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HF GROUND AND VEGETATION CONSTANTS

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Presented at the 3rd Annual Meeting of the
Applied Computational Electromagnetics Society (ACES)

Monterey, California

24-26 March 1987

SRI International®

ABSTRACT

Analytical models of propagation and antenna performance such as the Numerical Electromagnetics Code (NEC) require accurate input data in order to produce accurate answers. NEC-3 requires information about the macroscopic electrical properties of the soil, the permittivity (relative dielectric constant) and conductivity, in order to model properly wire antennas in proximity to the earth. Most of the values available in the literature are "constants," and many of them were derived from data taken at MF using AM broadcast stations so they do not necessarily pertain to the HF band. The actual values for most soils exhibit dispersion (i.e., they are a function of frequency) which is a primary function of the moisture content of the soil and a secondary function of other variables (e.g., temperature, compaction, mineralization, etc.). This has been known since the mid-1930s [Smith-Rose, 1934, 1935]. This paper will review selected handbook values for ground constants at HF; present examples of data measured at various sites in CONUS and around the world with the SRI open wire line (OWL) ground constants kit and E(d) method; and present recommended "generic" values for different types of terrain which are useful in the absence of measured data. These "generic" curves of ground constants versus frequency, when used in NEC, should provide some improvement in the predicted results relative to the results which would have been obtained using current handbook values. The "generic" curves are especially useful for sensitivity analyses. In-situ measurements with the SRI OWL kit should provide the best NEC results however, and such measured values should be used for NEC-3 validations, site calibration, etc. The E(d) (or wave tilt) techniques can be used in open areas to supplement the OWL technique.

INTRODUCTION

The macroscopic electrical and magnetic properties of media are the electrical permittivity (dielectric constant), the magnetic permeability, and the conductivity. It is convenient to normalize the permittivity and permeability by their free-space values to obtain the relative dielectric constant and relative permeability. These values are given in Table 1, where the SI units are given. Note that Siemens/m (S/m) has replaced mho/m as the preferred unit for conductivity.

A distinction needs to be made between the complex intrinsic electrical and magnetic properties useful for microscopic analyses of the media required for physical insight and the real effective electrical and magnetic properties required for use in models based on Maxwell's equations to solve antenna and propagation problems such as the Numerical Electro-

TABLE 1

MACROSCOPIC ELECTRICAL PARAMETERS

ε	=	Permittivity (Dielectric Constant), F/m
ε_0	=	8.8542×10^{-12} F/m
ε_r	=	$\varepsilon/\varepsilon_0$ = Relative Dielectric Constant
μ	=	Permeability, H/m
μ_0	=	4×10^{-7} H/m
μ_r	=	μ/μ_0 = Relative Permeability
σ	=	Conductivity, S/m (mho/m)

magnetics Code (NEC) [Burke and Poggio, 1981; Burke, 1983; Breakall, et al., 1985]. The equations for these intrinsic properties (given the subscript i) and the effective properties (given the subscript e) are summarized in Table 2, which also gives the relationship between the intrinsic and effective properties. The complex intrinsic values also can be used in Maxwell's equations, of course, when the equations are formulated using them properly; however, the NEC formulation assumes the real effective values.

In the general case, it is not possible to distinguish between σ' (the ionic conduction current at DC) and the $\omega\varepsilon_0 \varepsilon_r''$ (the polarization effect of the medium). Also, it is not possible to distinguish between ε_r' (the real part of the relative dielectric constant) and $\sigma''/\omega\varepsilon_0$ without an atomic or molecular interpretation of the medium and laboratory measurements of the variation of σ_e and ε_{re} with both frequency and temperature. For example, the ionic conduction is a function of temperature, but (to a first order) the polarization effect is independent of temperature [King, et al., 1981].

Table 2

CONSTITUTIVE RELATIONS FOR HOMOGENEOUS MEDIA

$$\bar{D} = \epsilon_r \epsilon_o \bar{E}$$
$$\bar{B} = \mu_r \mu_o \bar{H}$$

INTRINSIC (i)	EFFECTIVE (e)
COMPLEX	REAL
MICROSCOPIC	MACROSCOPIC
ATOMIC OR MOLECULAR	BULK PROPERTIES
$\epsilon_{ri} = \epsilon_r' - j\epsilon_r''$	$\epsilon_{re} = \epsilon_r' - \sigma''/\epsilon_o\omega$
$\sigma_i = \sigma' - j\sigma''$	$\sigma_e = \sigma' + \omega\epsilon_o\epsilon_r''$
$\mu_{ri} = \mu_r' - j\mu_r''$	$\mu_{re} \cong \mu_r' \cong \mu_o$

$$\sigma' - j\sigma'' + j\omega(\epsilon_o\epsilon_r' - j\epsilon_o\epsilon_r'') = \sigma_e + j\omega\epsilon_o\epsilon_{re} \quad \text{(EFFECTIVE CONDUCTIVITY)}$$

$$\underbrace{\frac{\sigma' + \omega\epsilon_o\epsilon_r''}{\omega\epsilon_o\epsilon_r' - \sigma''}}_{\text{USE FOR PHYSICAL INSIGHTS}} = \underbrace{\frac{\sigma_e}{\omega\epsilon_o\epsilon_{re}} = \delta_e \quad \text{(LOSS TANGENT)}}_{\text{USE IN MAXWELL'S EQUATIONS}}$$

When considering the macroscopic electrical and magnetic properties of soil for use in modeling antennas and propagation, one usually does not care whether the effective conductivity results from ionic conduction or from the polarization effect. The important consideration is that the proper effective value is used. It should be noted that soil in-situ is a mixture of components including air and water. The dielectric constant of mixtures [Encyclopedia of Physics, 1958] based upon fractional volumes provides bounds on the actual value, but the bounds are too broad to be useful for this application. The asymmetrical shape of the water molecule (H_2O) and the electrical properties of mixtures contribute to a variation of σ_e and ε_{re} with frequency (for any given soil) and moisture content (for the same soil and frequency)[King, et al., 1981]. One result is that ε_{re} for very moist soil can greatly exceed the value for water (approximately 80) at the low end of the HF band. This result has proven surprising to those who are accustomed to using handbook values [Terman, 1943; ITT, 1985; CCIR, 1982] for "ground constants" (see Table 3) under the assumption that these electrical and magnetic properties really are constants for a given type of soil independent of frequency and moisture content.

One method of determining the effective properties of a medium such as soil (also called earth or ground) is to measure the propagation constant $\Gamma = \alpha + j\beta$ in situ or in the laboratory and compute σ_e and ε_{re} from α and β. The values of σ_e and ε_{re} for the bulk medium (e.g., soil) are then used as σ and ε_r in models such as NEC or Norton's smooth earth model [Norton, 1941; as corrected by R.J. King], to solve antenna or propagation problems. Hereafter in this paper we will assume that σ and ε_r refer to the real macroscopic parameters which are used in Maxwell's equation in models such as NEC.

The relative magnetic permeability is unity at HF for most soils except for those containing magnetic minerals such as magnetite, ilmenite, etc. Therefore, we will concentrate in this paper on the effective values of permittivity and conductivity in the HF band (defined here as 2-30 MHz) as used (assuming $e^{j\omega t}$ time variation of $\overline{H}$ and $\overline{E}$):

Table 3

HANDBOOK VALUES OF GROUND CONSTANTS FOR SELECTED TERRAIN CATEGORIES

	Relative Dielectric Constant, ϵ_r			Conductivity (S/m)		
TERRAIN CATEGORY / SOURCE:	CCIR (HF)	ITT (LF,MF)	TERMAN (MF,HF)	CCIR (HF)	ITT (LF,MF)	TERMAN (MF,HF)
Sea Water	70	80	81	5	5	4.64
Fresh Water (20^0)	80	80	80	0.003	0.008	0.001
Wet Ground	30			0.01		
Pastoral, low hills, rich soil (e.g., Dallas, TX; Lincoln, NE)			20			0.03
Rich agri[illegible]l land, low hills		15				0.01
Medium dry ground	15			0.001		
Pastoral, low hills, rich soil (e.g., OH, IL)			14		0.01	
Rocky soil, steep hills (New England)			14			0.002
Pastoral, medium hills, forestation, (e.g., MD, PA, NY.)			13			0.006
Pastoral land, medium hills, forest		13			0.005	
Pastoral, medium hills, forestation, heavy clay (e.g., VA.)			13			0.004
Marshy, forested flat land		12			0.008	
Flat country, marshy, densely wooded (e.g., LA near Mississippi River)			12			0.0075
Rocky land, steep hills		10			0.002	
Sandy, dry flat coastal land		10	10		0.002	0.002
Cities, residential area		5			0.002	
Mountainous, hills up to 3000 Feet		5			0.001	
Cities, industrial areas (average attenuation)			5			0.001
Cities, industrial areas (maximum attenuation)		3	3		0.0001	0.0001
Very dry ground	3			0.0001		
Dry glacier in mountainous area, northern perma-frost (MF)				0.00001		
Antarctica (MF)				0.000001		

$$\nabla \times \overline{H} = (\sigma + j\omega \varepsilon_0 \varepsilon_r)\overline{E}$$

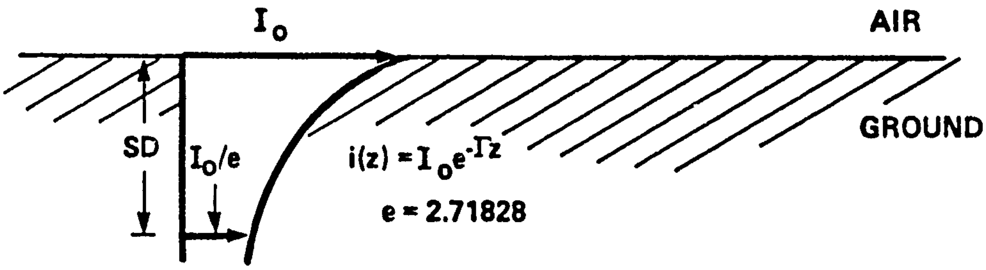
$$\nabla \times \overline{E} = \mu_r \mu_0 \overline{H}$$

Other useful parameters to compute from the effective properties are the dissipation factor and skin depths. The dissipation factor (DF, also called loss tangent) is defined as $\sigma / \omega \varepsilon_0 \varepsilon_r$. When DF >> 1 we have a lossy conductor and when DF << 1 we have a lossy dielectric. The transition when DF $\approx$ 1 (corresponding to a semiconductor) occurs in (or just below) the HF band for many soils.

The skin depth (SD) is that depth into the medium at which the currents have decreased to 1/e of their value at the surface, where e = 2.71828. This concept is illustrated in Figure 1. The equation for skin depth pertinent to a lossy conductor has been given in nomograph form [Wheeler, 1952]. Unfortunately, this nomogram does not apply at HF for most soils, and the more general equation given in Figure 1 must be used.

METHODS OF MEASUREMENT

Many methods of measurement have been developed for obtaining the effective electrical and magnetic properties of soil, and some of these are listed in Table 4. These methods were surveyed by the CCIR [1982a] and by Lytle in 1974 and 1979. The IEEE has recommended practices for measuring ground conductivity and these [IEEE, 1974] are being reviewed and revised by the IEEE Antennas and Propagation Wave Propagation Standards Committee [King, Cavanagh, 1987]. The data and generic curves of relative dielectric constant and conductivity presented in this paper were obtained using the SRI open wire line (OWL) ground constants kit [Goldstein, et al., 1967; Hagn and Gaddie, 1983, 1984] which was developed using techniques originally suggested by Kirkscether in 1960. The SRI OWL kit (see Figure 2) permits sampling in situ in proposed and existing antenna fields. The kit works well in the HF band, but it is not possible to insert the probes down to a skin depth in the drier soils. It is necessary to use a priori knowledge of the homogeneity of soil's electrical and magnetic properties



LOSSY CONDUCTOR $(\sigma >> \omega \epsilon_r \epsilon_o)$

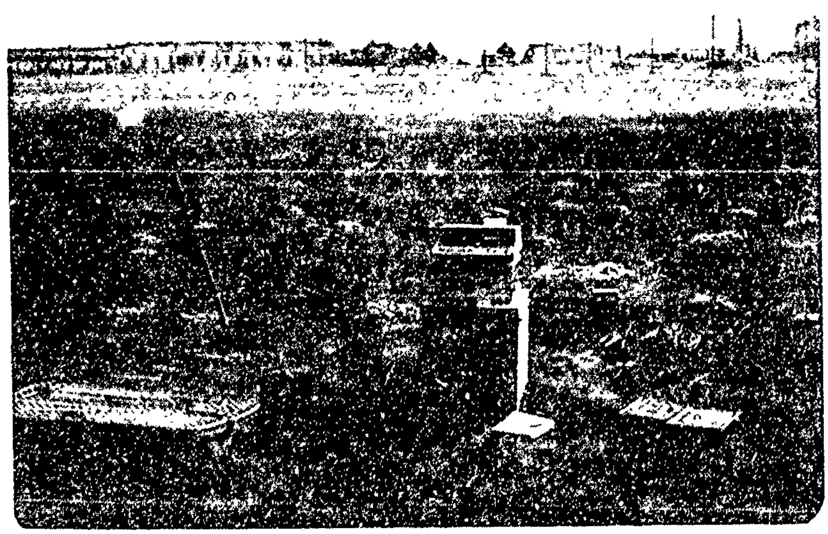
$$SD = \frac{\sqrt{2}}{\sqrt{\sigma \omega \mu}} \text{ , m}$$

GENERAL CASE $(\sigma \leq \omega \epsilon_r \epsilon_o)$

$$SD = \frac{1}{\sqrt{\sqrt{\frac{\omega^4 \mu^2 \epsilon_o^2 \epsilon_r^2}{4} + \frac{\sigma^2 \omega^2 \mu^2}{4}} - \frac{\omega^2 \mu \epsilon_o \epsilon_r}{2}}} \text{ , m}$$

Figure 1 SKIN DEPTH (SD)

a) View toward Gang 1



b) View toward Transmitter Building

Figure 2 SRI OWL KIT IN USE AT LOCATION 10, KAVALA, GREECE

TABLE 4

METHODS OF IN-SITU MEASUREMENT

EARTH	VEGETATION
E (d,f)	E(d,f,h)
OWL	OWL
WAVE TILT	
RESONANT AND SHORT MONOPOLE	
POLARIMETER	
INDUCTION (TWO LOOP)	
REFLECTION COEFFICIENT	
TRANSMISSION COEFFICIENT	
TIME DOMAIN REFLECTOMETER	
RADAR	

with depth to determine if the surface values measured with such probes can be expected to apply down to a skin depth. The depth of water in nearby wells or the use of DC, ELF or VLF geophysical prospecting techniques [Keller and Frischknecht, 1966; Wait, 1971] are useful in making this determination. When dry soils overlay a shallow water table, it frequently is necessary to use a two-layer slab model to describe antenna characteristics and propagation over terrain without vegetation similar to the model used at HF for the forested case (see Figure 3). A modified version of the SRI OWL kit can be used to measure the conductivity and relative dielectric constant of vegetation [Parker and Hagn, 1966; Hagn and Barker, 1970; Hagn, 1974]. The E(d) methods of measuring field strength vs distance do not give unique solutions, but they can be used to check results obtained using other techniques.

TYPES OF GROUND

There are several important variables which should be measured as ground truth data to describe the soil for which the data on electrical and magnetic properties apply (see Table 5). Perhaps the most important variable is volumetric moisture content (often approximated by measurements of

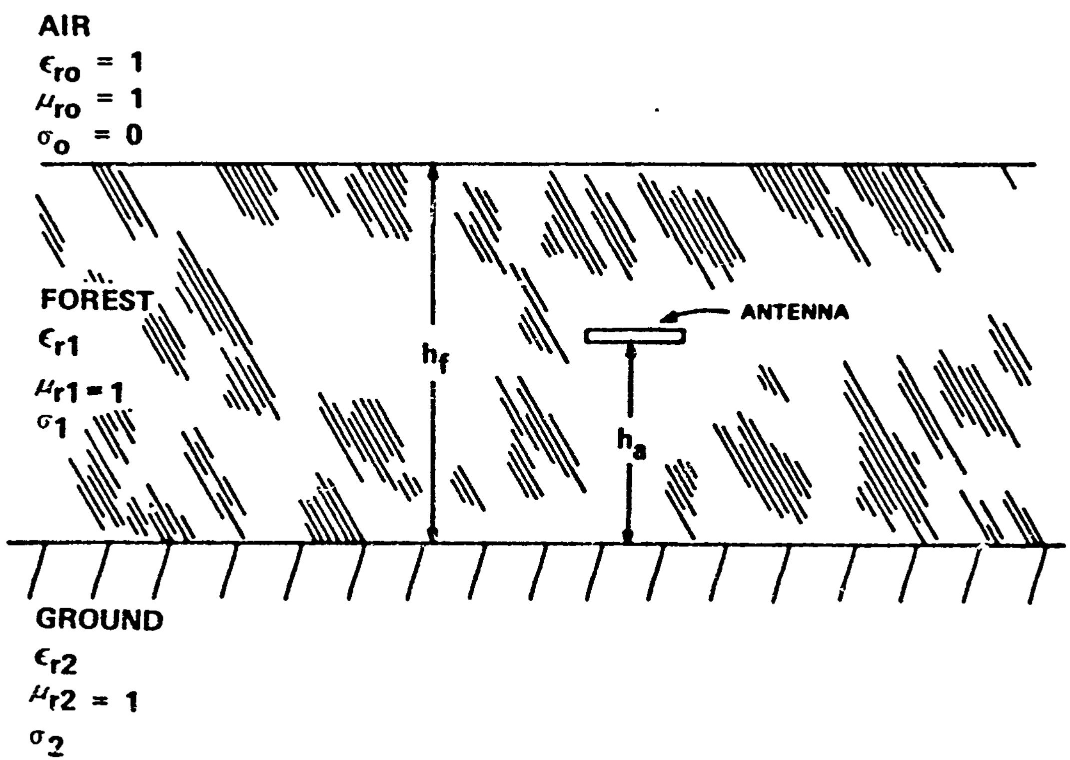


Figure 3 IDEALIZED LOSSY DIELECTRIC SLAB MODEL

the percent moisture content by weight). Longmire and Smith [1975] have developed expressions for permittivity and conductivity (except for the additive DC conductivity) versus frequency which are solely a function of moisture content. The Longmire and Smith predictions show good agreement with measured data for relative dielectric constant and for conductivity when accurate values of the DC conductivity are known. Temperature can be important, especially if a change of state of the ground is involved (i.e., if it is frozen). The soil type and mineralization is important in determining the conductivity (DC conduction), and the compaction of the soil can be important for both conductivty and permittivity. Soil color is important regarding soil homogeneity. Other parameters (e.g., pH) also can be measured to help describe a soil. Handbook authors have given several types of categories to soils, ranging from the magnitude of the conductivity (e.g., good ground, poor ground) to a description of the environmental setting (e.g., pastoral) to the amount of moisture (e.g., dry, moist). We will revisit this issue when discussing generic values for permittivity and conductivity which are more accurate than the constant values given in handbooks (but less accurate than values measured at a site of interest). At frequencies below HF the skin depth is so great that the geology underlying the soil is very important. Geologic maps have been

TABLE 5

IMPORTANT VARIABLES

- PERMITTIVITY
  - MOISTURE CONTENT
  - TEMPERATURE
- CONDUCTIVITY
  - MOISTURE CONTENT
  - TEMPERATURE
  - SOIL TYPE & MINERALIZATION (IONS AVAILABLE)
  - COMPACTION

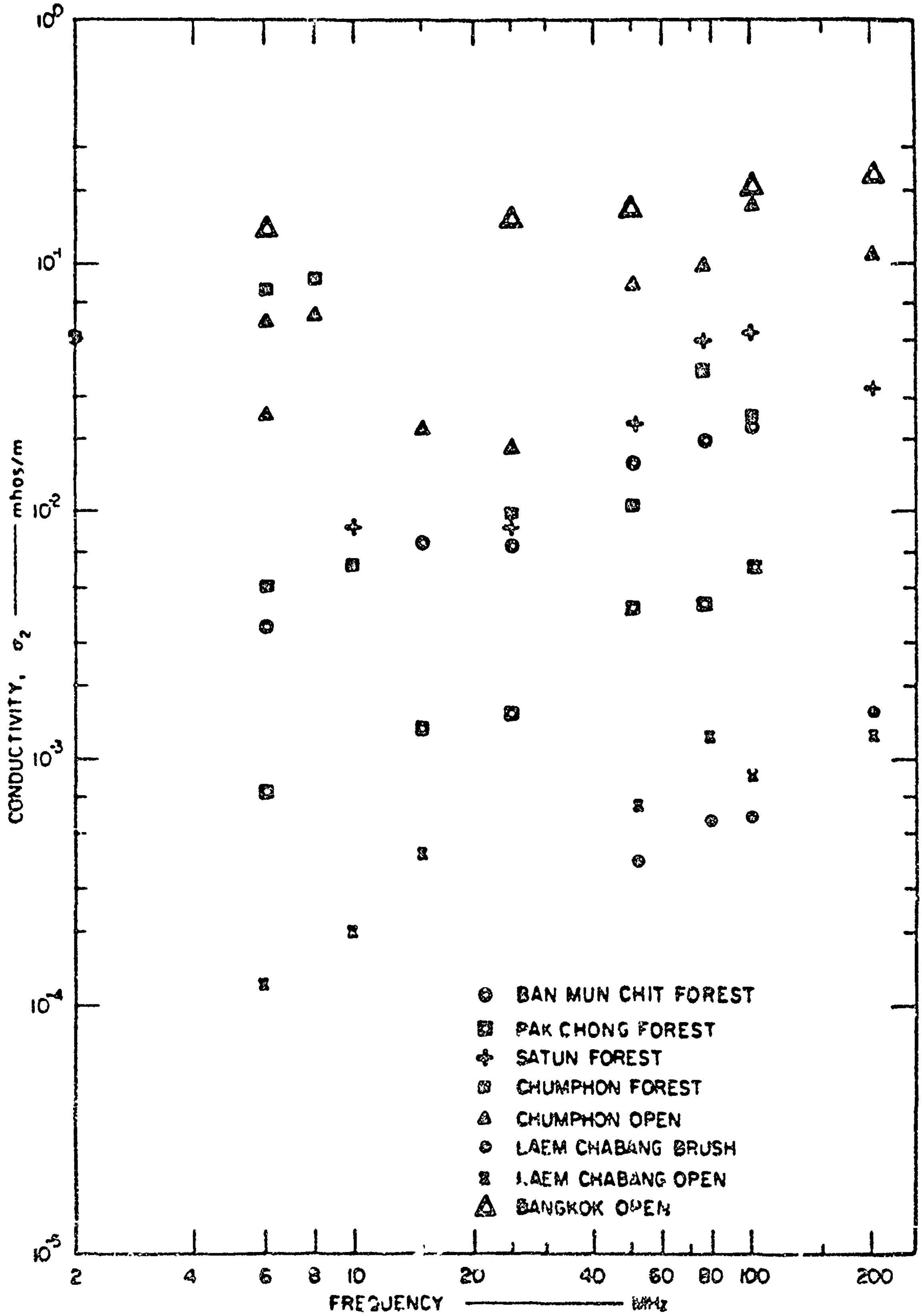
used to develop conductivity maps of the world and of specific countries like the U.S. [Fine, 1954] and Thailand [Kovattana, 1967]. At HF, the soil down to a few meters (or tens of meters in dry soil at 2 MHz) tends to be more important than the underlying geology due to the skin depth.

EXAMPLES OF MEASURED SITE MEDIAN DATA USING OWL KIT

We now will consider some measured values of conductivity and relative dielectric constant measured with the SRI open wire line (OWL) kit. The first use of this kit was in CONUS [Goldstein, et al., 1969] and in Thailand [Parker and Makarabhiromya, 1967] in the 1960s. Data from eight sites in Thailand for conductivity and relative dielectric constant for the band 2-200 MHz are given in Figures 4 and 5, respectively [Parker and Makarabhiromya, 1967; Hagn and Barker, 1970]. Note that there is greater frequency dispersion for lower conductivities (drier soil such as the dry beach sand at Laem Chabang) and for higher relative dielectric constants (moist, but not flooded, rice paddy labeled Bangkok open). The conductivity increases with increasing frequency, and it varies over three orders of magnitude for this set of data. The relative dielectric constant varies over one order of magnitude for the frequencies above 15 MHz and it decreases with increasing frequency for a given soil. The relative dielectric constant values for frequencies below 15 MHz exceed 90 for the rice paddy.

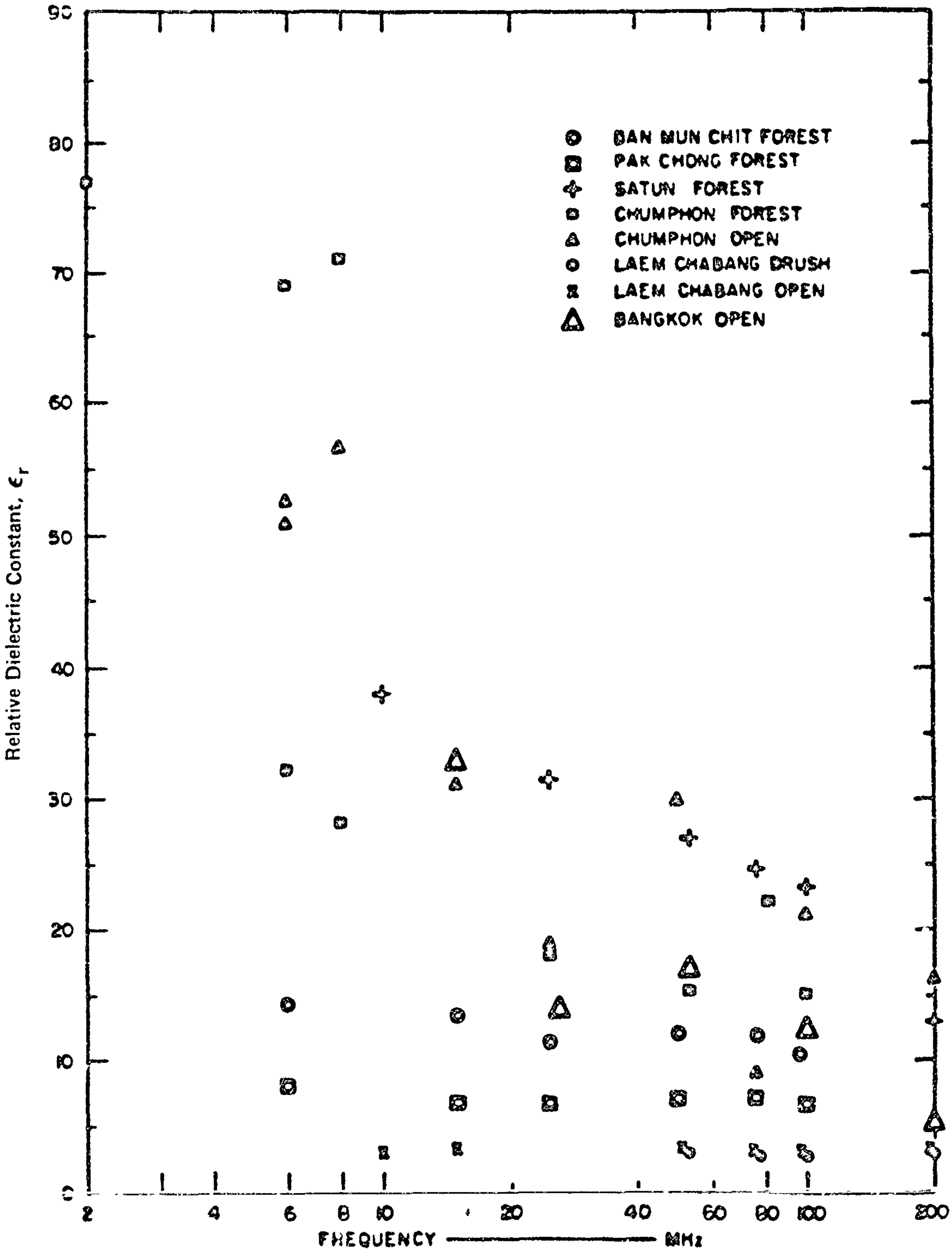
Site median values of conductivity and relative dielectric constant for six U.S. Army bases are shown in Figures 6 and 7 [Hagn and Gaddie, 1984]. The soil at Ft. Lewis, WA was very dry and contained small stones. The values were similar to those obtained in dry beach sand at Laem Chabang. The data from Ft. Leavenworth, KS were taken in moist soil very near the banks of the Missouri River, and they are comparable to the values obtained in the Bangkok rice paddy.

Data were taken recently at several Voice of America (VOA) transmitter sites around the world [Hagn and Sarran, 1985; Hagn and Faulconer, 1985a-f; Sarran, et al., 1985], and the median surface values for these sites are



(Parker and Makarabhiromya, 1967)

Figure 4 MEDIAN SURFACE CONDUCTIVITY OF GROUND AT SELECTED SITES IN THAILAND



(Parker and Makarabhiromya, 1967)

Figure 5 MEDIAN SURFACE GROUND PERMITTIVITY MEASURED AT SELECTED SITES IN THAILAND

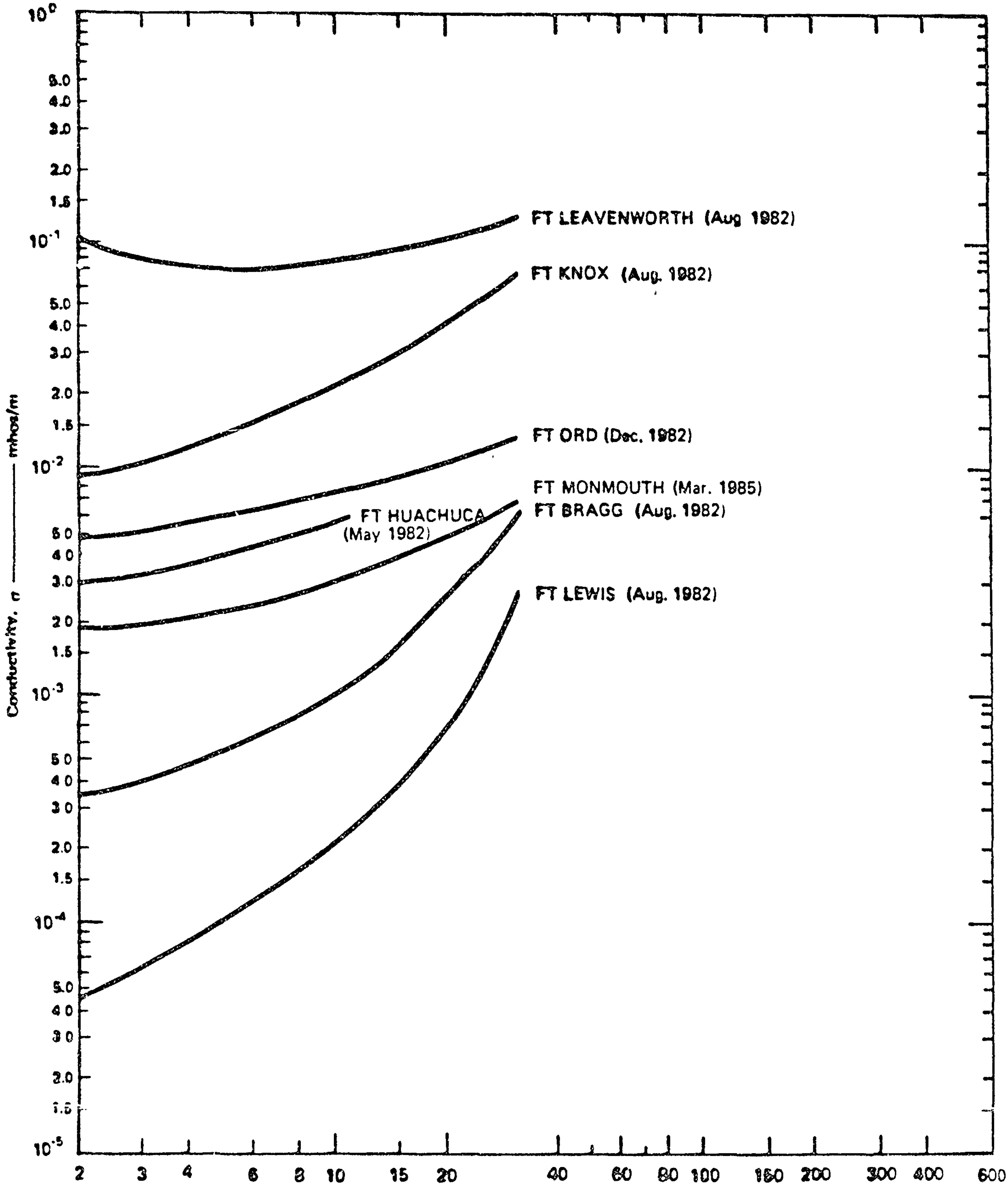


Figure 6 COMPARISON OF MEDIAN CONDUCTIVITIES MEASURED AT SELECTED U.S ARMY BASES

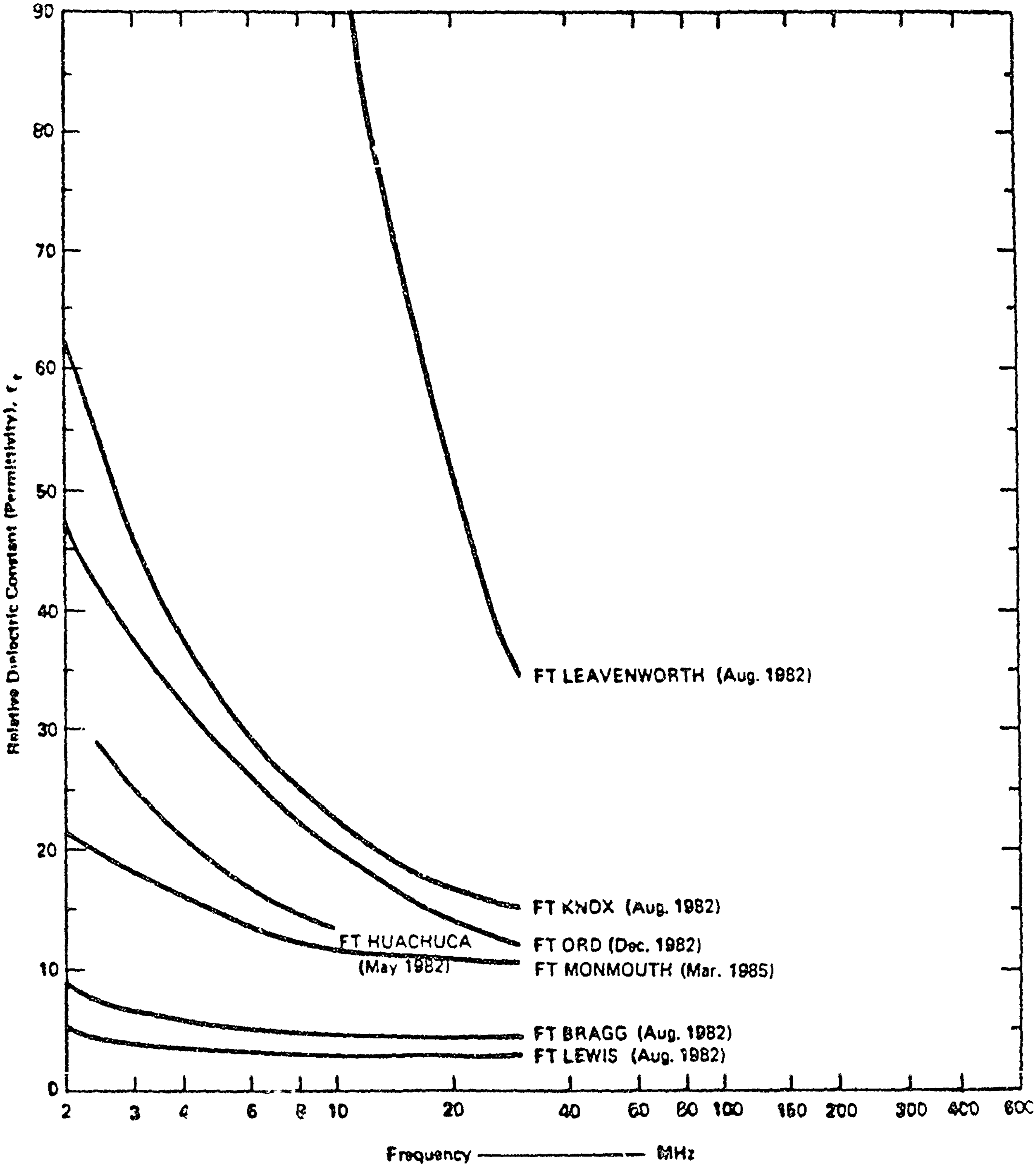


Figure 7 COMPARISON OF MEDIAN RELATIVE DIELECTRIC CONSTANTS MEASURED AT SELECTED U.S. ARMY BASES

given in Figures 8 and 9 for conductivity and relative dielectric constant. The data at Tinang in the Philippines are comparable to the Bangkok rice paddy data, but the Delano, CA data values are even higher. The Delano soil was a highly compacted dry lake bed with mineralization. The data for the dry beach sand at Chilaw, Sri Lanka is comparable to the data for the dry beach sand at Laem Chabang. Except for the high values at Delano and Tinang, the conductivity values follow fairly regular trends. The data sample for Poro in the Philippines was not a true site median. It was not possible to get the OWL probes far enough into the coral rock and only two samples were taken with short probes. At several of the VOA sites the water table was closer to the surface than the skin depth of the overlaying soil, so a two-layer model was required to adequately describe the ground.

VARIABILITY ABOUT SITE MEDIAN VALUES

There can be considerable variability about the site median for both the conductivity and the relative dielectric constant (particularly at the lower frequencies in the HF band). Let us consider as an example the data in Figures 10 and 11 taken at Site 2 with a 12-inch probe at Ft. Ord, CA [Hagn and Gaddie, 1983a]. These data from different sample locations separated by several hundred meters are reasonably closely grouped at a given frequency. Data taken at Site 1, only 150 m away, on a steeper slope of the same hill, showed greater variability. The bounds on the data from both of these sites are shown in Figures 12 and 13. Such bounds are useful when performing sensitivity analyses to determine the robustness of NEC results to changes in the ground constants.

The results obtained at any given site and location depend on the probe length due to a lack of soil homogeneity with depth. This is caused primarily by a gradient of soil moisture content. Figures 14 and 15 give values taken with 6-inch and 9-inch probes in thawed permafrost in Fairbanks silt [Hagn, 1983b]. At this site the soil was more moist nearer the surface. The appropriate probe length at any given site is the length closest to the skin depth at the frequency of interest. For this reason, SRI OWL kit probes of different lengths are required to cover the HF band.

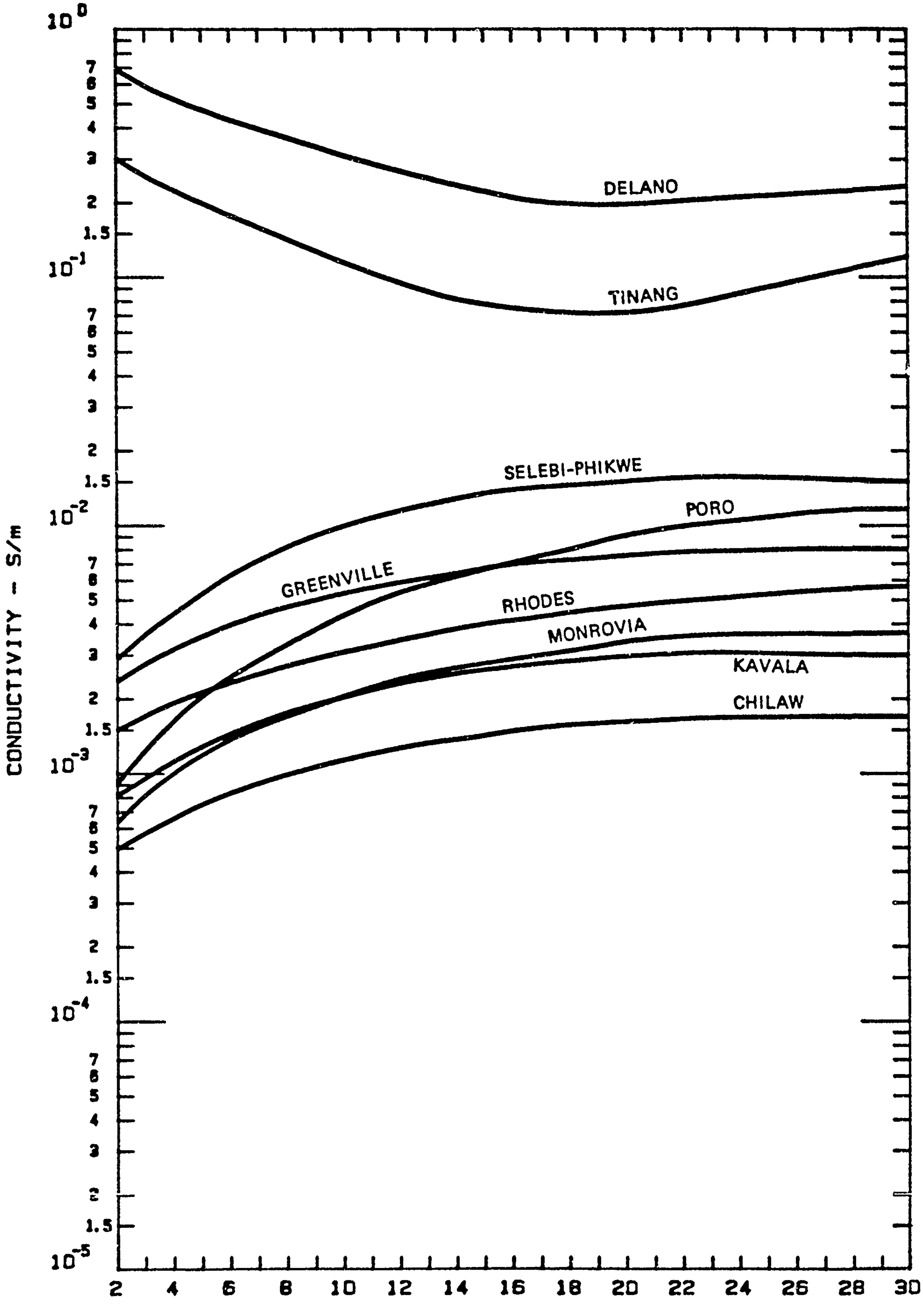


Figure 8 SITE MEDIAN VALUES OF CONDUCTIVITY VS FREQUENCY FOR SELECTED VOA TRANSMITTER SITES

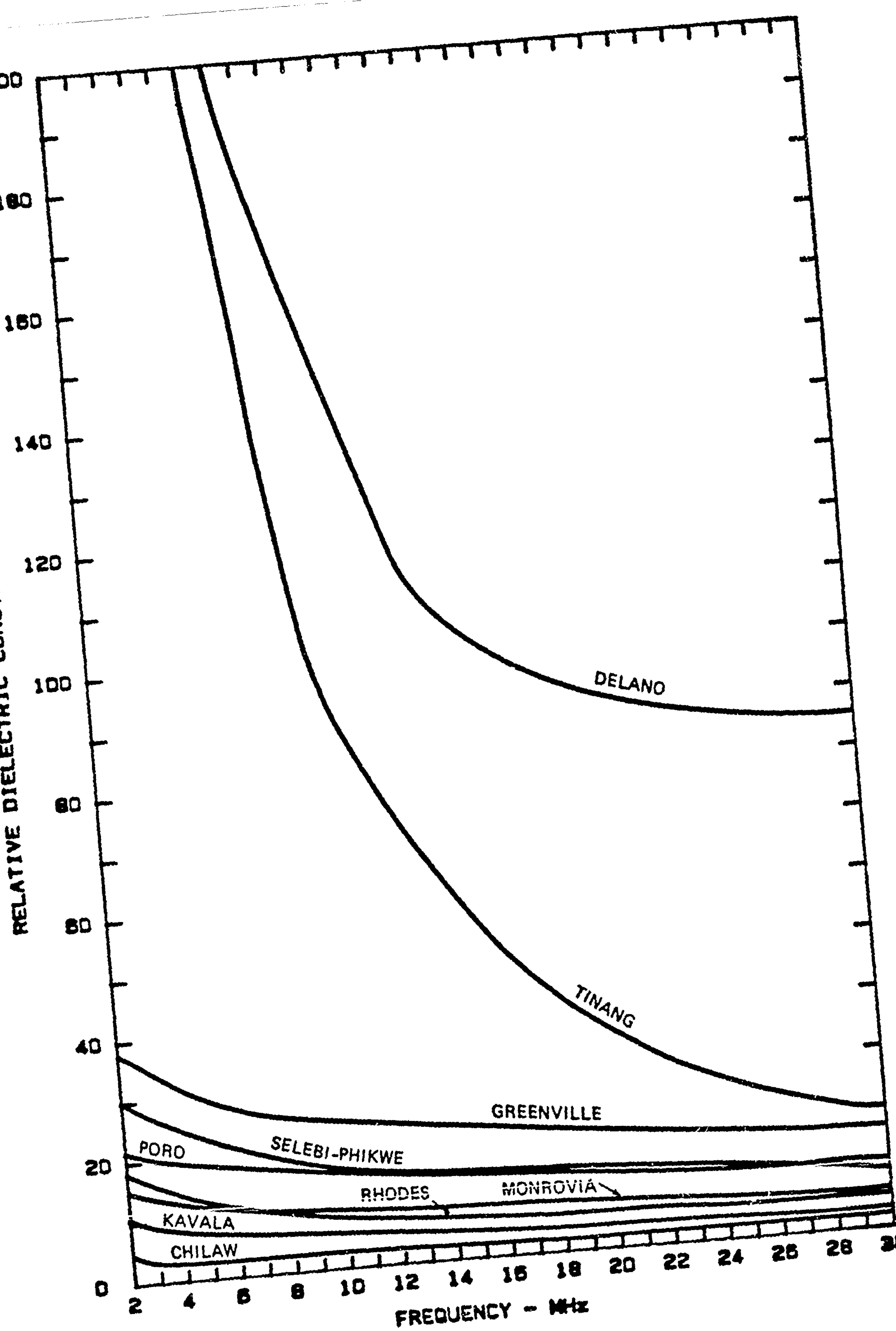
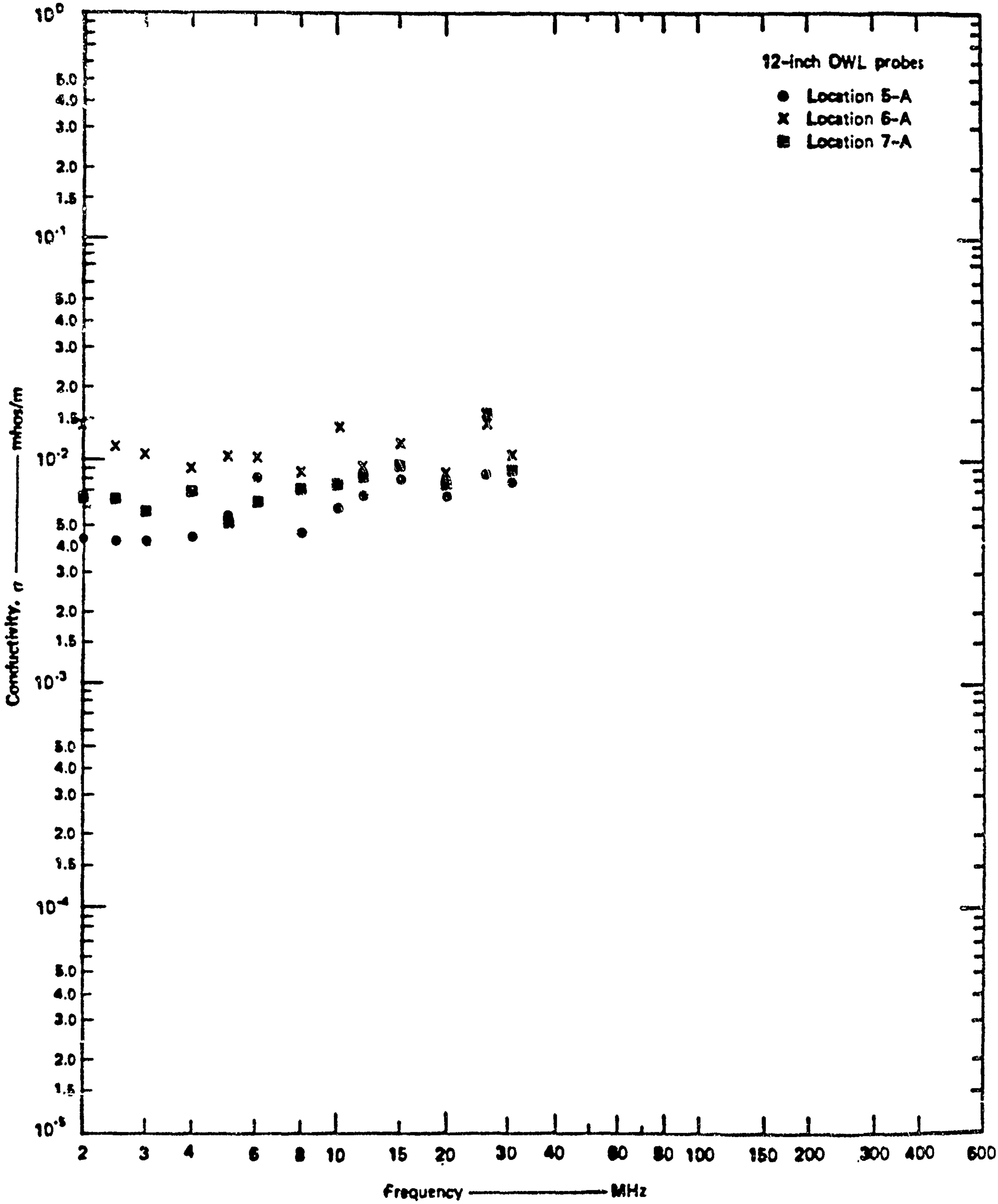
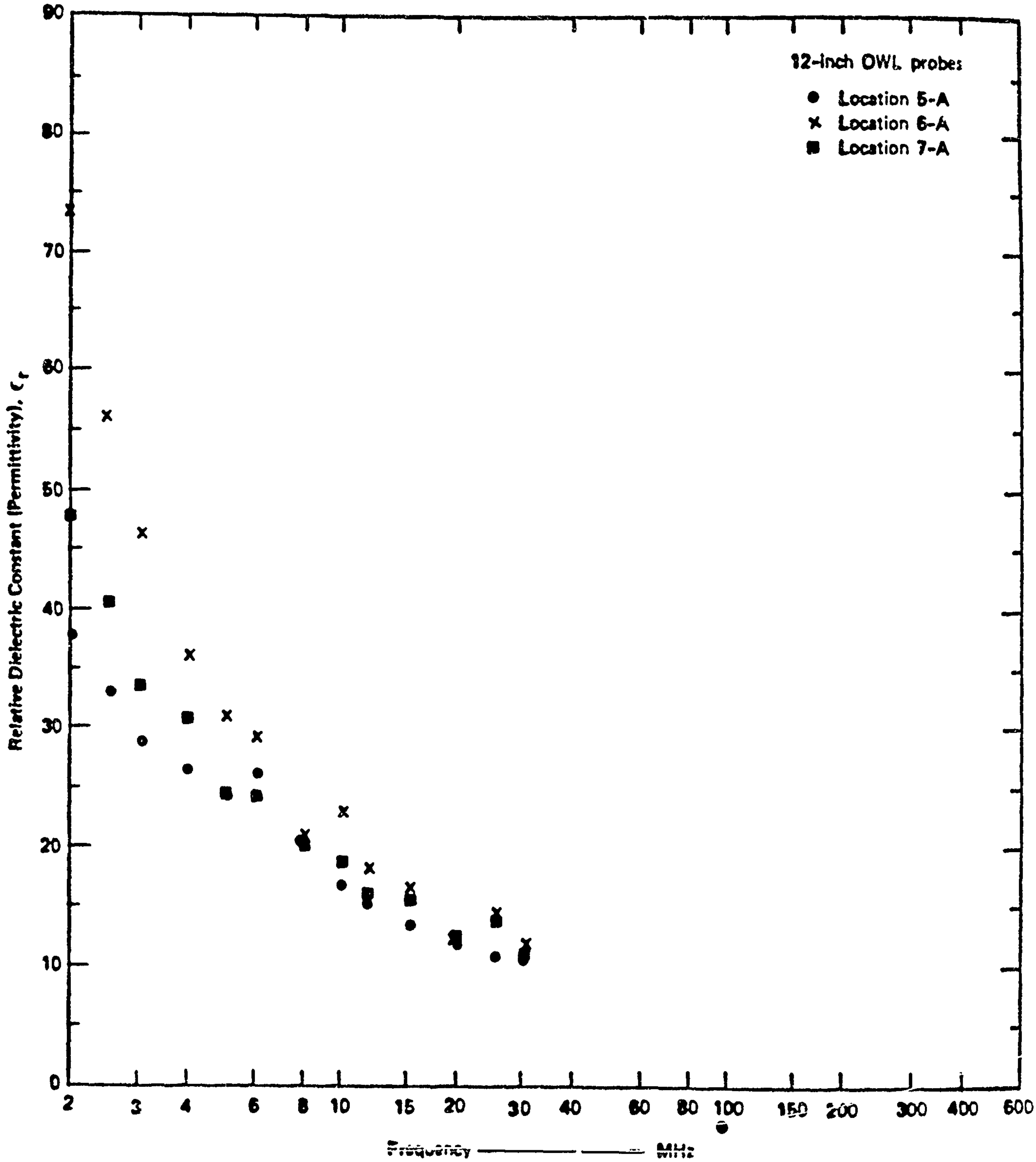


Figure 9 SITE MEDIAN VALUES OF RELATIVE DIELECTRIC CONSTANT VS FREQUENCY FOR SELECTED VOA TRANSMITTER SITES



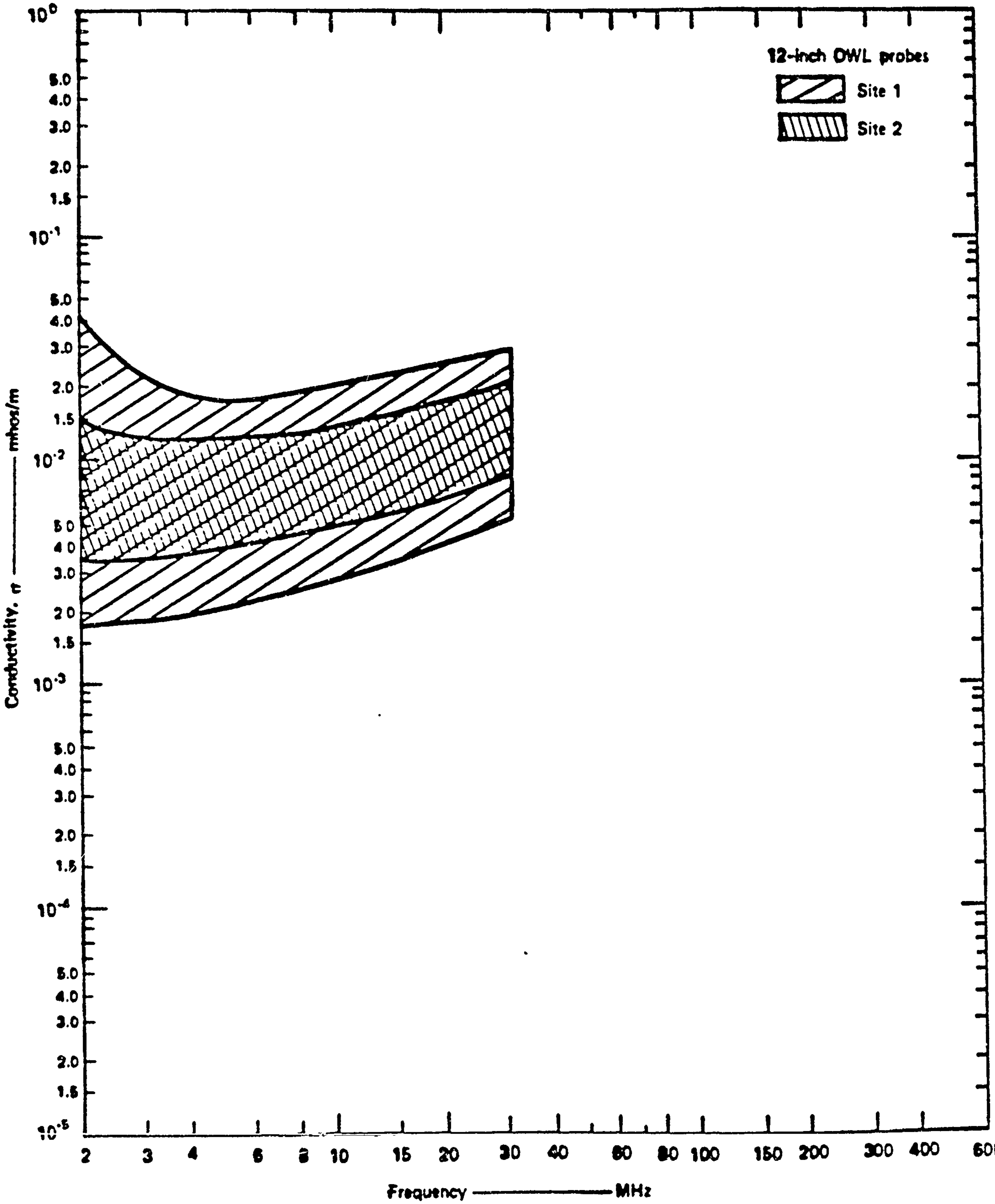
(Hagn and Gaddie, February 1983)

Figure 10 EXAMPLES OF EFFECTIVE GROUND CONDUCTIVITY VS FREQUENCY AT SITE 2 AT FORT ORD



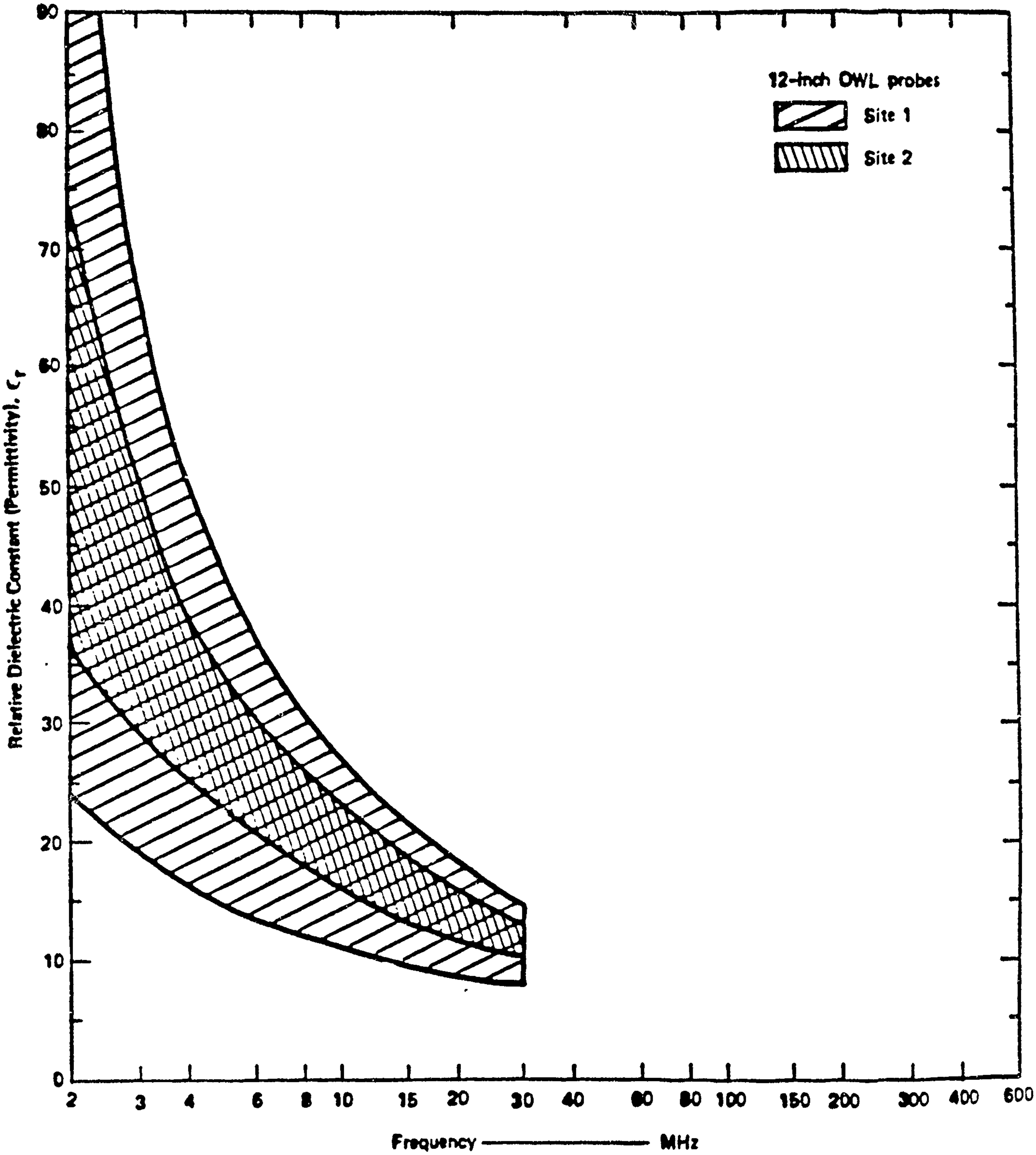
(Hagn and Gaddie, February 1983)

Figure 11 EXAMPLES OF RELATIVE DIELECTRIC CONSTANT VS FREQUENCY AT SITE 2 AT FORT ORD



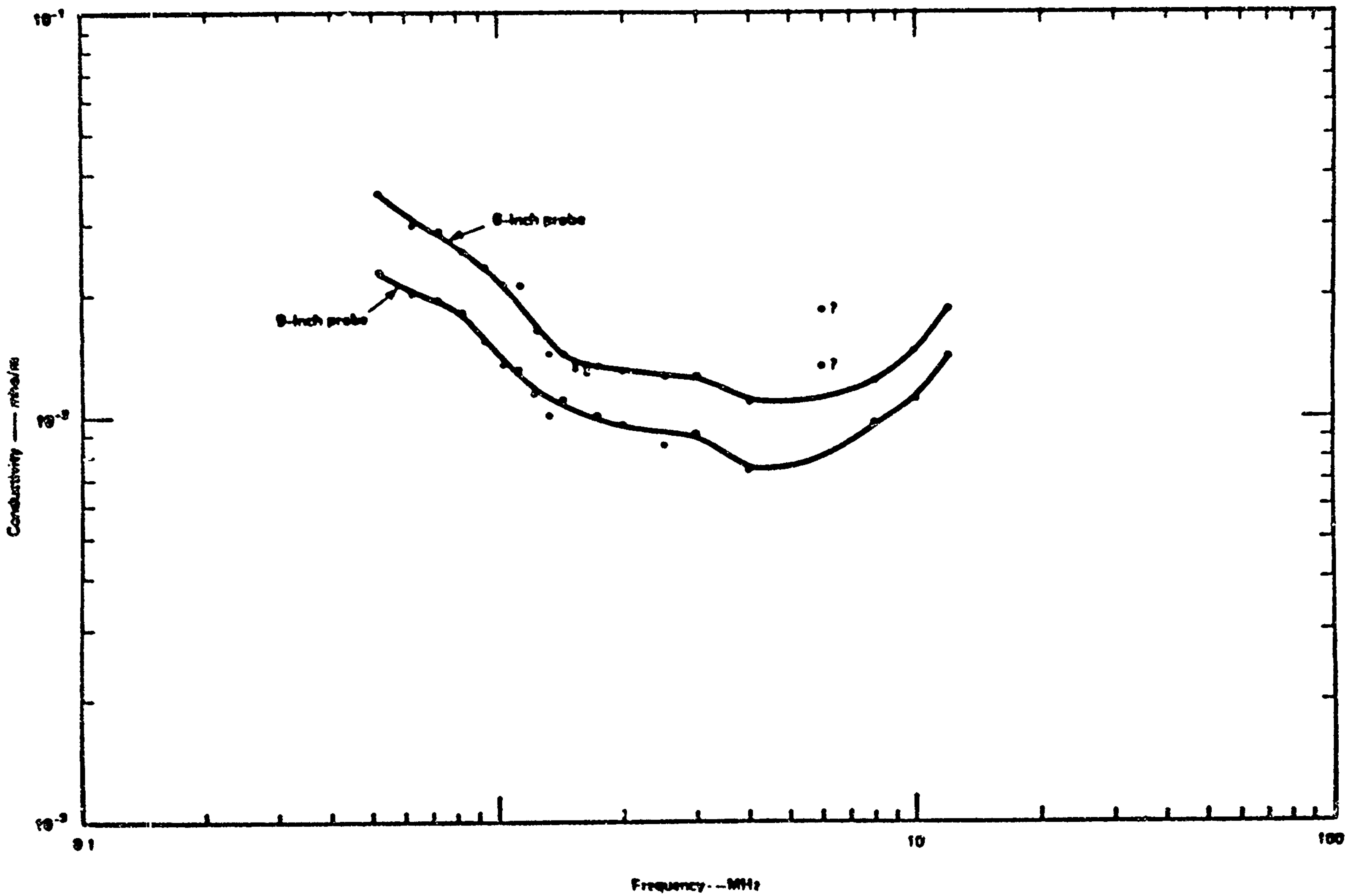
(Hagn and Gaddie, February 1983)

Figure 12 EFFECTIVE GROUND CONDUCTIVITY VS FREQUENCY FROM SRI OWL DATA AT FORT ORD



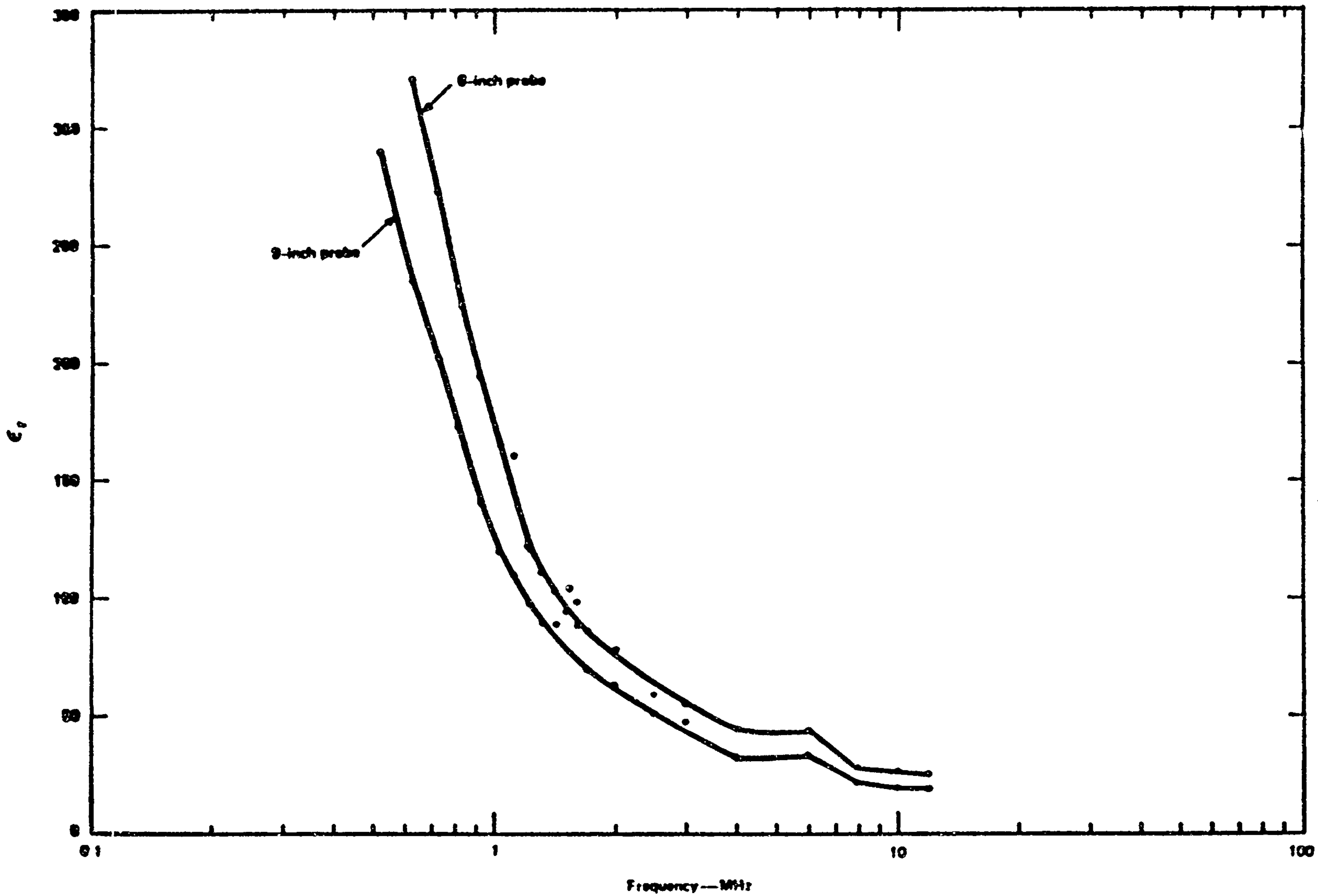
(Hagn and Gaddie, February 1983)

Figure 13 EFFECTIVE GROUND RELATIVE DIELECTRIC CONSTANT VS FREQUENCY FROM SRI OWL DATA AT FORT ORD



(Hagn, April 1983)

Figure 14 CONDUCTIVITY VS FREQUENCY FOR THAWED PERMAFROST AT FAIRBANKS



(Hagn, April 1983)

Figure 15 RELATIVE DIELECTRIC CONSTANT VS FREQUENCY FOR THAWED PERMAFROST AT FAIRBANKS

COMPARISON OF OWL AND E(d) DATA

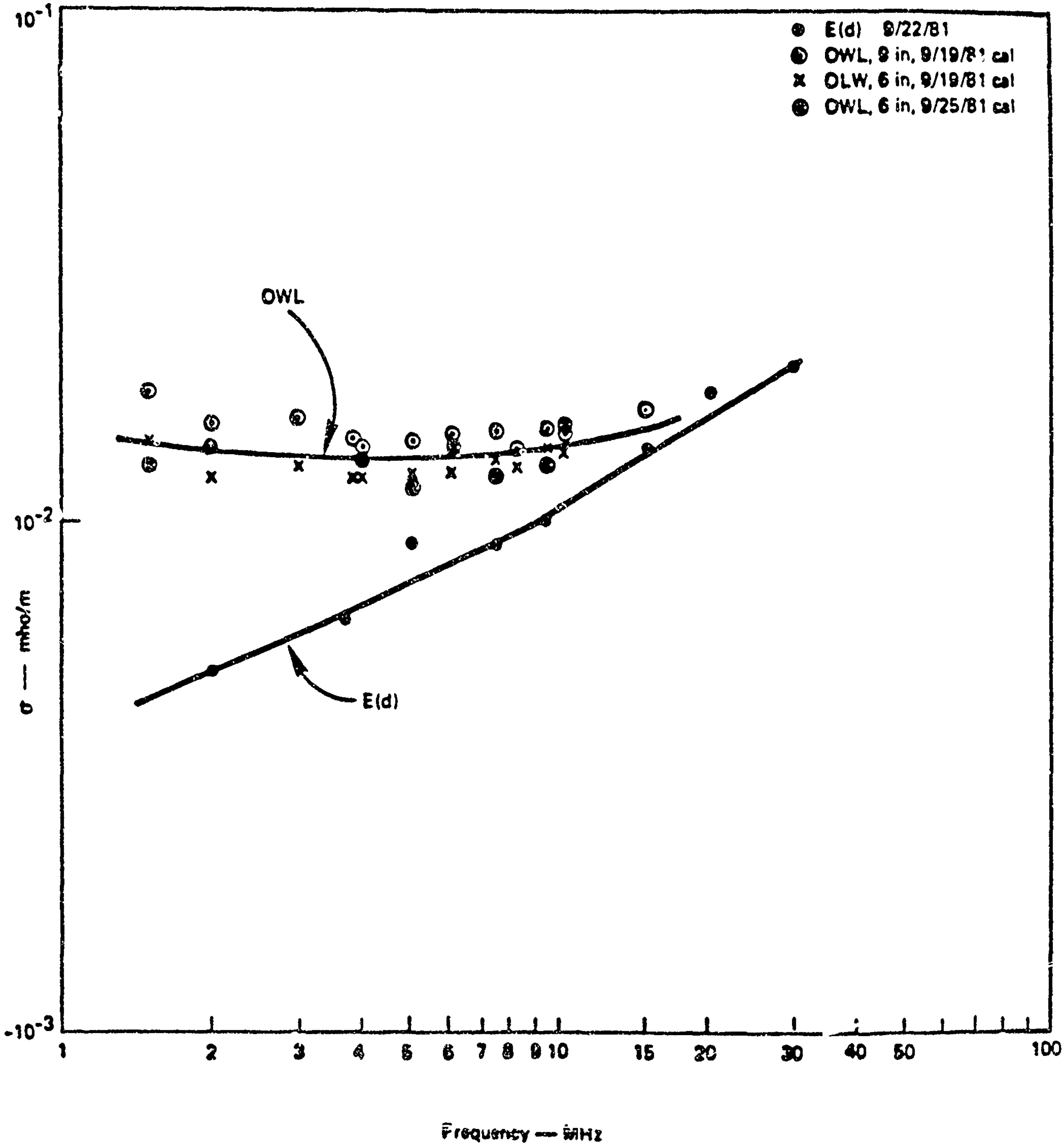
SRI has used the OWL kit and the E(d) method based on Norton's solution to the Sommerfeld integral [Norton, 1941] at several sites. The E(d) data were taken using the SRI XELEDOP [Barker, 1973; Hagn and Harnish, 1986] at 6 ft above ground as the source and measuring the vertically polarized ground wave versus distance out to 1500 feet. The results for a rice paddy are given in Figures 16 and 17 [Hagn, 1982a]. The data for the relative dielectric constant showed good agreement, but the conductivity only agreed at the higher frequencies. The reason for the disagreement of the conductivity data is not totally understood. The E(d) data were obtained down a dry road through the rice paddy; whereas, the OWL data were taken at several locations out in the dry paddy. The rice paddy had considerable "night soil" added to it for fertilizer.

This type of experiment was repeated for the lava fields at the Keflavik, Iceland NATO base [Hagn and Gaddie, 1983b] (see Figures 18 and 19). Here the agreement was reasonable for both the conductivity and relative dielectric constant. There was considerable variability from one sample location to another due to lateral variation of moisture content. The E(d) data tend to smooth out these lateral variations. The site median OWL data provide reasonable agreement with the E(d) data.

Note that the E(d) technique can only give valid estimates for both conductivity and dielectric constant when the DF is reasonably close to unity. When DF >> 1 it is not possible to get good estimates of the relative dielectric constant. For the same reason, however, good values of relative dielectric are not needed for this situation.

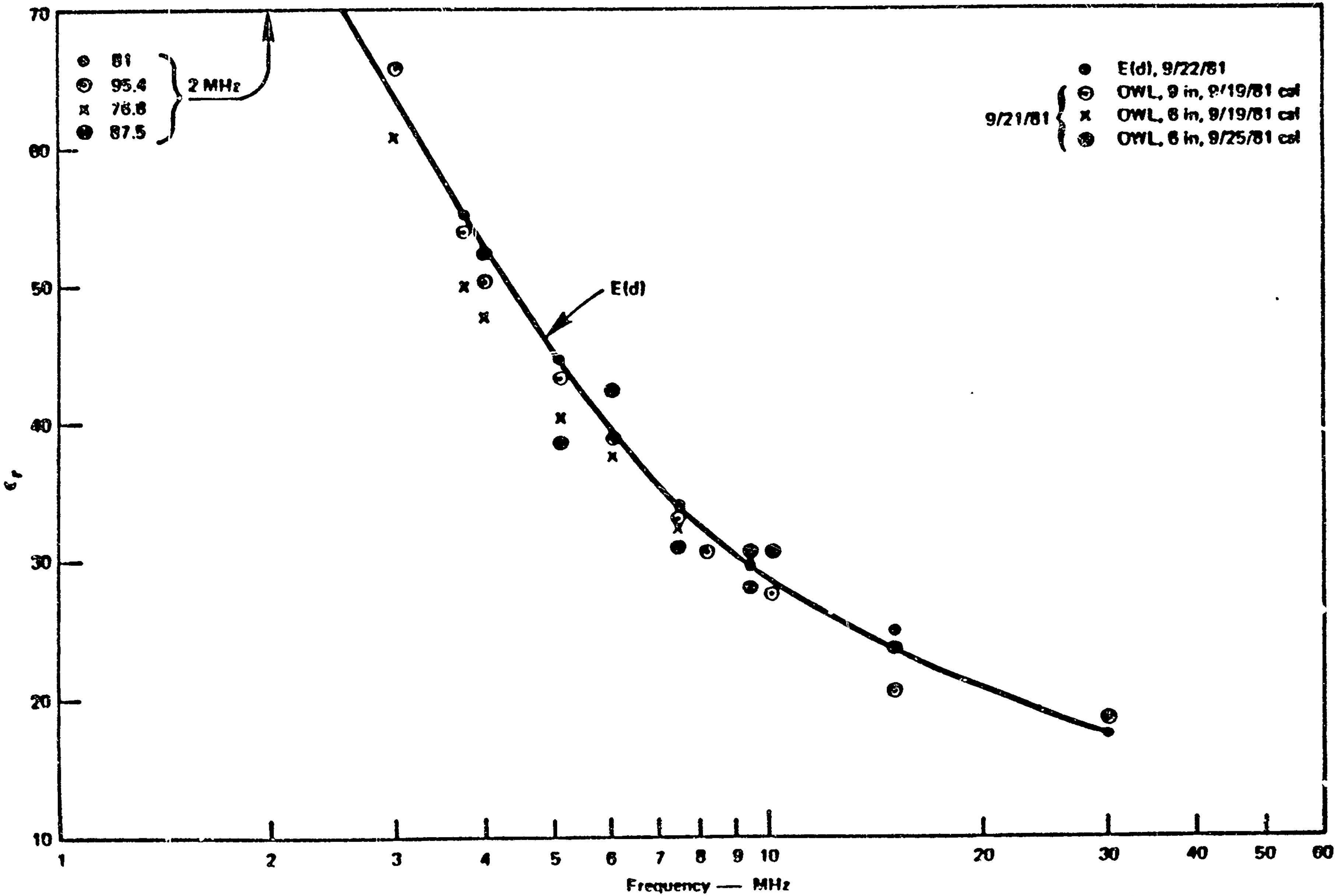
GENERIC GROUND CONSTANTS AT HF

Ideally, one could use measured values of ground constants for input values for NEC or other models based upon Maxwell's equations, but this usually is not practical. The alternatives are to use handbook values or data from sites which appeared to be similar. The current handbook values



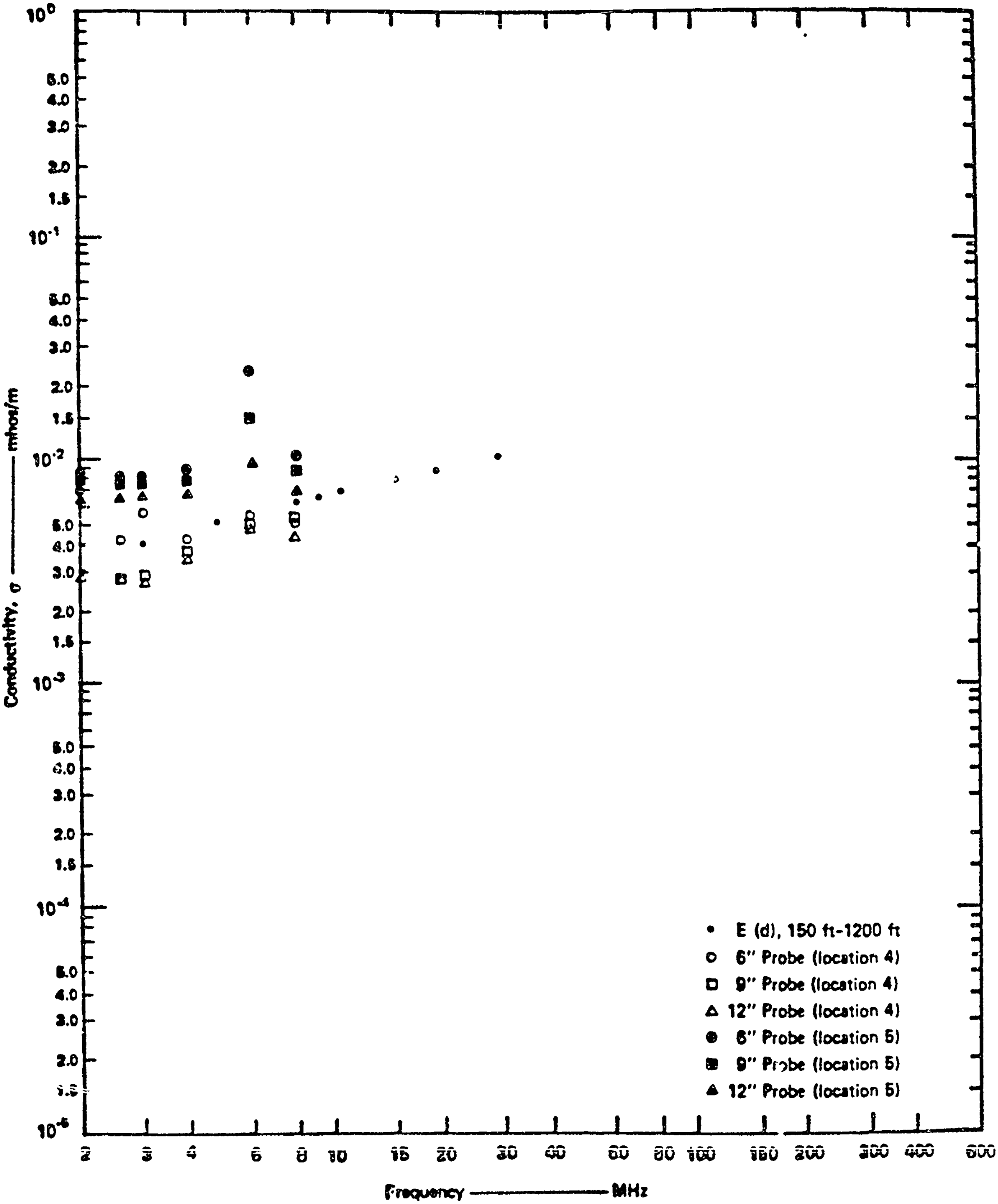
(Hagn, 1981)

Figure 16 CONDUCTIVITY VS FREQUENCY FOR RICE PADDY



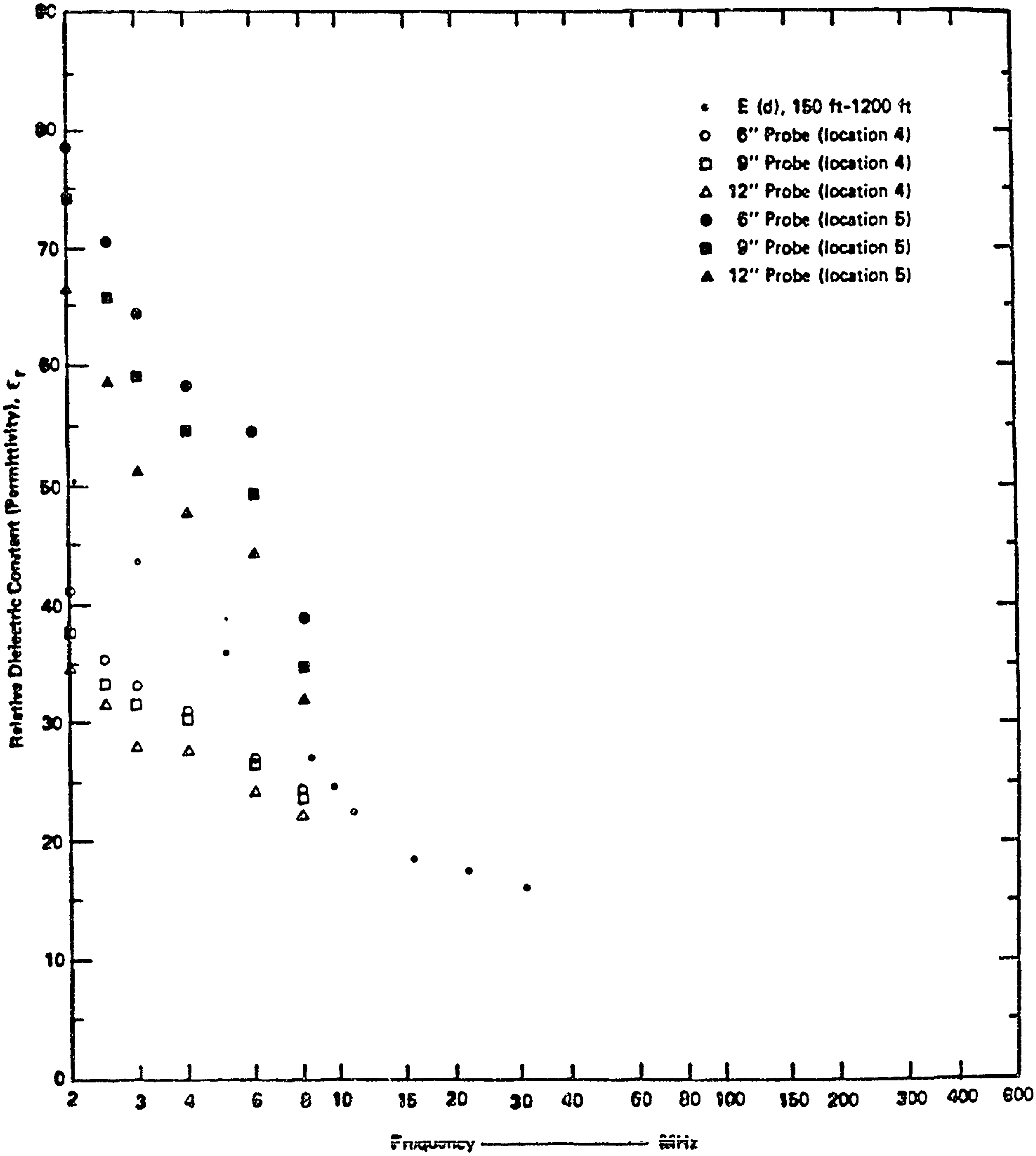
(Hagn, 1981)

Figure 17 RELATIVE DIELECTRIC CONSTANT VS FREQUENCY FOR RICE PADDY



(Hagn and Gaddie, May 1983)

Figure 18 MEDIAN CONDUCTIVITY OF THE GROUND AT ICELAND LOCATIONS 4 AND 5 VS FREQUENCY MEASURED WITH THE SRI OWL KIT



(Hagn and Gaddie, May 1983)

Figure 19 MEDIAN RELATIVE DIELECTRIC CONSTANT OF THE GROUND AT ICELAND LOCATIONS 4 AND 5 VS FREQUENCY MEASURED WITH THE SRI OWL KIT are inadequate because they do not allow for variation with frequency across the HF band. The CCIR has presented generic curves of ground constant with different moisture content vs frequency [CCIR, 1982] which were developed some years ago by Albrecht [1965] and others (see Figure 20). The CCIR also provides curves of penetration depth (skin depth computed using the correct equation) based upon these generic curves (see Figure 21). While the CCIR curves do vary with frequency, they exhibit no dispersion in the HF band. The author developed generic curves [Hagn, et al., 1982a] which were based primarily on the Thailand data and other limited data then available. Handbook-type physical descriptions were applied, and the data were extrapolated from 200 MHz to 600 MHz using the trends below 200 MHz. The purpose was to provide a source of input data for the SRICOM model [Hagn, 1980; Hagn, et al., 1982a]. These generic curves are reproduced here as Figures 22 and 23. Mr. William Moision of the Naval Ocean Systems Center developed equations to describe these curves in the HF band (see Table 6 and [Sailors, et al., 1984]). These equations are depicted for conductivity and relative dielectric constant in Figures 24 and 25, and the corresponding values of DF and SD are given in Figures 26 and 27, respectively.

COMPARISON OF GENERIC CURVES WITH MEASURED DATA

How well do these generic curves work? Figures 28 and 29 show data obtained at the same site in Iceland in 1981 and 1982 inferred from E(d) data [Hagn and Gaddie, 1983b]. The data taken in 1981 from the relatively dry lava agrees well with the generic curve for mountains and rocky, steep hills. The data taken in 1982 after significant rains, exhibited somewhat higher values as expected due to the increase in moisture content. The results followed the shape of the generic curves; but, the conductivity was more closely approximated by pastoral land; whereas, the relative dielectric constant followed the generic curve for rich agricultural land. In other words, the curve pairs did not match up too well.

Other comparisons for site median data taken in CONUS with the SRI OWL kit are given in Figures 30 through 33. The Platteville, CO and Fort

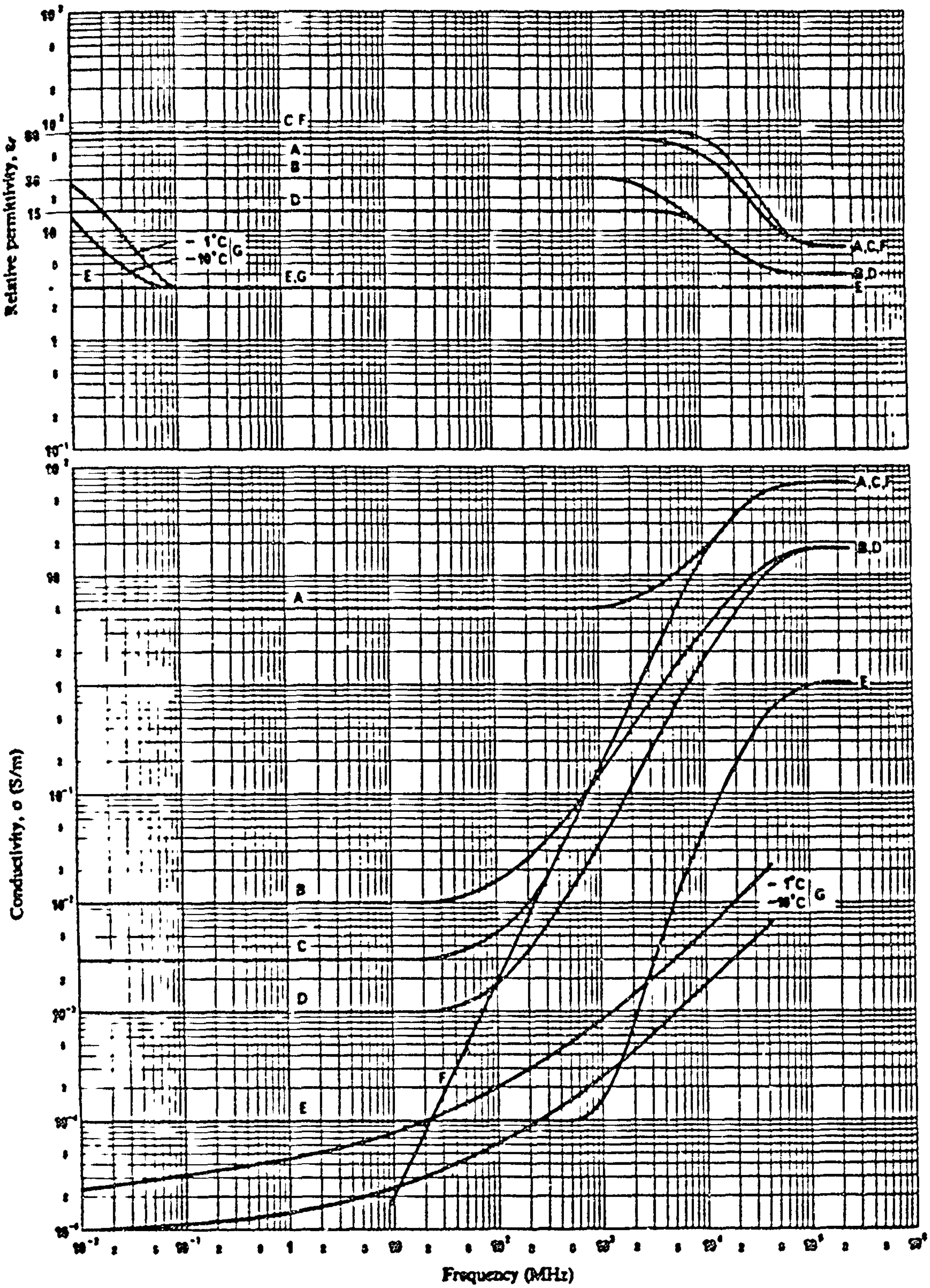
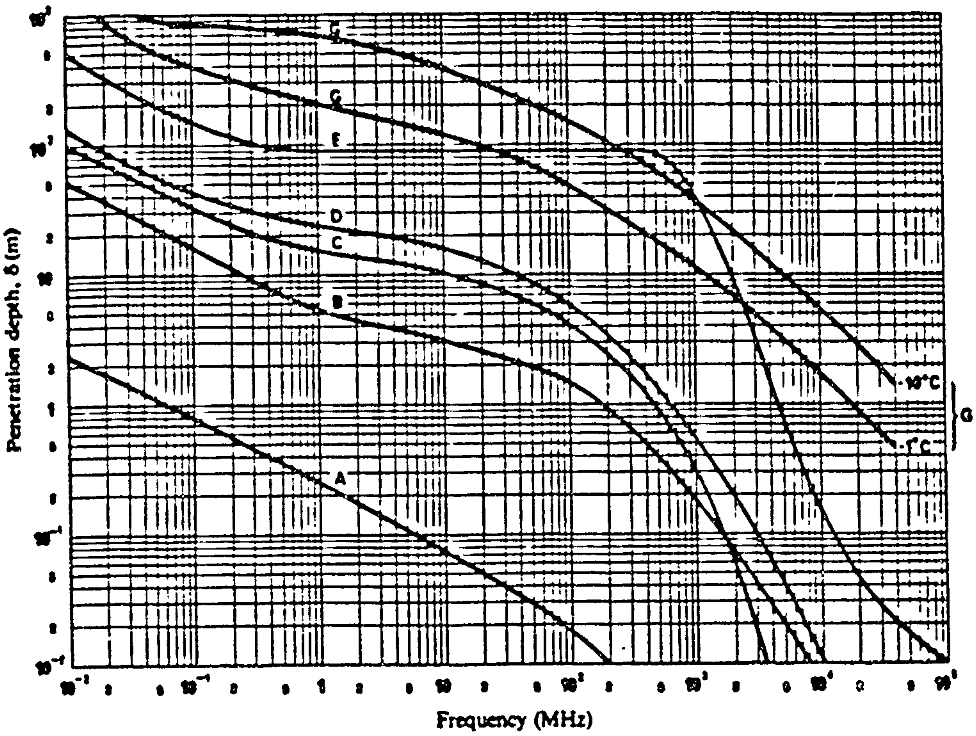


Figure 20 RELATIVE PERMITTIVITY, ϵ_r, AND CONDUCTIVITY, σ, AS A FUNCTION OF FREQUENCY

A: sea water (average salinity), 20° C
B: wet ground
C: fresh water, 20° C
D: medium dry ground
E: very dry ground
F: pure water, 20° C
G: ice (fresh water)

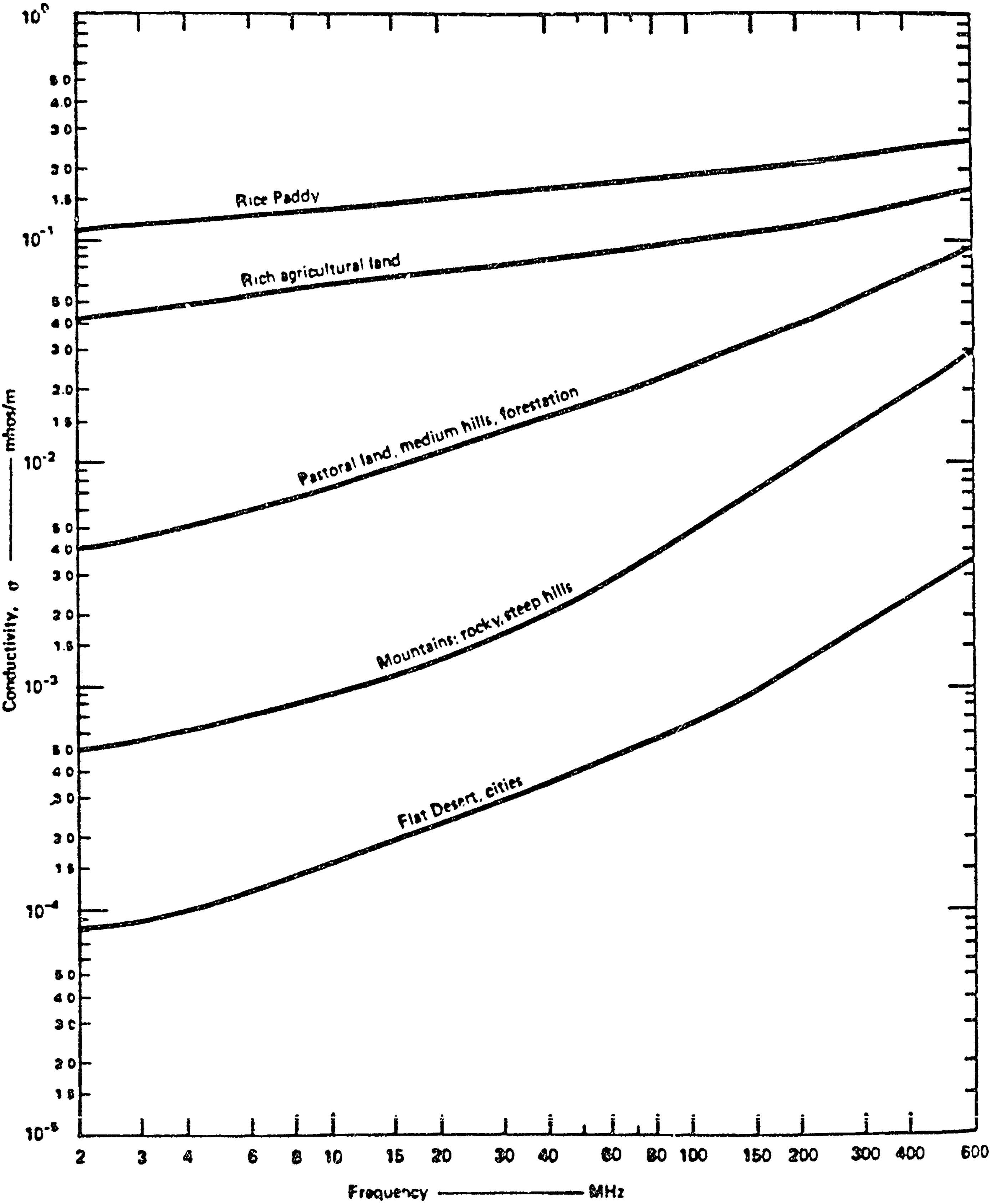
(CCIR, Vol. V,1982)



A: sea water
B: wet ground
C: fresh water
D: medium dry ground
E: very dry ground
G: ice (fresh water)

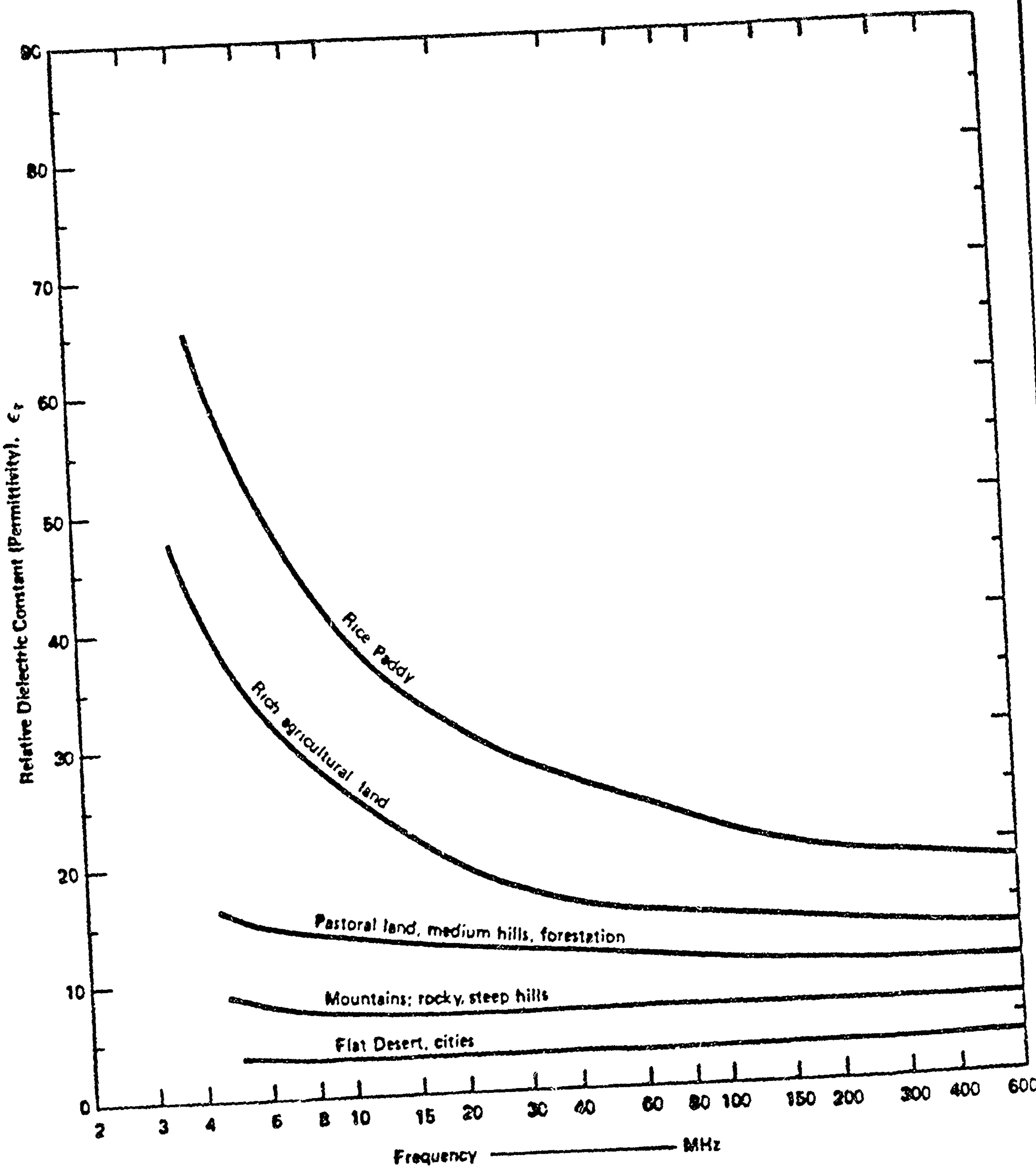
(CCIR, Vol. V, 1982)

Figure 21 PENETRATION DEPTH δ AS A FUNCTION OF FREQUENCY



(Hagn, et al., May 1982)

Figure 22 EFFECTIVE GROUND CONDUCTIVITY VS FREQUENCY FOR SELECTED TERRAIN CATEGORIES



(Hagn, et al., May 1982)

Figure 23 EFFECTIVE GROUND RELATIVE DIELECTRIC CONSTANT VS FREQUENCY FOR SELECTED TERRAIN CATEGORIES

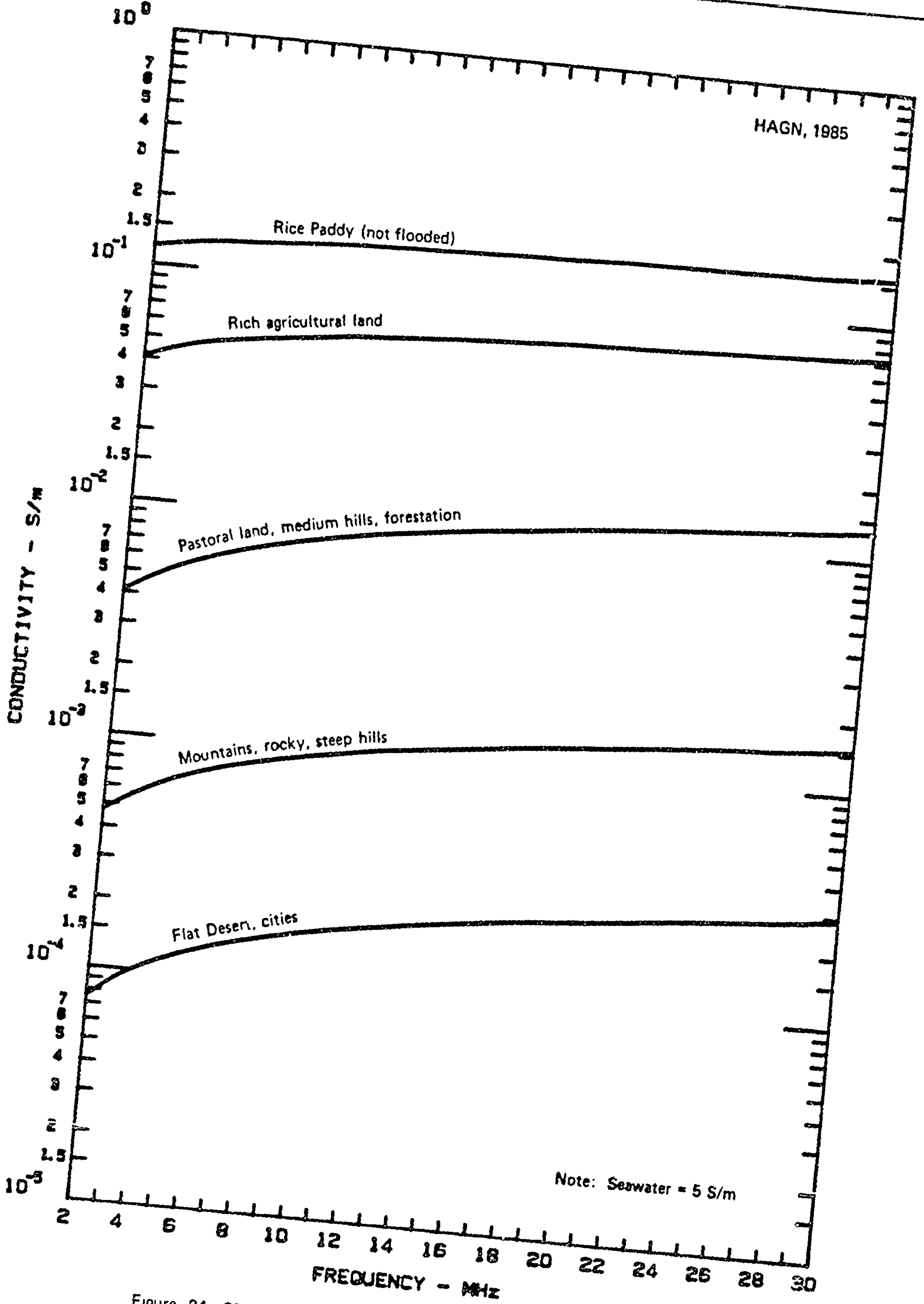


Figure 24 SRI GENERIC CURVES OF EFFECTIVE GROUND CONDUCTIVITY VS FREQUENCY FOR SELECTED TERRAIN CATEGORIES

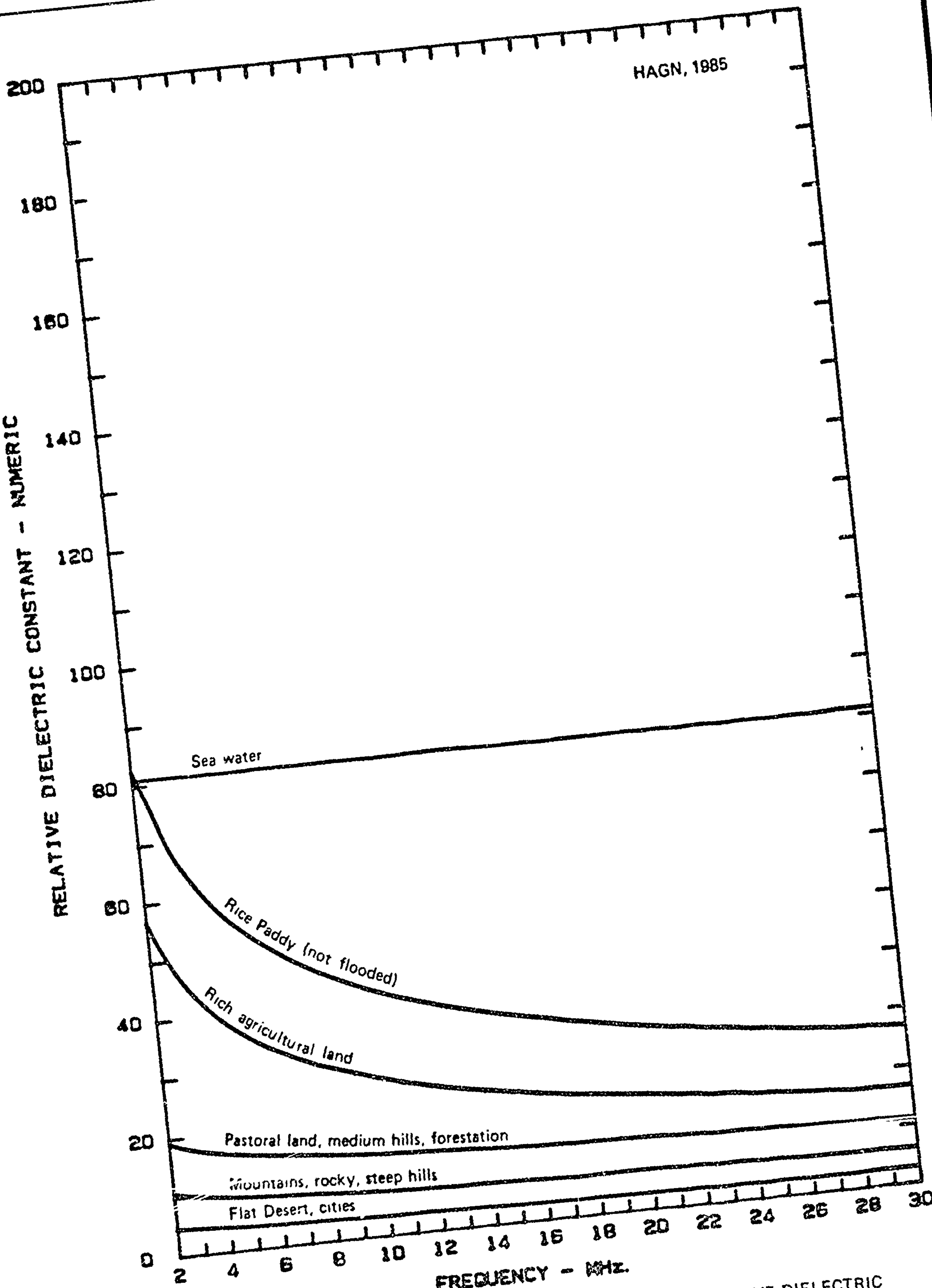


Figure 25 SRI GENERIC CURVES OF EFFECTIVE GROUND RELATIVE DIELECTRIC CONSTANT VS FREQUENCY FOR SELECTED TERRAIN CATEGORIES

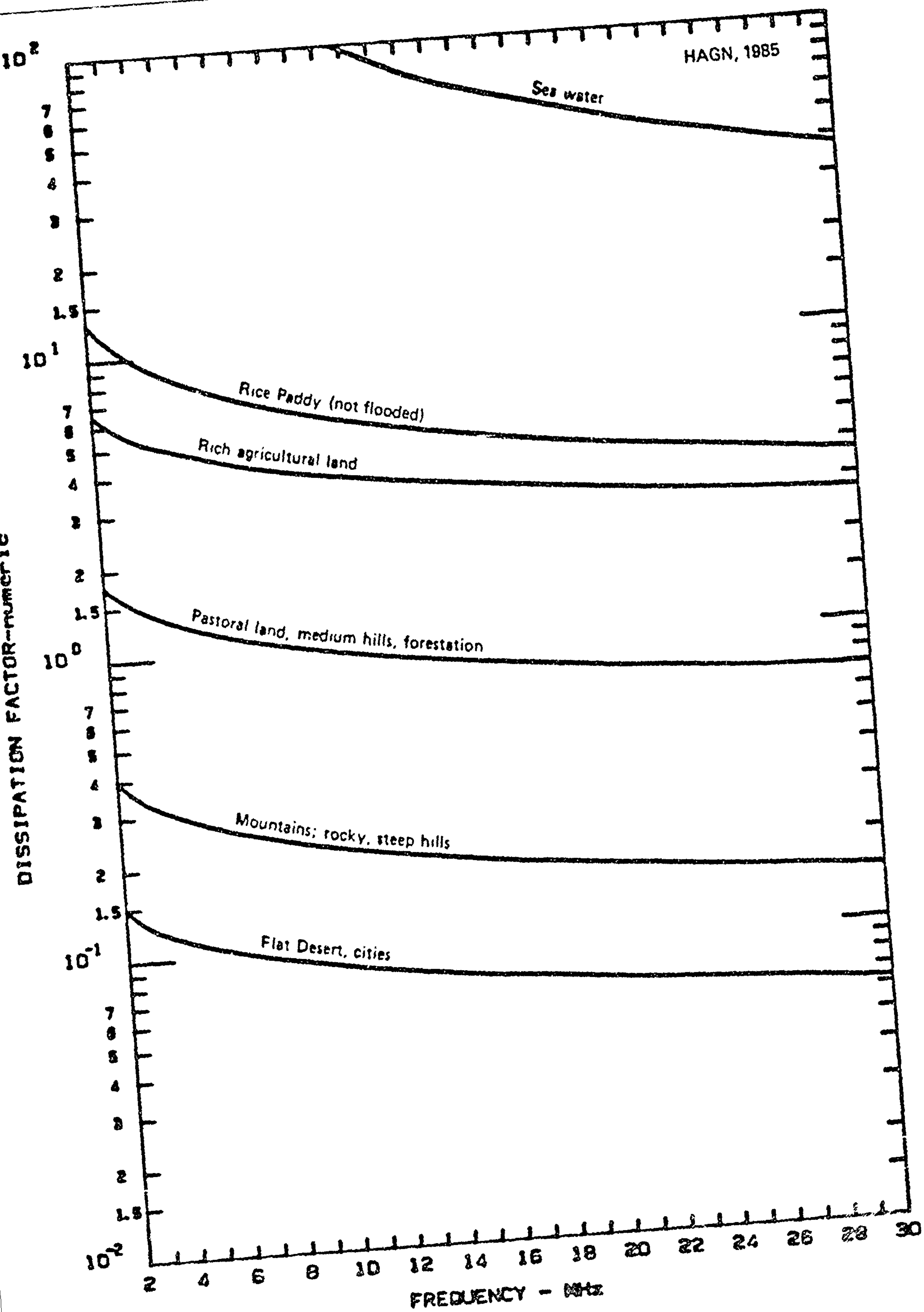


Figure 26 SRI GENERIC CURVES OF EFFECTIVE GROUND DISSIPATION FACTOR VS FREQUENCY FOR SELECTED TERRAIN CATEGORIES

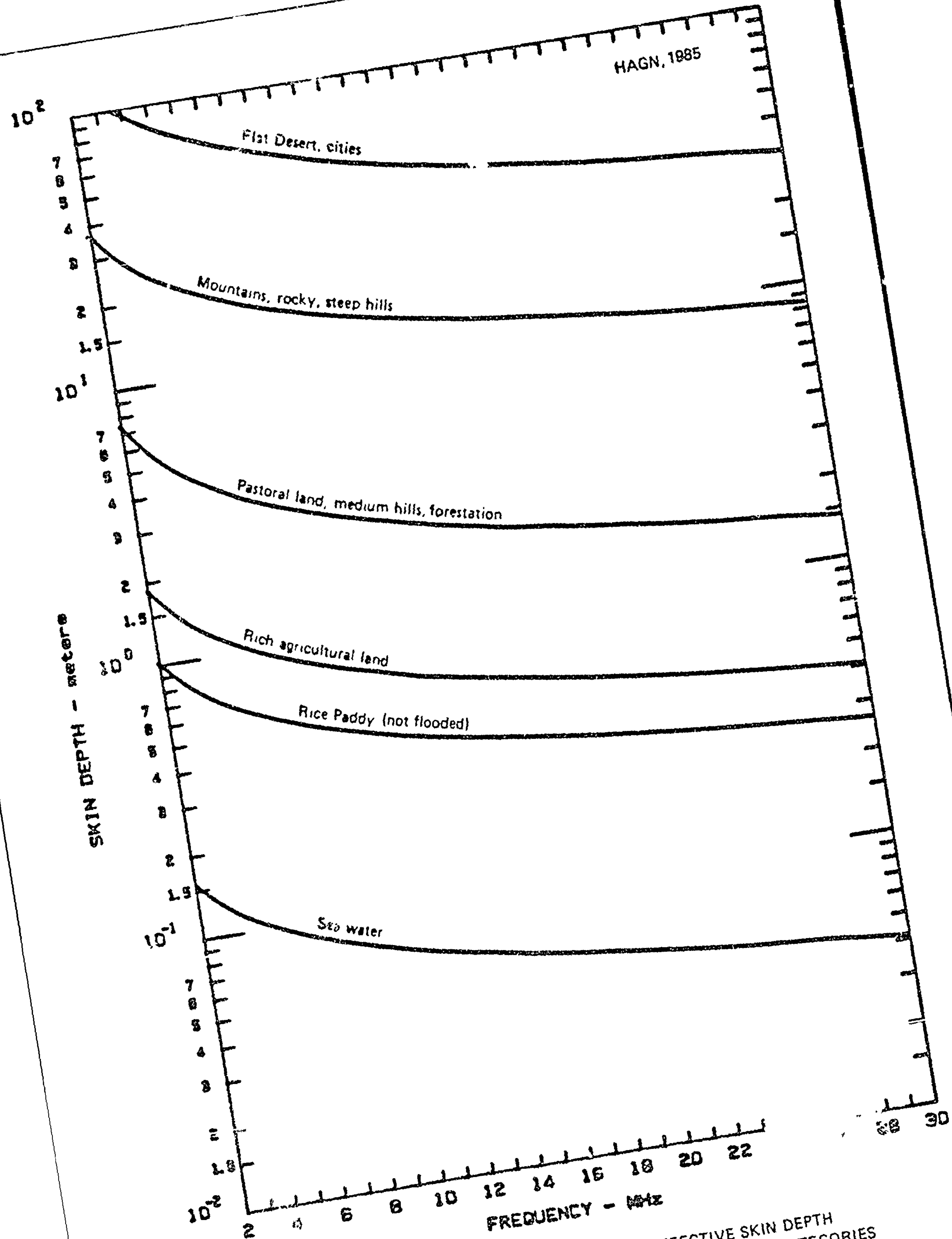
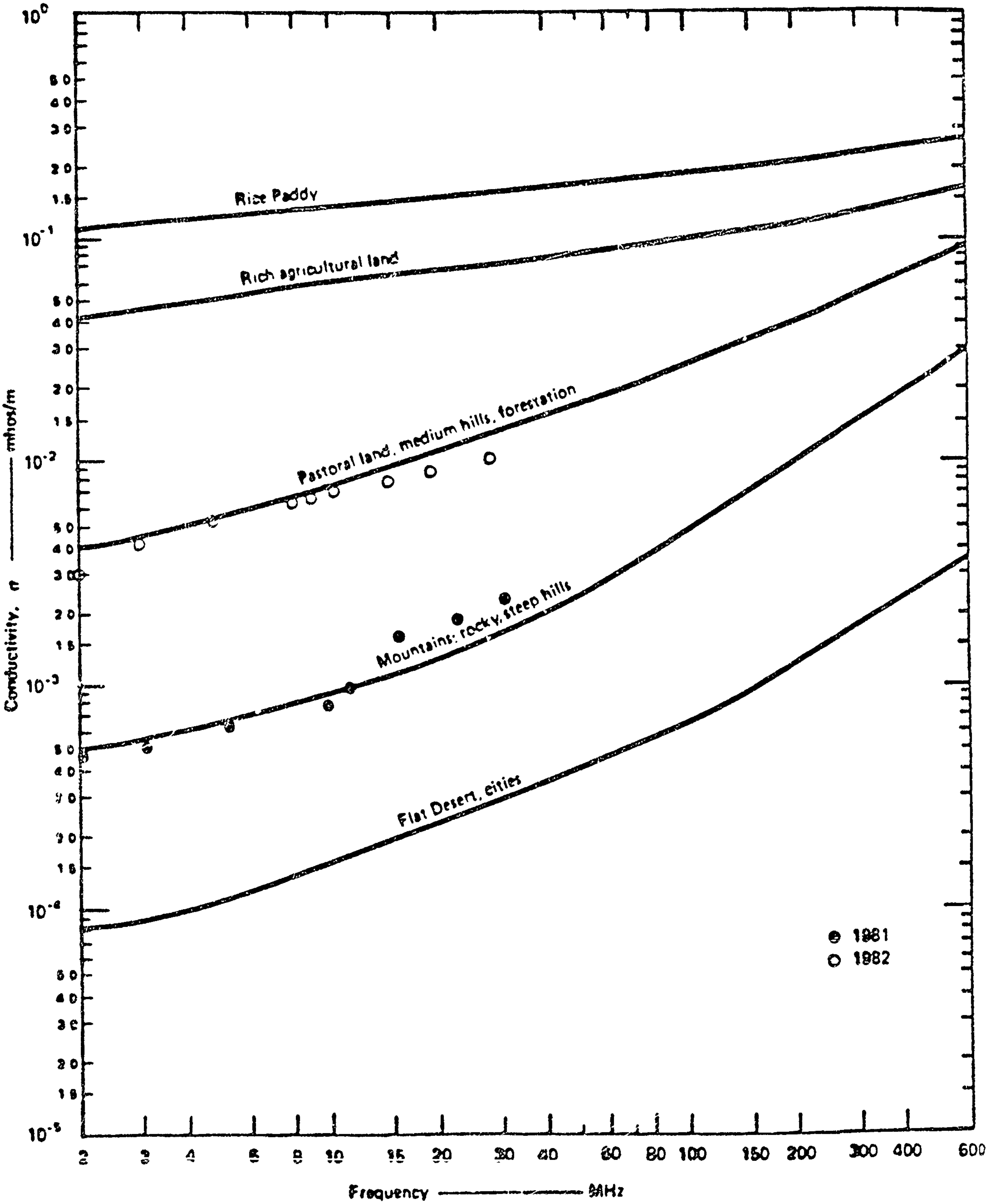
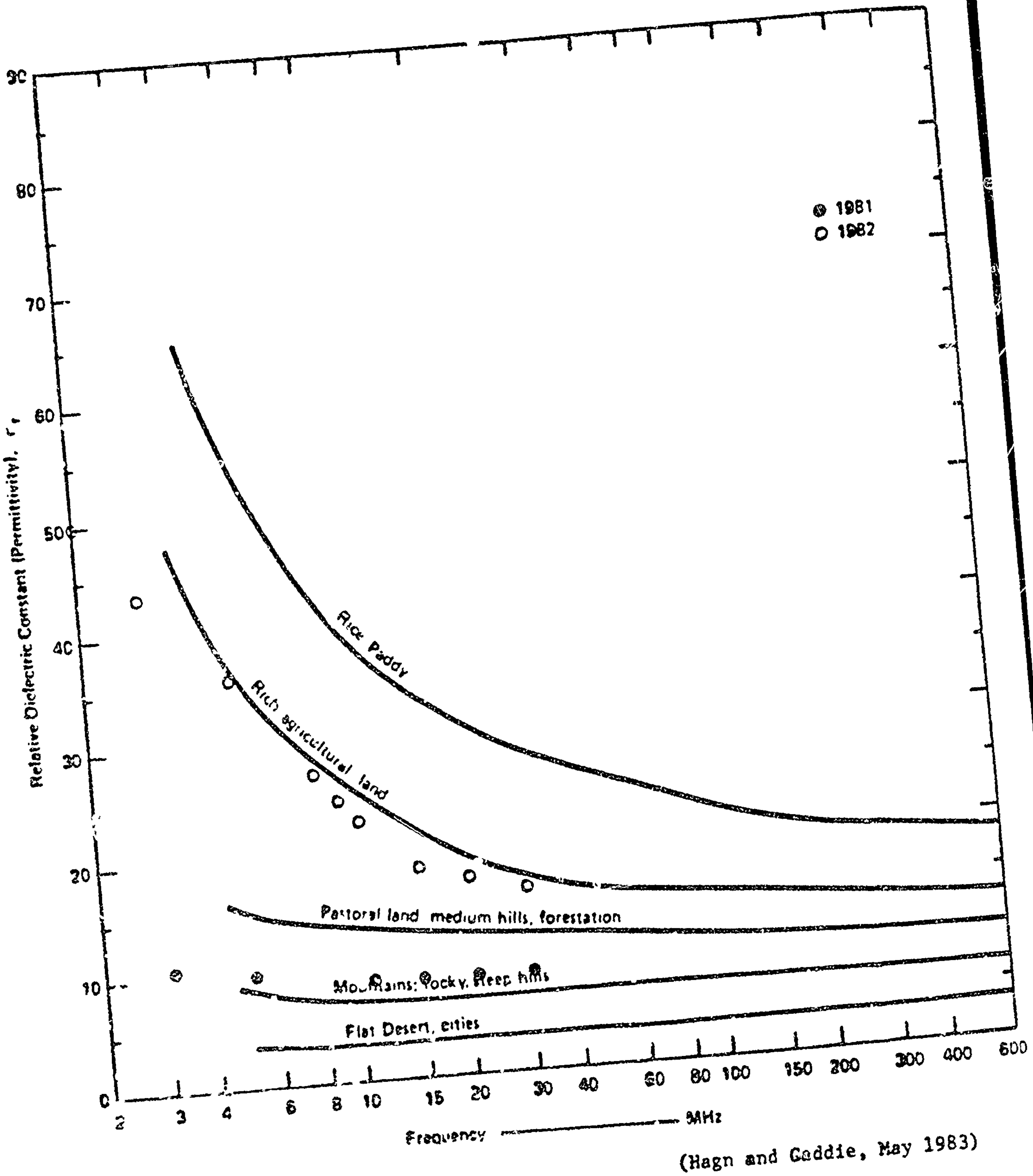


Figure 27 SRI GENERIC CURVES OF EFFECTIVE SKIN DEPTH VS FREQUENCY FOR SELECTED TERRAIN CATEGORIES



(Hagn and Gaddie, May 1983)

Figure 28 EFFECTIVE GROUND CONDUCTIVITY VS FREQUENCY INFERRED FROM E(d) DATA



(Hagn and Gaddie, May 1983)

Figure 29 EFFECTIVE GROUND RELATIVE DIELECTRIC CO~~STANT VS FREQUENCY INFERRED FROM THE E(d) DA~A

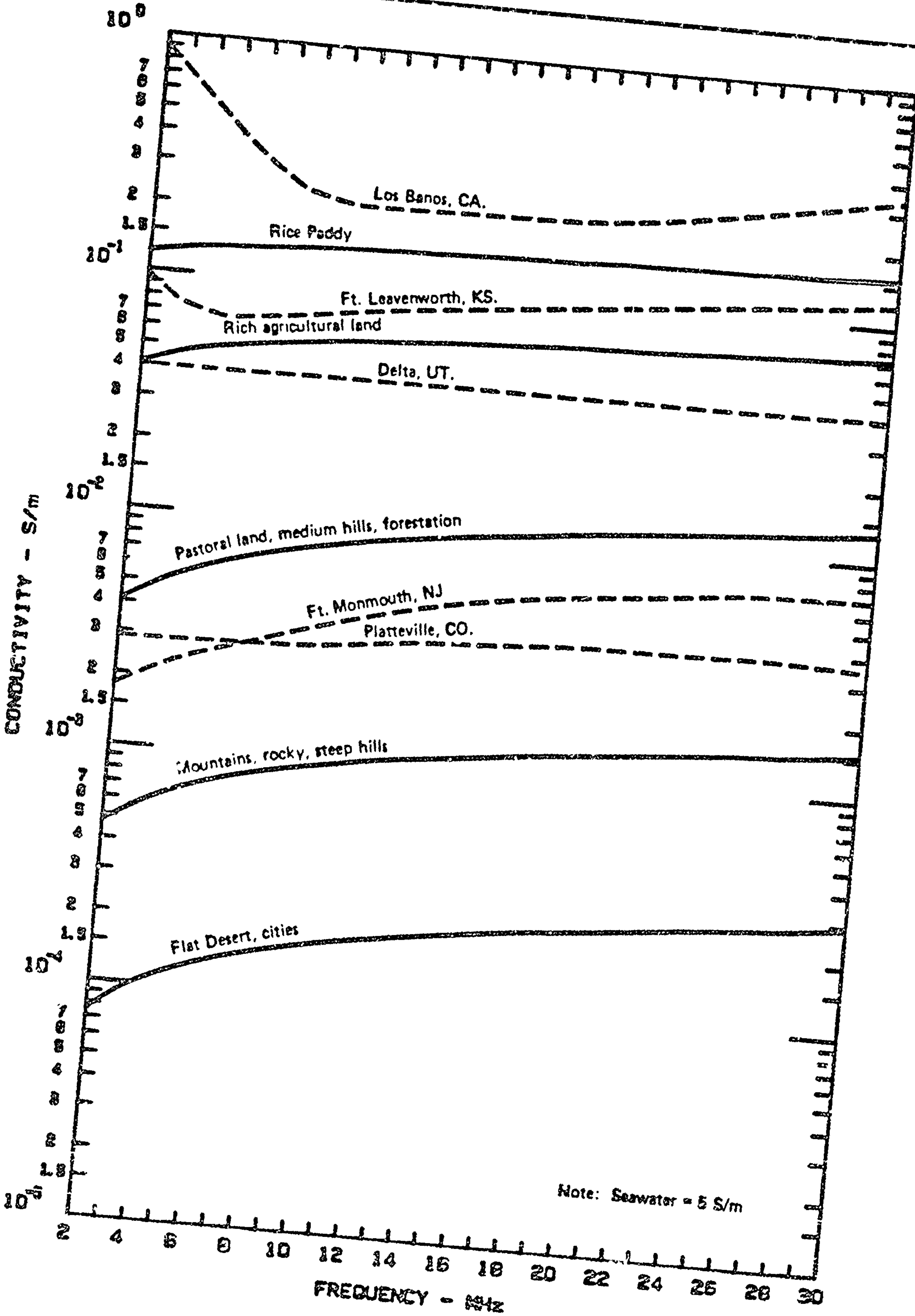


Figure 30 EFFECTIVE GROUND CONDUCTIVITY FOR FIVE ANTENNA TEST FIELD SITES VS SRI GENERIC CURVES FOR SELECTED TERRAIN CATEGORIES

(Harnish, et al., 1985)

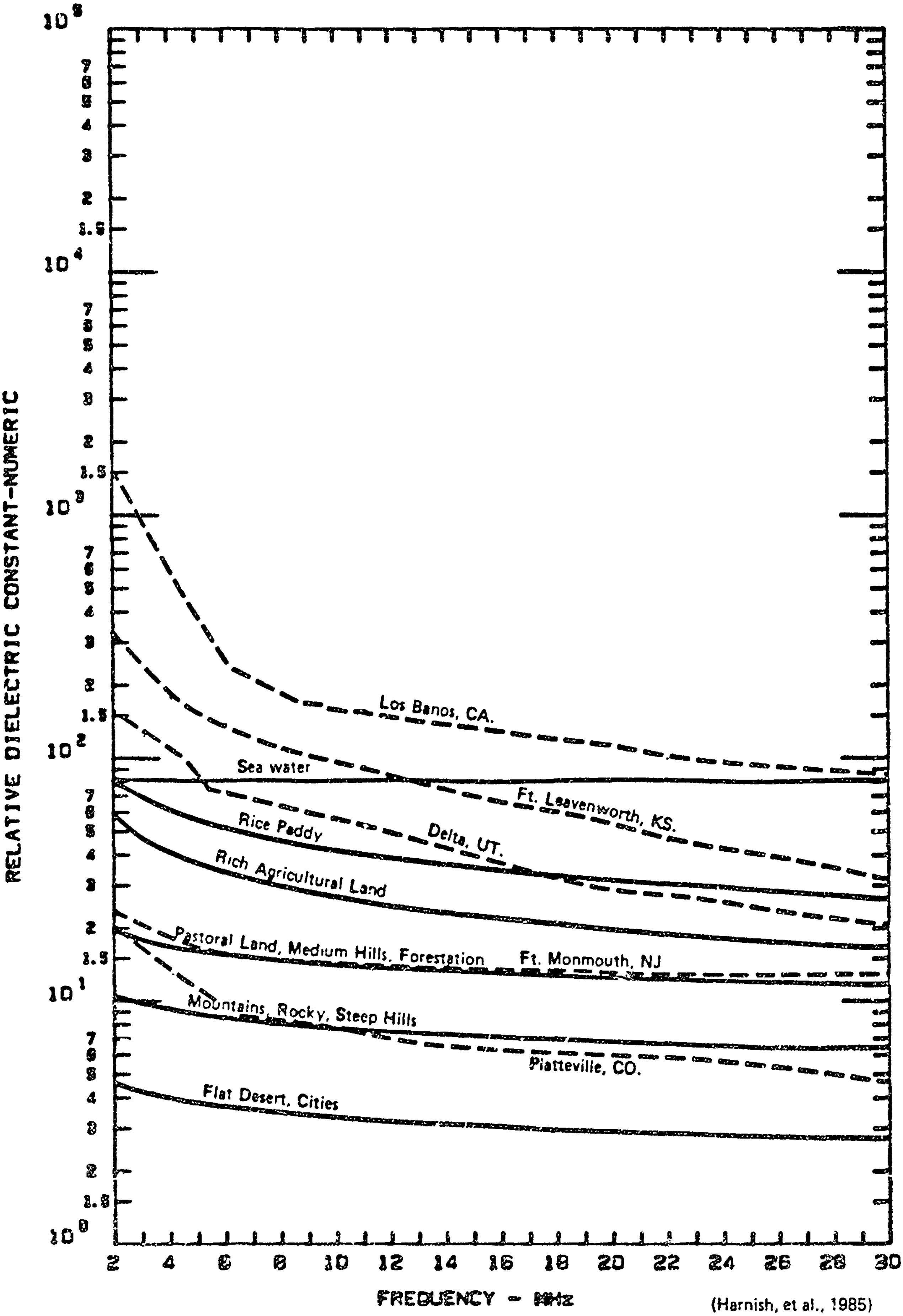
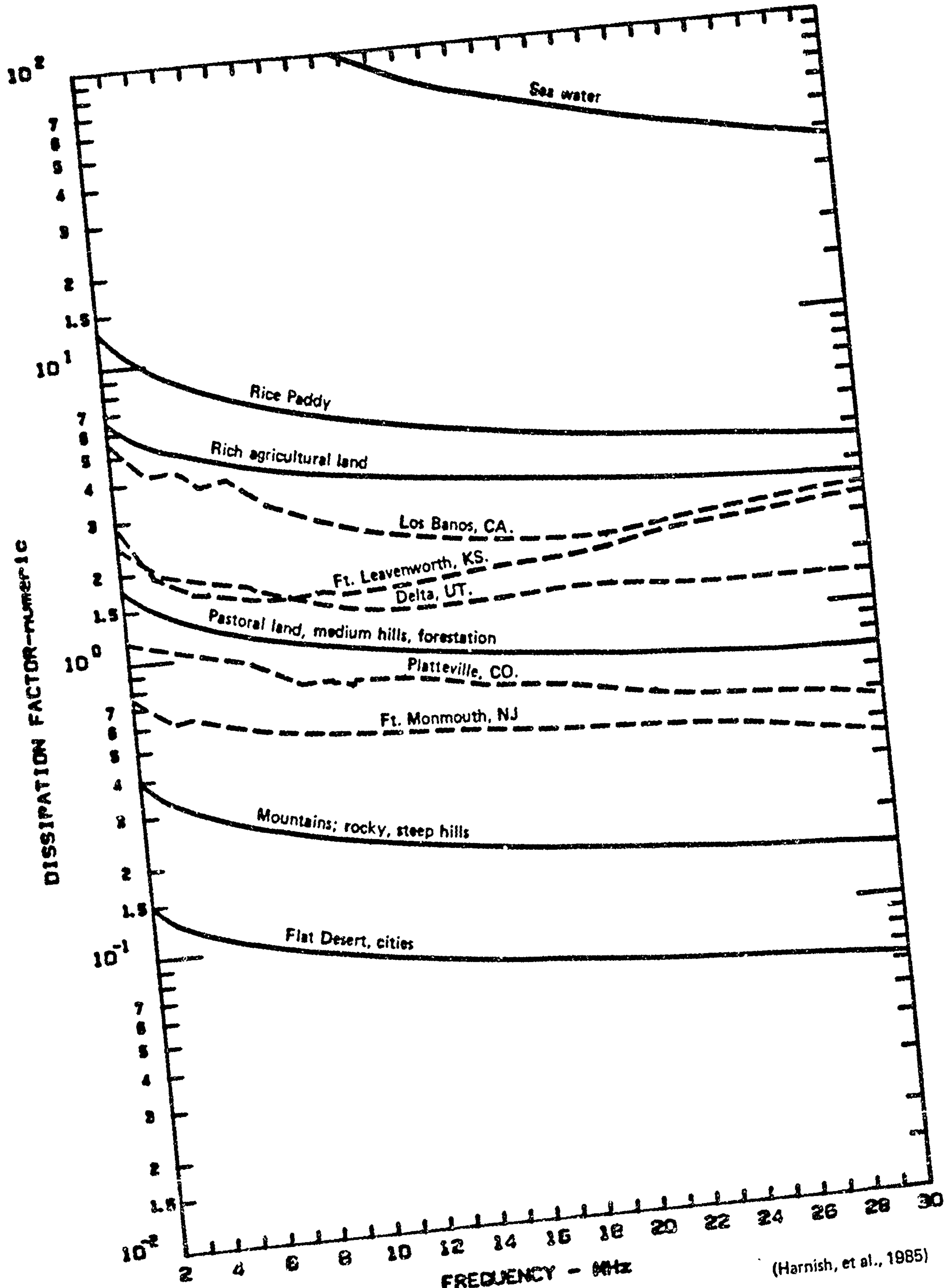


Figure 31 EFFECTIVE RELATIVE DIELECTRIC CONSTANT FOR FIVE ANTENNA TEST FIELD SITES VS SRI GENERIC CURVES FOR SELECTED TERRAIN CATEGORIES



(Harnish, et al., 1985)

Figure 32 EFFECTIVE GROUND DISSIPATION FACTOR FOR FIVE ANTENNA TEST FIELD SITES VS SRI GENERIC CURVES FOR SELECTED ~RRAIN CATEGORIES

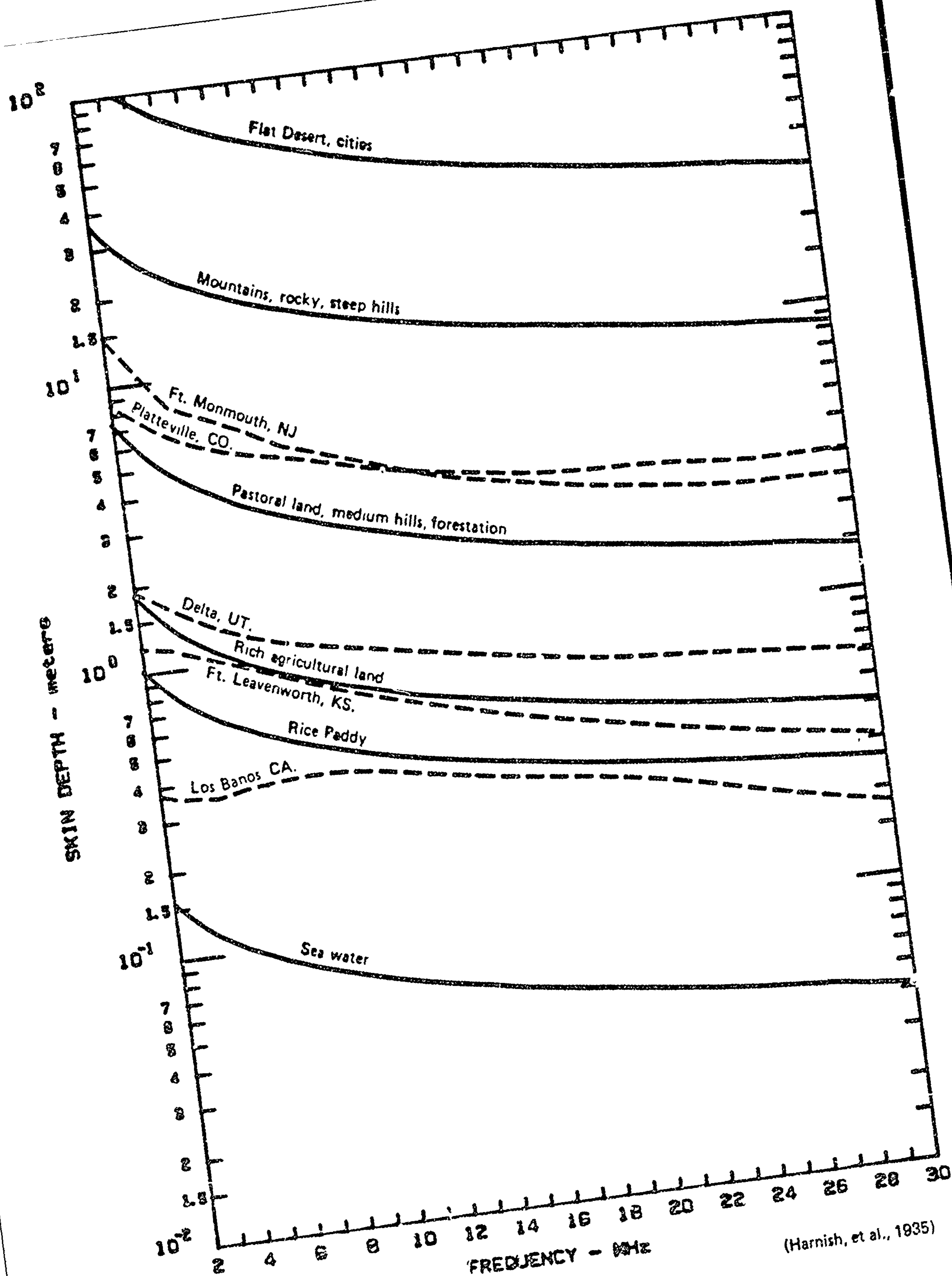


Figure 33 EFFECTIVE SKIN DEPTH FOR FIVE ANTENNA TEST FIELD SITES VS SRI GENERIC CURVES FOR SELECTED TERRAIN CATEGORIES

TABLE 6

Bill Moision's Equation for
Hagn's Generic Effective Ground Relative Dielectric Constant
and Ground Conductivity Versus Frequency (2 to 30 MHz) Model
for Selected Terrain Categories:

$y = BX^M$, where X = Frequency in MHz

TERRAIN TYPE	RELATIVE DIELECTRIC CONSTANT	CONDUCTIVITY
1. Seawater	B = 81.0 M = 0.0	B = 5.0 M = 0.0
2. Marsh (Rice Paddy)	B = 110.295 M = -0.417	B = 0.1115 M = 0.106
3. Rich agricultural land	B = 78.349 M = -0.459	B = 3.547×10^{-2} M = 0.214
4. Medium hills, forestation	B = 22.142 M = -0.192	B = 2.754×10^{-3} M = 0.459
5. Mountains, rock, steep hills	B = 12.323 M = -0.198	B = 3.419×10^{-4} M = 0.447
6. Flat Desert, cities	B = 5.256 M = -0.195	B = 5.300×10^{-5} M = 0.495
7. Permafrost - winter	B = 14.417 M = -0.128	B = 5.973×10^{-4} M = 0.559
8. Permafrost - summer	B = 110.295 M = -0.417	B = 0.1115 M = 0.106

[Sailors, 1984] (Corrected by Hagn, 1985)

Monmouth, NJ sites were in what could be described as pastoral land. The Delta, UT site was on a good farm and the Ft. Leavenworth, KS site was at the edge of a very fertile corn field, and both could be described as rich agricultural land, which, when wet, could even approximate a rice paddy. The dry mineralized lake bed at Los Banos (and Delano, see Figures 8 and 9) is a special type of soil which was not considered when the original generic curves were developed. The agreement by category is at least fair, and the agreement between curve pairs is reasonable with the higher conductivity and the higher relative dielectric constant coming from the same site.

CONCLUSIONS

The following conclusions are offered:

- The current handbook values for ground constants are incorrect at HF, and they can cause significant errors in predictions made by models such as NEC.
- The effective permittivity and conductivity of most soils are both important at HF and they are a function of frequency in the HF band (i.e., they are not constant as assumed by the CCIR and others).
- The effective permittivity and conductivity for a specific soil are a strong function of the volumetric moisture content (MC) of the soil and the MC varies with depth at a given time and with time after a rain at a given depth. This variation of moisture content vs type of soil with depth and time has not yet been modeled.
- Despite the variations of moisture content and electrical properties of soil with time, it is useful to develop curves of "ground constants" versus frequency for different types of soils described in environmentally relevant terms.
- The generic curves of ground constants versus frequency given in this paper are the best available values to use in NEC and other antenna or propagation models in the absence of data measured at HF, but they should be revised in light of the data now available.
- These generic curves are useful for parameter sensitivity studies, but measured values of permittivity and conductivity on the frequency of interest are required for validation of NEC and for other applications (e.g., radiation hazard fields) where accurate predictions of antenna or propagation characteristics are required.
- The SRI OWL kit is useful in open fields and in existing antenna fields and in forests; whereas, the E(d) method is restricted to open areas.

- In the absence of measured values for the effective permittivity and conductivity, but when volumetric moisture content is known, the universal curves of Longmire and Smith provide reasonable estimates at HF. Measured or a priori estimates of dc conductivity are required to use the Longmire and Smith curves to estimate conductivity.

RECOMMENDATIONS

It is recommended that:

- The generic curves for relative permittivity and conductivity versus frequency presented in this paper should be used at HF instead of the current handbook values.

- Where measured volumetric moisture content data are available, the universal curves of Longmire and Smith can be used to estimate relative permittivity, and they can be used along with the matching generic curve to estimate conductivity (i.e., to estimate the effect of dc conductivity).

- The generic curves should be used in a parameter sensitivity analysis to determine the accuracy of ground constants needed for a given application.

- When more accurate values than the generic curves are required (e.g., NEC validation, important installations, antenna calibration, etc.) it is necessary to perform in situ measurements from the surface down to the skin depth using the SRI OWL kit in a sampling manner.

- The E(d) technique can be used at open sites in conjunction with the SRI OWL kit.

- If measurements down to the skin depth are not practical (e.g., 2 MHz in dry soil), then it is important to determine soil homogeneity with depth by other means (e.g., geophysical prospecting, a priori knowledge, etc.) for depths beyond the probe depth for HF techniques involving probes inserted into the soil.

- The data now available should be used to revise and improve the generic curves, and equations should be developed to describe these new curves.

- The relacionship between volumetric moisture content and any new generic curves should be developed.

- The accuracy of any new generic curves should be estimated based upon the data used to develop them and upon independent checks.

ACKNOWLEDGMENTS

The author appreciates the support in data acquisition form Mr. A. Sparks and Mr. R. Ball of Contel Federal Systems, Inc. at the VOA sites, and from Messrs. H. Parker, W. Makarabhiromya, J. Gaddie, R. Sarran and L. Harnish of SRI for the remainder of the sites. Mr. Sarran also generated the software used for data reduction and for creation of the generic curves. Any errors of omission or commission are the responsibility of the author.

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NOTE ADDED IN PROOF:

The measured conductivity data for highly conducting ground exhibit a decreasing trend with increasing frequency in the lower part of the HF band. This is an instrumentation effect, and it was accounted for in making the generic curves.