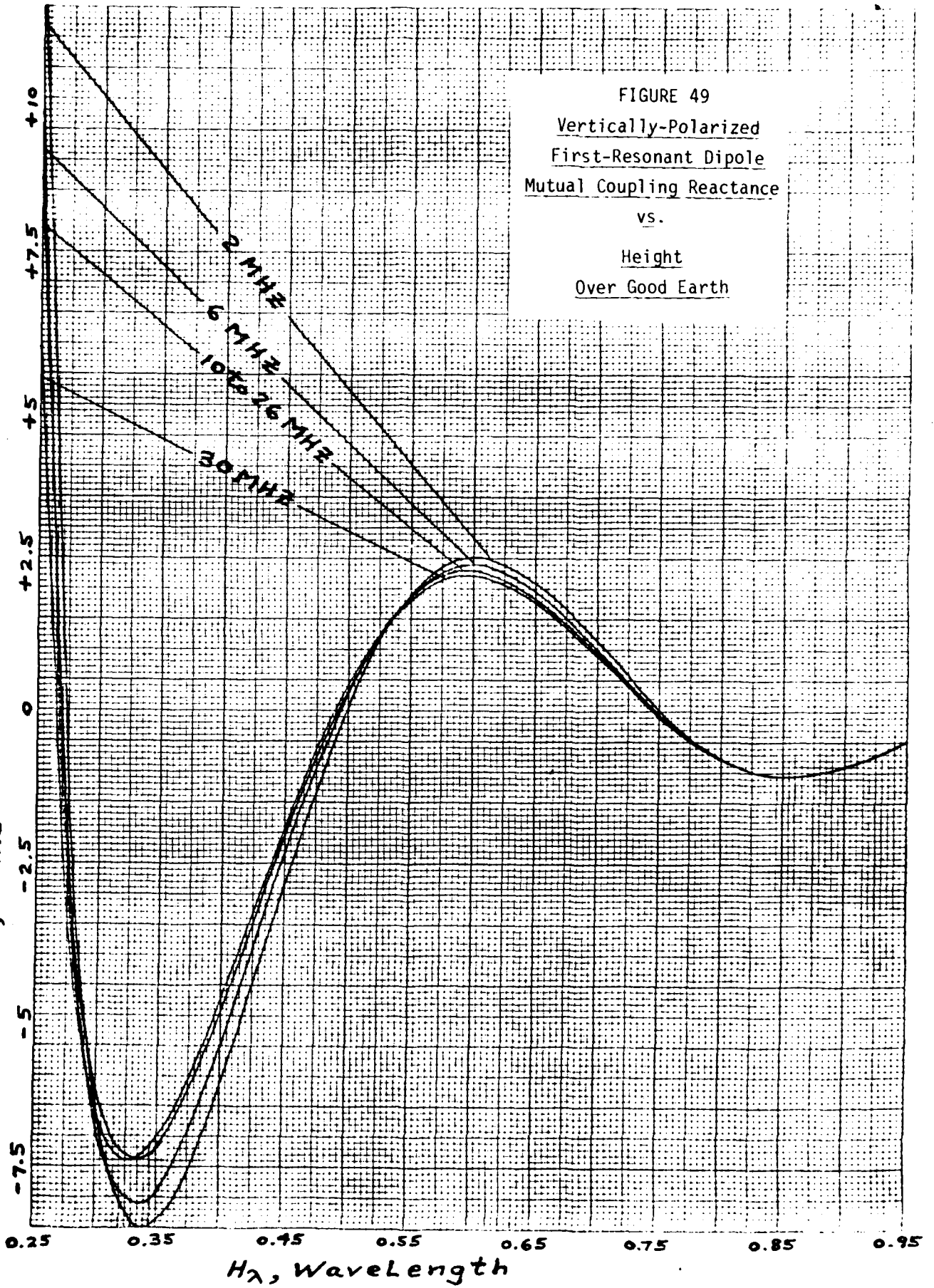


FIGURE 49  
Vertically-Polarized  
First-Resonant Dipole  
Mutual Coupling Reactance  
 vs.  
Height  
Over Good Earth

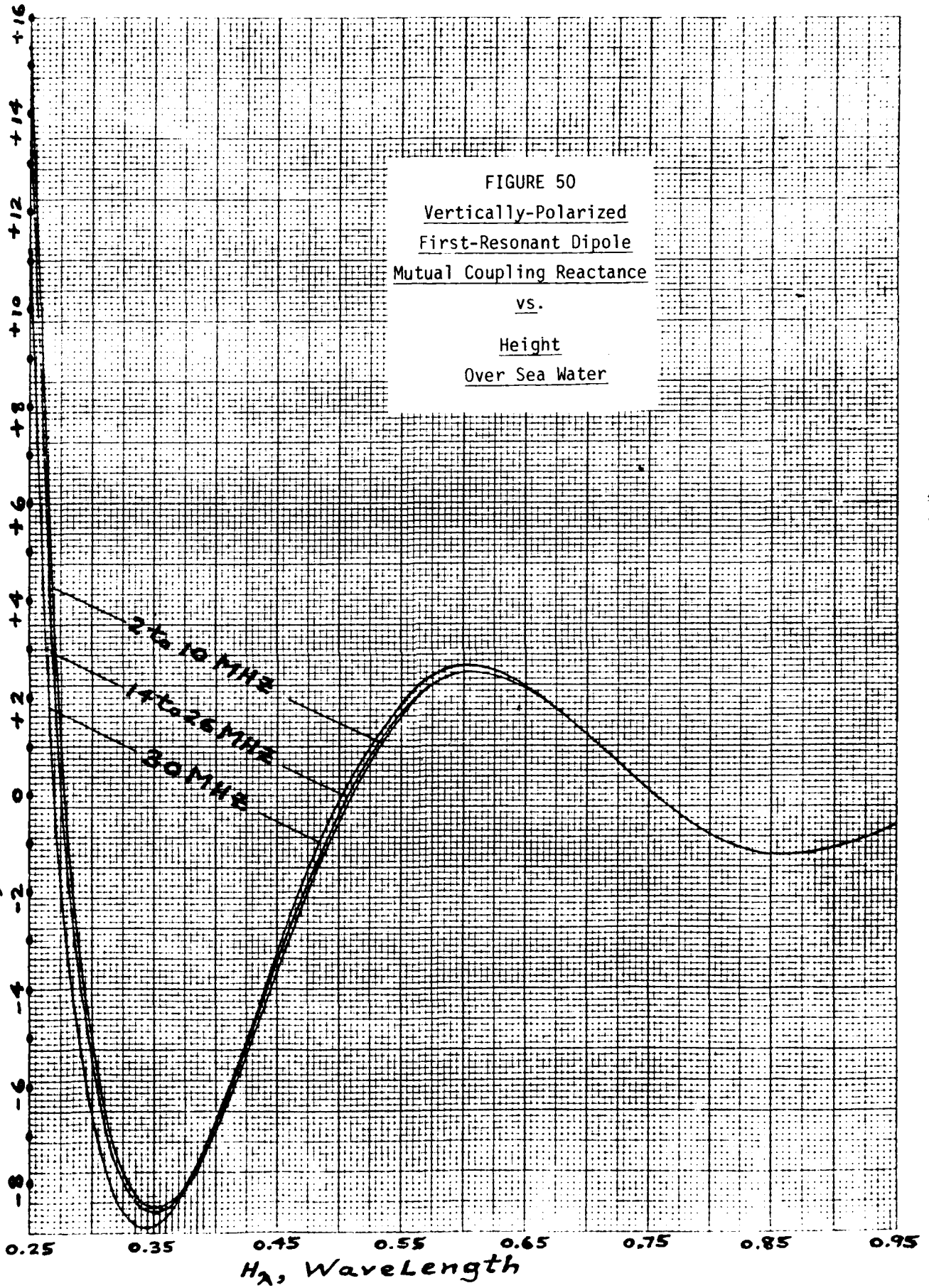
$H\lambda$ , Wavelength

FIGURE 50  
Vertically-Polarized  
First-Resonant Dipole  
Mutual Coupling Reactance  
vs.  
Height  
Over Sea Water

46 1323

K<sup>o</sup>E 10 X 10 TO 1/4 INCH 7 X 10 INCHES  
KEUFFEL & ESSER CO. MADE IN U.S.A.

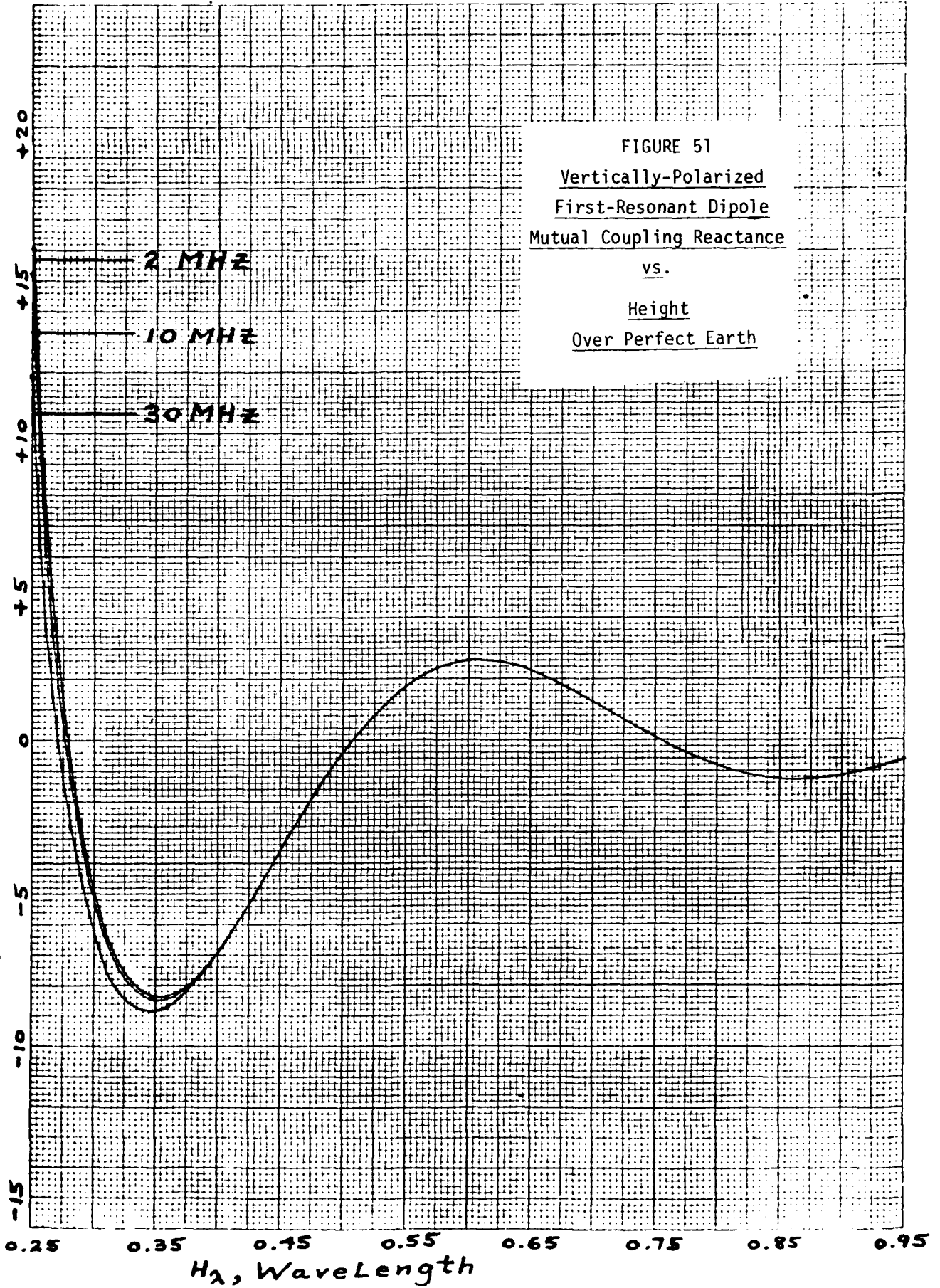
$X_{21}$ , Ohms



46 1323

K&E 10 X 10 TO 1/2 INCH  
KEUFFEL & ESSER CO. MADE IN U.S.A.

$X_{21}$ , Ohms



These figures, too, appear to be highly accurate, and vertically-polarized mutual reactance is not very significant at HF when  $H_\lambda > 0.70$  wavelength.

#### VI. SUMMARY.

While this report is not complex, it required so much computer and data reduction time that it discouraged any desire to include solutions for other antenna lengths. An analysis of computer solutions indicated the validity range of simplified equations was so narrow that such an approach is impractical. This is very apparent at heights,  $H_\lambda$ , greater than 0.15 wavelengths where solutions became oscillatory. Hence, all of the reduced data is plotted on the enclosed figures for general use.

The accuracy of these results depends upon the accuracy of the equations used in program subroutines. That is, with the exception of horizontal polarization and  $0.01 \leq H_\lambda \leq 0.03$  wavelength over sea water, the curves on the figures are continuous, and the results are highly predictable. The highly accurate results on Figures 42-51 indicate that computational errors will be more related to the Hertzian parallel electric  $\pi_x$  component equation than to the Hertzian perpendicular electric  $\pi_z$  component equation used in the program Sommerfeld subroutine.

As noted above, solutions plotted on Figures 12-21 and 32-41 are oscillatory when  $H_\lambda > 0.15$  wavelength. The individual figures suggest that  $R_{21}$  and  $X_{21}$  solutions are highly sensitive to frequency when the earth's permittivity is highly conductive. When the figures are reviewed collectively, frequency is less important than the earth's permittivity. This leads to the conclusion that the frequency, per se, effect is more one of length,  $L$ , effect where length at first resonance is a function of the length-to-diameter,  $L/D$ , ratio equation 4 in Reference 4.

The practical L/D ratios used in this report are plotted on Figure 52, where No. 12 wire ( $D = 0.08081$  inches) was used at 2-26 MHz and 1.0 inch diameter tubing was used at 30 MHz. Thus, the 6 MHz first-resonant dipole is 0.3% shorter than the 2 MHz first-resonant dipole, the 10 MHz first-resonant dipole is 0.5% shorter than the 2 MHz first-resonant dipole, the 14 MHz first-resonant dipole is 0.6% shorter than the 2 MHz first-resonant dipole, the 18 MHz first-resonant dipole is 0.7% shorter than the 2 MHz first-resonant dipole, the 22 MHz first-resonant dipole is 0.8% shorter than the 2 MHz first-resonant dipole, the 26 MHz first-resonant dipole is 0.9% shorter than the 2 MHz first-resonant dipole, and the 30 MHz first-resonant dipole is 3.1% shorter than the 2 MHz first-resonant dipole. This behavior is apparent near the max-min regions on Figures 12-21 and 32-41. It also gives an explanation for the relatively large capacitive solutions at 30 MHz on Figures 2-5 when the first-resonant dipole is very near the ground.

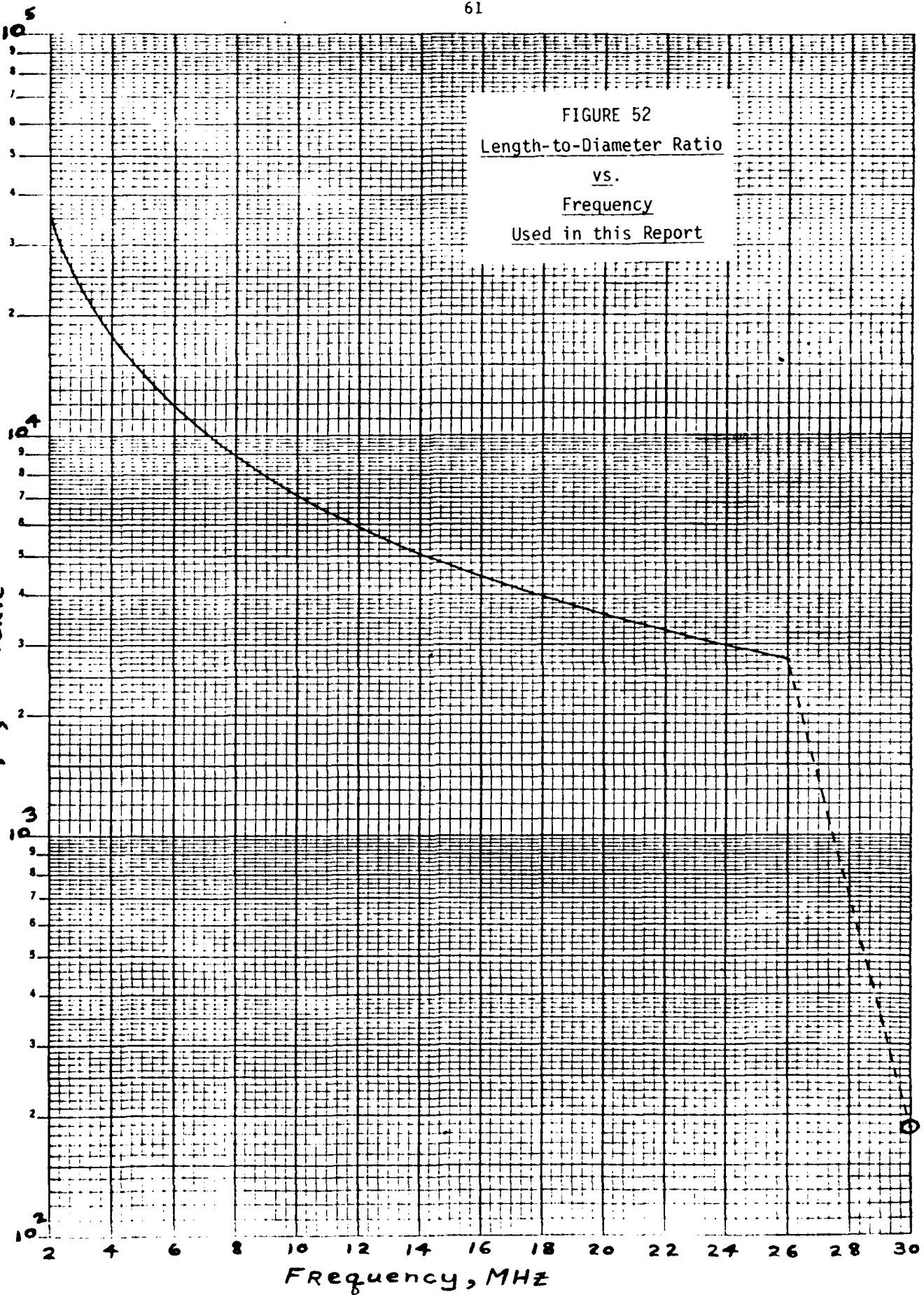
If the 30 MHz first-resonant dipole had been made of No. 12 wire, it would have been 2.1% longer than that of the 2 MHz first-resonant dipole, the NEC solution on Figure 4 would have been -82.9 ohms when  $H_\lambda = 0.002$  wavelength, and the NEC solution on Figure 24 would have been -210.6 ohms when  $H_\lambda = 0.002$  wavelength (approximate the 26 MHz solutions!) On the other hand, if the 30 MHz first resonant dipole L/D ratio had been the same as that of the 2 MHz first resonant dipole, the NEC solution on Figure 4 would have been -69.9 ohms when  $H_\lambda = 0.002$  wavelength, and the NEC solution on Figure 24 would have been -202.8 ohms when  $H_\lambda = 0.002$  wavelength (approximate the 14 MHz solutions!) Therefore, at low antenna heights, solutions are highly dependent upon dipole length.

The behavior of mutual  $R_{21}$  and  $X_{21}$  vs.  $H_\lambda$  for the 5 defined near earths can be presented in general terms when frequency [and L/D] dependence is eliminated. The horizontally-polarized results at all 8 frequencies were averaged for each earth, and the average results vs.  $H_\lambda$  are plotted on Figures 53 and 54. These results show:

FIGURE 52  
Length-to-Diameter Ratio  
 vs.  
Frequency  
 Used in this Report

STUFFEL & ESSER CO., N. Y. NO. 200-72  
 Semi-Logarithmic 3 Cycles X 6 to the 1/2 Inch  
 MADE IN U.S.A.

*L/D, Numeric*



46 1323

K&E 10 X 10 TO 1/4 INCH 7 X 10 INCHES  
KELUFFEL & EBERER CO. MADE IN U.S.A.

$R_{21}$ , Ohms

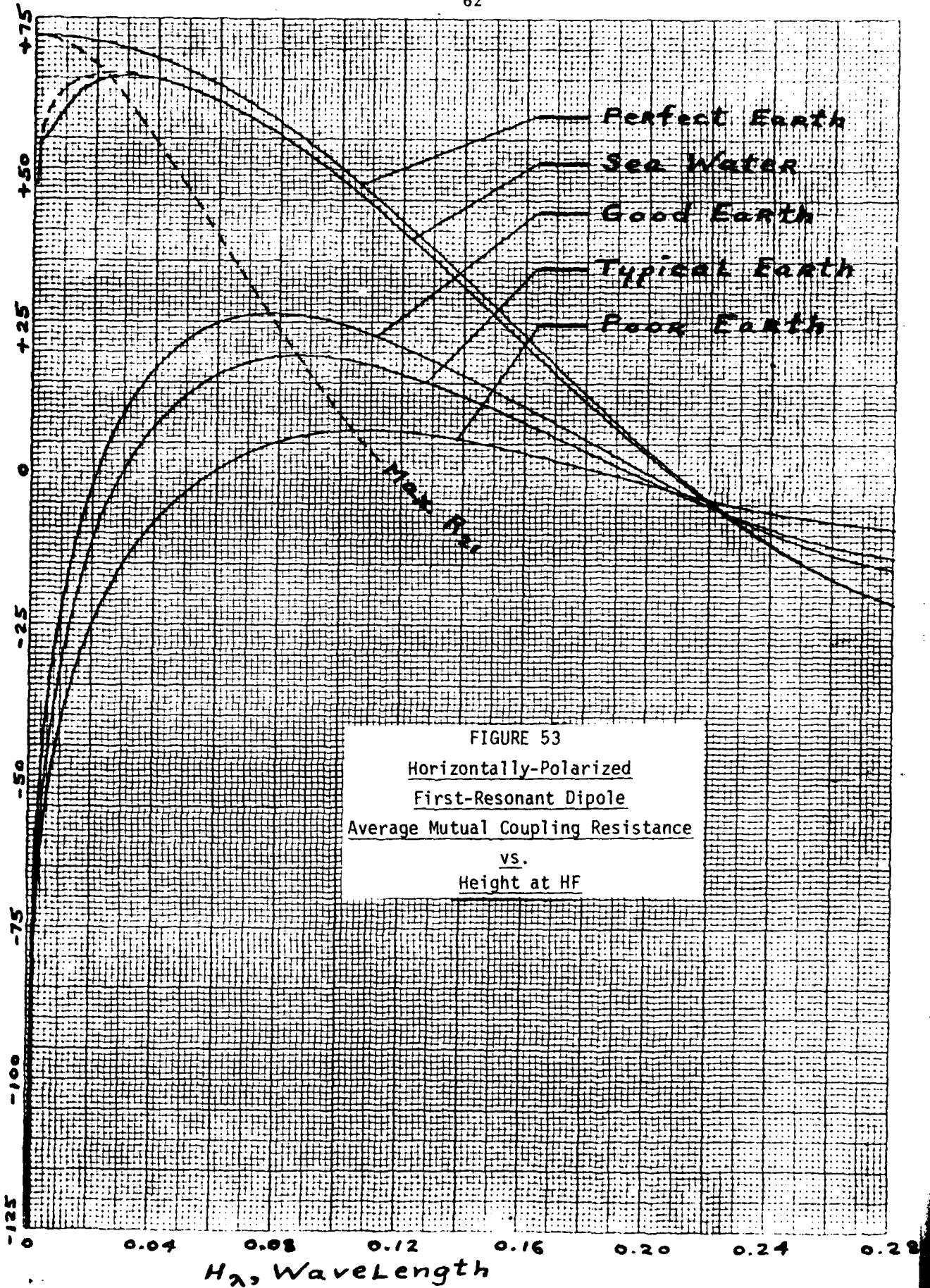


FIGURE 53  
 Horizontally-Polarized  
 First-Resonant Dipole  
 Average Mutual Coupling Resistance  
 vs.  
 Height at HF

46 1323

K·E 10 X 10 TO 1 1/2 INCH 7 X 10 INCHES  
KEUFFEL & ESSER CO. MADE IN U.S.A.

$X_{21}$ , Ohms

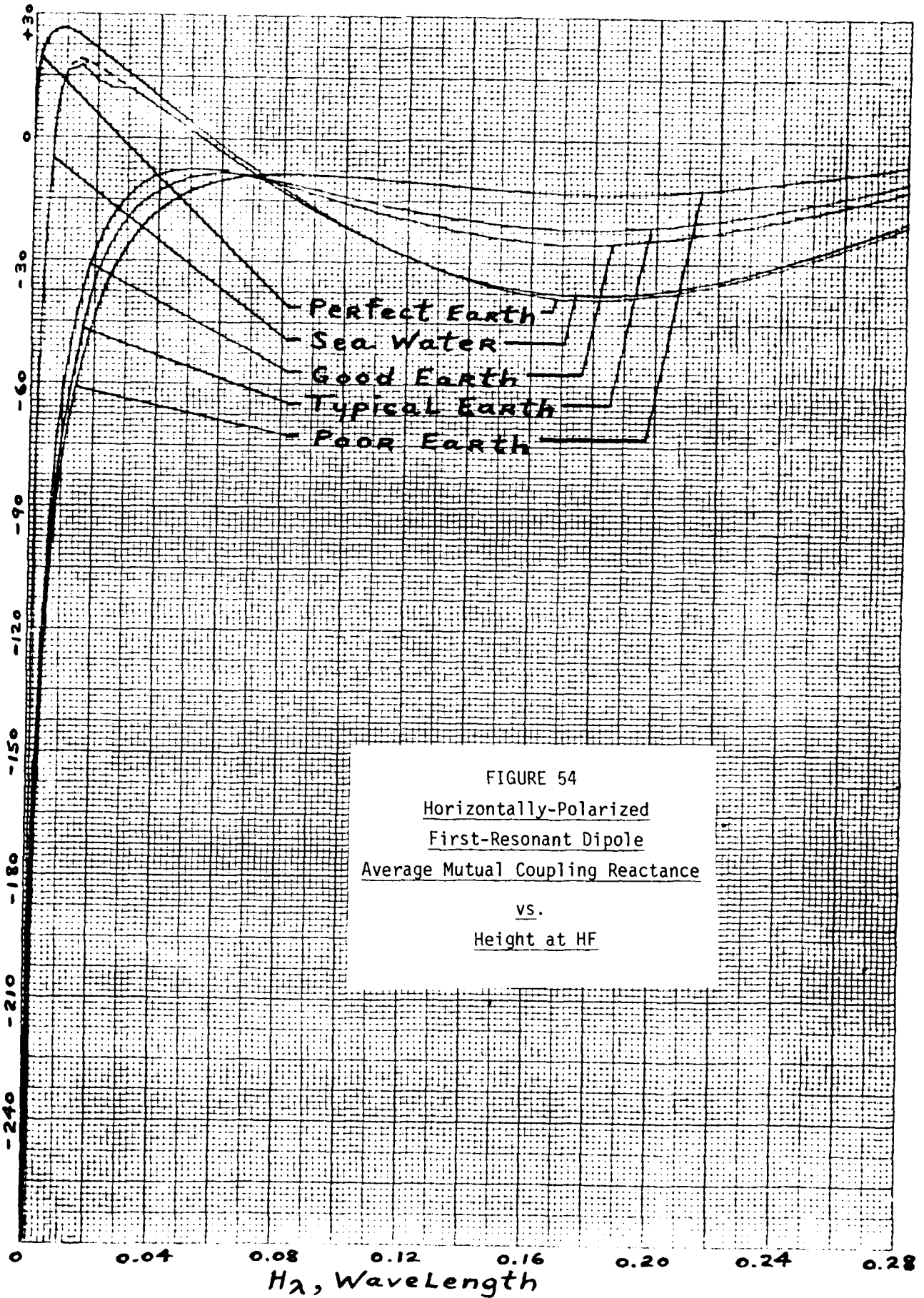


FIGURE 54  
Horizontally-Polarized  
First-Resonant Dipole  
Average Mutual Coupling Reactance  
 vs.  
Height at HF

1. The inaccuracy of NEC in the  $0.01 \leq H_\lambda \leq 0.03$  region over sea water.

2. Both  $R_{21}$  and  $X_{21}$  have maximum values as a function of earth's electrical properties.

3. The height,  $H_\lambda$ , at which maximum  $R_{21}$  and  $X_{21}$ , occur depends inversely upon how good the earth is as a conductor.

4. With the exception of sea water and perfect earth, the mutual impedance terms,  $R_{21}$  and  $X_{21}$ , are highly negative when the horizontal first-resonant dipole is very near the earth.

While the results presented in this report are not precise, they are as accurate as one can expect without resorting to solutions involving a large number of L/D ratios. The problem is, as it turns out, that solutions are as much a function of first-resonant dipole length as they are to the electrical properties of the earth beneath the dipoles.

I am indebted to a number of PED personnel. Mr. Danny Fink set up the programs. Ms. Lee Ann Sampson and SP5 Virgil Brown were the terminal operators. SSG Robert Pulliam, SP5 Alvin Mack, and Mr. Steve Aubrey collated the stacks of printouts. Without the coordinated effort, of all, this lengthy report would have been impossible.

\*\*\*\*\*

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8. R. Corry, "Partial Validation of the Numerical Electromagnetic Code Computer Program Using Data Measured in Thailand," EMEO-PED-80-8, p. 9; September 1980.
9. In a 1968 discussion with U.S. Army Signal Corps Officer LTC L.F. Kruse, retired (now deceased), he had noticed a number of years earlier that first-resonant horizontal dipoles at Ft. Huachuca had to be shortened when set up at the same height over better earth in Missouri.