NBS

Technical Note 175

CURVES OF GROUND PROXIMITY LOSS FOR DIPOLE ANTENNAS

L. E. VOGLER AND J. L. NOBLE

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

THE NATIONAL BUREAU OF STANDARDS

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CURVES OF GROUND PROXIMITY LOSS FOR DIPOLE ANTENNAS[1]

L. E. Vogler and J. L. Noble

Ground proximity loss, defined as the decibel ratio of antenna input resistance to its free space resistance, is presented in graphical form for four types of antennas: vertical and horizontal electric and magnetic elementary dipoles. Assuming a non-layered ground characterized throughout by a relative dielectric constance ϵ_r and conductivity σ, curves are given showing the ground proximity loss for a wide range of values of ground constants, antenna height above the ground surface, and frequency.

1. INTRODUCTION

In the design and evaluation of radio communication systems a knowledge of the losses in power due to the ground near antennas is necessary. An appreciable amount of the input power to a transmitting antenna will be absorbed by the nearby ground rather than being radiated into space; also, the ground near a receiving antenna will absorb power with a consequent reduction in available power to the receiver.

The ground proximity loss of an actual antenna depends on a number of factors: the frequency of the radio waves, the electromagnetic characteristics of the ground beneath the antenna together with the nearby terrain features and other environmental structures, the electromagnetic properties of the atmosphere in which the antenna is placed, the height of the antenna above the ground surface, and the type of antenna used. In this paper discussion will be restricted to antennas placed in a vacuum at a variable height h above an isotropic and homogeneous conducting half-space with relative dielectric constant ϵ_r (referred to air as unity) and conductivity σ (measured in mhos

[1] Most of the work in this report was sponsored by the Jet Propulsion Laboratory, Pasadena, California, as part of the Lunar Point-to-Point Communication Study.

per meter); the magnetic permeability of the whole space is taken as the free space value μ_o. The lower half-space, corresponding to the ground, may represent a wide variety of conditions ranging from relatively highly conducting materials such as sea water to the very poorly conducting grounds characterized by ϵ_r's near unity which possibly may be encountered in lunar surface communication [Vogler, 1963].

Four types of antennas are considered: the vertical and horizontal electric and magnetic elementary dipoles, the current in which is assumed to vary as $I_o e^{i\omega t}$ with I_o a constant along the antenna. The elementary dipoles are assumed to be of length $d\ell$, and the magnetic dipoles are then equivalent to circular loops of area $dA = d\ell/\beta$, where β is the free space wave number $(= 2\pi/\lambda)$. For practical short antennas having a linear distribution of current, $d\ell$ should be replaced by an effective length $\ell_e = d\ell/2$.

2. EXPRESSIONS FOR THE INPUT RESISTANCE

Ground proximity loss $L_{t,r}$ is defined as the decibel ratio of the antenna input resistance r to the free space radiation resistance r_f:

$$L_{t,r} = 10 \log(r/r_f) , \tag{1}$$

the subscripts t or r denoting a transmitting or receiving antenna. By assuming a sinusoidally varying current in the antenna of the form $I_o e^{i\omega t}$, the input resistance may be obtained from the field at the antenna through the relationships

$$r = E_{\rho,z}\, d\ell/I_o \text{ (electric dipoles)} , \tag{2a}$$

$$r = \omega B_{\rho,z}\, dA/I_o \text{ (magnetic dipoles)} , \tag{2b}$$

where, referring to a cylindrical coordinate system (ρ, ϕ, z), $E_{\rho,z}$ denotes the ρ or z component of the electric field at the antenna (in volts per meter), $B_{\rho,z}$ denotes the ρ or z component of the magnetic field at the antenna (in webers per square meter), and $\omega = 2\pi c/\lambda$ is the angular frequency of the wave. The horizontal dipoles are assumed to be oriented in the $\phi = 0$ direction. Derivations of the electromagnetic field components E_z for VED*, E_ρ for HED, B_z for VMD, and B_ρ for HMD are given in earlier literature [Sommerfeld and Renner, 1942; Wait, 1953, 1961; King, 1956] and only the final expressions used in calculations will be presented here. The above cited reference by King [1956] (see Chapter VII) contains a detailed discussion of the field components for all four antennas.

The formulas used for the calculation of the resistance ratio r/r_f in (1) are:

$$\text{VED: } r/r_f = 1 + \mathrm{Re}\{i(3/2\alpha^3)[I_1(N^2) + I_2(N^2)]\},\quad r_f = 20\beta^2(d\ell)^2, \tag{3a}$$

$$\text{HED: } r/r_f = 1 + \mathrm{Re}\{i(3/4\alpha^3)[I_1(1) + I_2(N^2)]\},\quad r_f = 20\beta^2(d\ell)^2\cos\phi, \tag{3b}$$

$$\text{VMD: } r/r_f = 1 + \mathrm{Re}\{i(3/2\alpha^3)[I_1(1) + I_2(1)]\},\quad r_f = 20\beta^4(dA)^2, \tag{3c}$$

$$\text{HMD: } r/r_f = 1 + \mathrm{Re}\{i(3/4\alpha^3)[I_1(N^2) + I_2(1)]\},\quad r_f = 20\beta^4(dA)^2\cos\phi, \tag{3d}$$

where

$$I_1(\delta) = \alpha^2 \int_{i\alpha}^{\infty} \left\{ \frac{\delta x - \sqrt{x^2 - A^2}}{\delta x + \sqrt{x^2 - A^2}} \right\} e^{-x}\, dx, \tag{4a}$$

---

* In the remainder of this paper the letters VED, HED, VMD, and HMD will denote, respectively, vertical electric dipole, horizontal electric dipole, vertical magnetic dipole, and horizontal magnetic dipole.

$$I_2(\delta) = \int_{i\alpha}^{\infty} x^2 \left\{ \frac{\delta x - \sqrt{x^2 - A^2}}{\delta x + \sqrt{x^2 - A^2}} \right\} e^{-x}\, dx, \tag{4b}$$

and

$$\alpha = 2h\beta = 2h(2\pi/\lambda), \quad A = \alpha\sqrt{N^2 - 1},$$

$$N^2 = \epsilon_r - is, \quad s = 60\lambda\sigma(\text{mhos/m}),$$

with λ being the free space wavelength and h the height of the antenna above the ground, both measured in meters.

The variable x in the integrals of (4a) and (4b) assumes purely imaginary values from the lower limit to zero and, from there, takes on real values to the upper limit (see Appendix). The integrals were numerically integrated on an electronic computer for various values of the parameters α, ϵ_r, and s. The graphs in this report show the results of these calculations for the four different antennas.

3. DISCUSSION OF NUMERICAL RESULTS

It is apparent from the curves that ground proximity loss can have a considerable effect on the design of some radio communication systems. For certain combinations of ground conductivity and frequency the loss becomes quite large as the antenna height is decreased. On the other hand as the ratio h/λ is increased, the effect of the ground becomes negligible and the loss approaches zero for all conductivities and frequencies.

For a highly conducting ground and wavelength large enough such that $s \to \infty$, the ground proximity loss approaches the value expected for an antenna located above an infinitely conducting plane. Expressions for the loss in this case are well known and are given by:

$$\text{VED:}\quad L_{t,r} = 10 \log \left[1 + (3/\alpha^3) \{\sin\alpha - \alpha\cos\alpha\} \right], \tag{5a}$$

$$\text{HED:}\quad L_{t,r} = 10 \log \left[1 + (3/2\alpha^3) \{(1-\alpha^2) \sin\alpha - \alpha\cos\alpha\} \right], \tag{5b}$$

$$\text{VMD:}\quad L_{t,r} = 10 \log \left[1 - (3/\alpha^3) \{\sin\alpha - \alpha\cos\alpha\} \right], \tag{5c}$$

$$\text{HMD:}\quad L_{t,r} = 10 \log \left[1 - (3/2\alpha^3) \{(1-\alpha^2) \sin\alpha - \alpha\cos\alpha\} \right]. \tag{5d}$$

It should be noticed that (5a) - (5d) do not necessarily give a good estimate of the ground proximity loss for highly conducting grounds at all frequencies. The loss may be approximated by these equations only for large values of the ratio $\sigma(\text{mhos/m})/f_{Mc}$; i.e., for $s \to \infty$.

The curves of ground proximity loss presented here may be used in the evaluation of radio systems through the concept of system loss [Norton, 1959]. System loss L_s is defined as the decibel ratio of the power available at the input terminals of the transmitting antenna to the power delivered to the receiver. In terms of the attenuation A_t relative to an inverse distance field in free space between isotropic antennas separated a distance d_o, system loss may be written as

$$L_s = 10 \log (4\pi d_o/\lambda)^2 + A_t - (G_t + G_r) + (L_t + L_r), \tag{6}$$

where $G_{t,r}$ is the transmitting or receiving antenna gain relative to an isotropic antenna, and $L_{t,r}$ is the antenna ground proximity loss defined by (1).

The authors would like to thank Mr. R. E. Wilkerson for his assistance in some of the mathematical investigations pertaining to this work.

4. REFERENCES

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5. APPENDIX

The following transformation was used in the evaluation of (4a) and (4b):

$$I_1(\delta) = -i\,\alpha^2 \int_0^{\alpha} \left\{ \frac{\delta y - \sqrt{y^2 + A^2}}{\delta y + \sqrt{y^2 + A^2}} \right\} e^{-iy}\, dy$$

$$+ \alpha^2 \int_0^{\infty} \left\{ \frac{\delta x - \sqrt{x^2 - A^2}}{\delta x + \sqrt{x^2 - A^2}} \right\} e^{-x}\, dx, \qquad \text{(A-1)}$$

$$I_2(\delta) = i \int_0^{\alpha} y^2 \left\{ \frac{\delta y - \sqrt{y^2 + A^2}}{\delta y + \sqrt{y^2 + A^2}} \right\} e^{-iy}\, dy$$

$$+ \int_0^{\infty} x^2 \left\{ \frac{\delta x - \sqrt{x^2 - A^2}}{\delta x + \sqrt{x^2 - A^2}} \right\} e^{-x}\, dx, \qquad \text{(A-2)}$$

where $\mathrm{Re}\sqrt{x^2 - A^2} > 0$. These integrals were then evaluated numerically using 96-point Gaussian and 32-point Gauss-Laguerre quadrature. When necessary, the second integrals on the right were further divided into sub-intervals to insure the required accuracy.

6. GRAPHS OF GROUND PROXIMITY LOSS,

$$L_{t,r} = 10 \log (r/r_f)$$

Vertical Electric Dipole (VED)

Horizontal Electric Dipole (HED)

Vertical Magnetic Dipole (VMD)

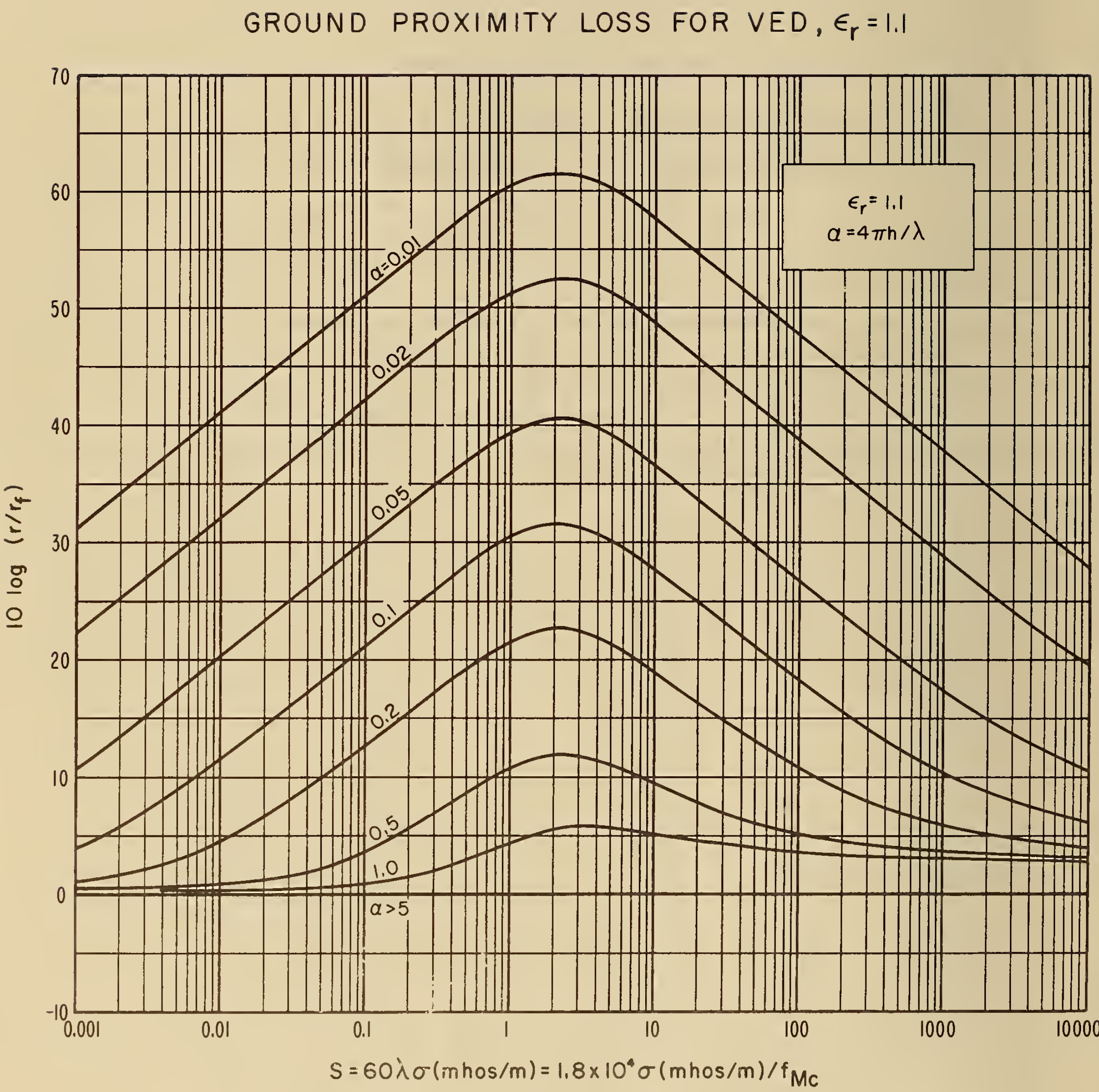
Horizontal Magnetic Dipole (HMD)

ϵ_r: relative dielectric constant of ground

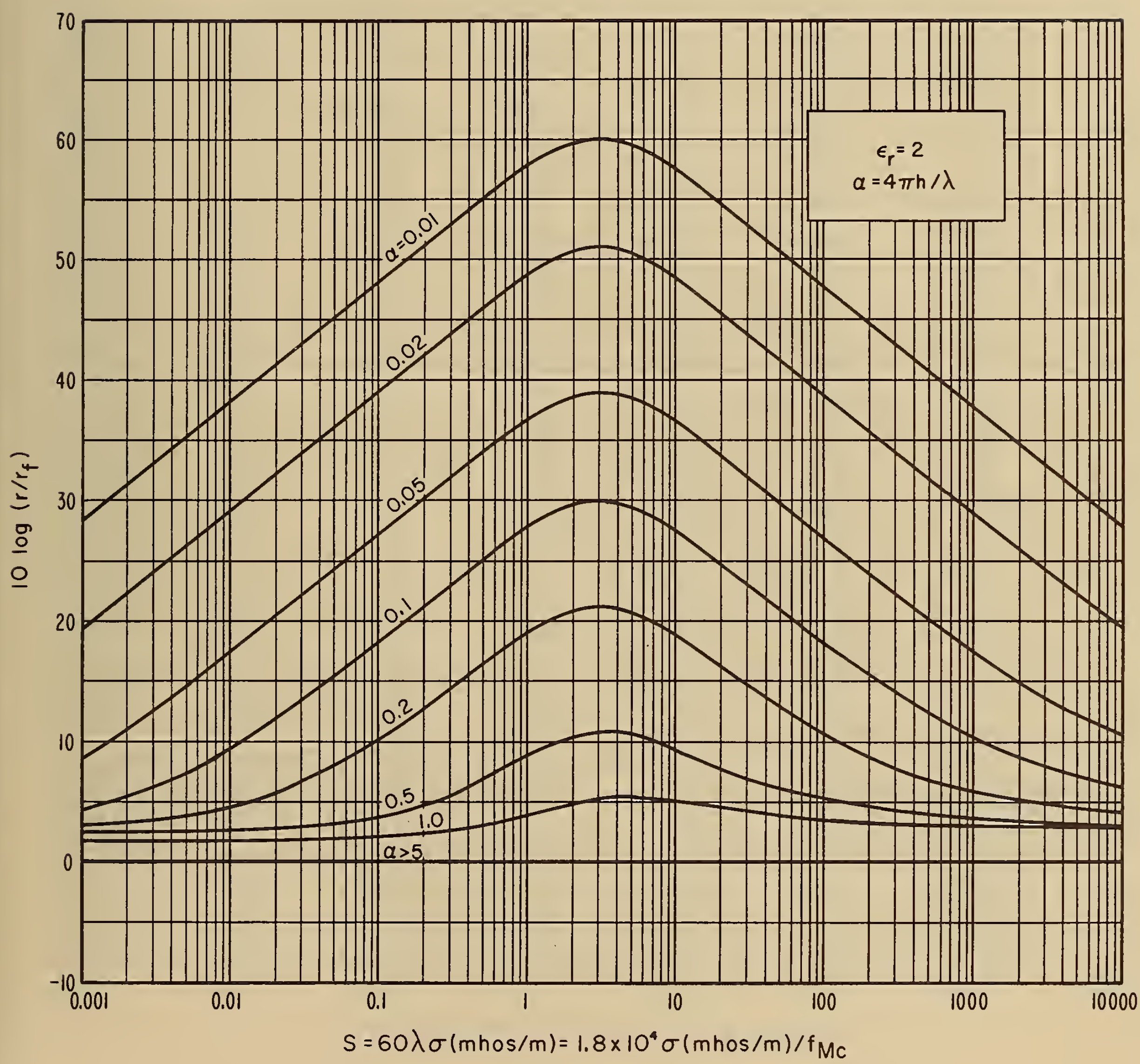
σ(mhos/m): conductivity of ground

h: height in meters of antenna above ground

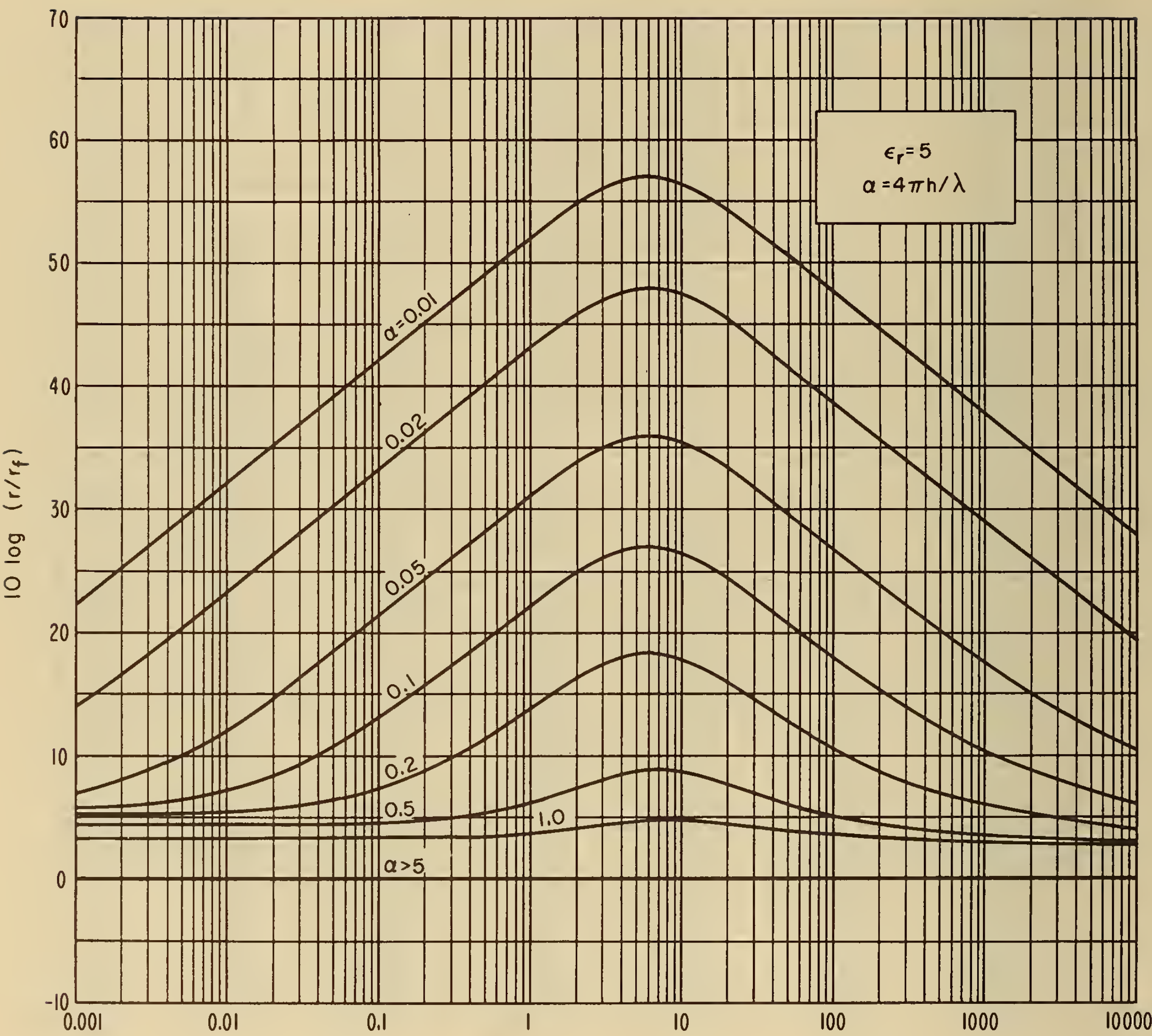
λ: wavelength in meters


GROUND PROXIMITY LOSS FOR VED, $\epsilon_r = 1.1$
$\epsilon_r = 1.1$
$\alpha = 4\pi h/\lambda$
α=0.01
0.02
0.05
0.1
0.2
0.5
1.0
$\alpha > 5$
10 log (r/r_f)
70
60
50
40
30
20
10
0
-10
0.001
0.01
0.1
1
10
100
1000
10000
$S = 60\lambda\sigma$(mhos/m) = $1.8 \times 10^4 \sigma$(mhos/m)/f_{Mc}

GROUND PROXIMITY LOSS FOR VED, $\epsilon_r = 2$

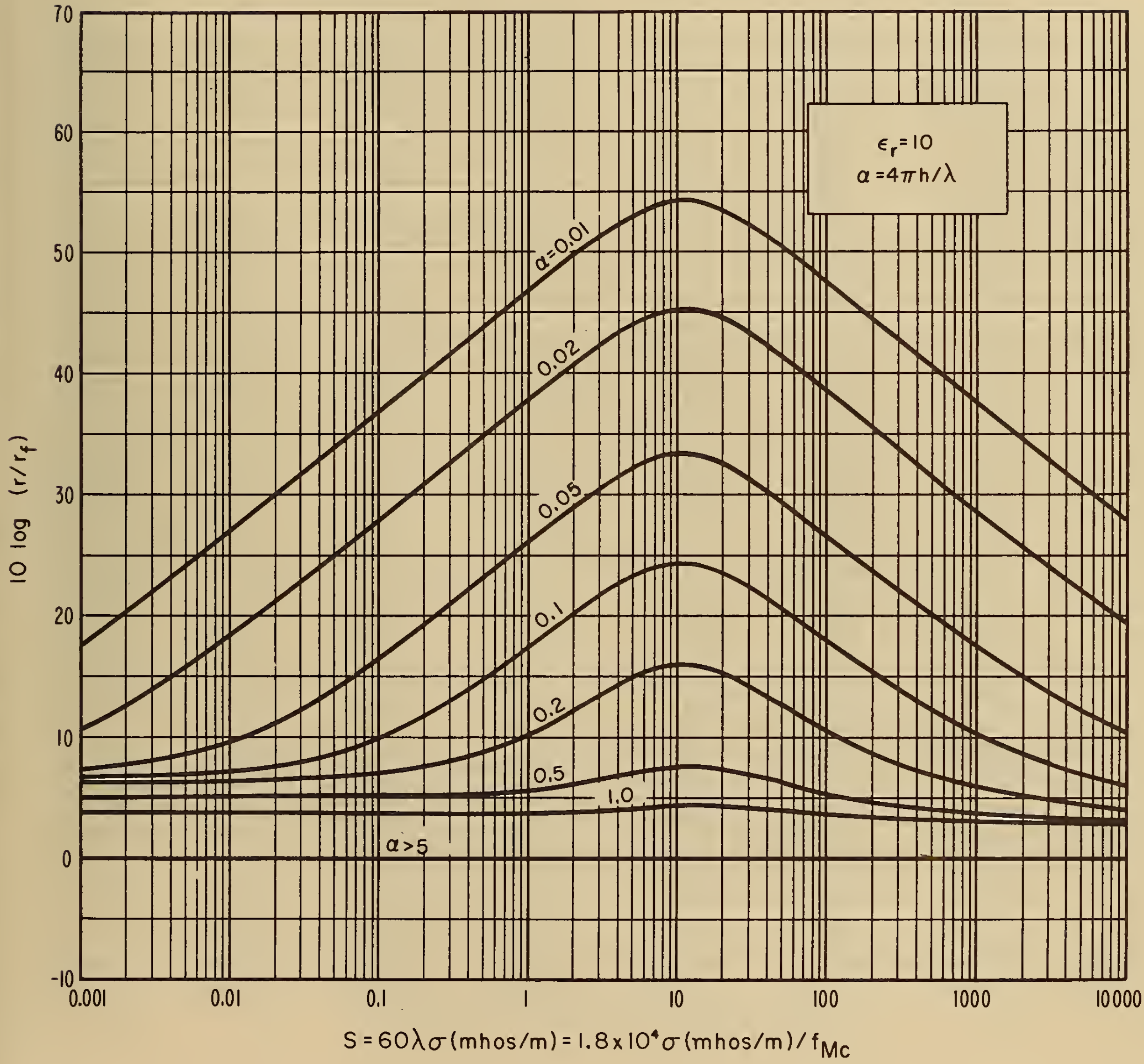


GROUND PROXIMITY LOSS FOR VED, $\epsilon_r = 5$

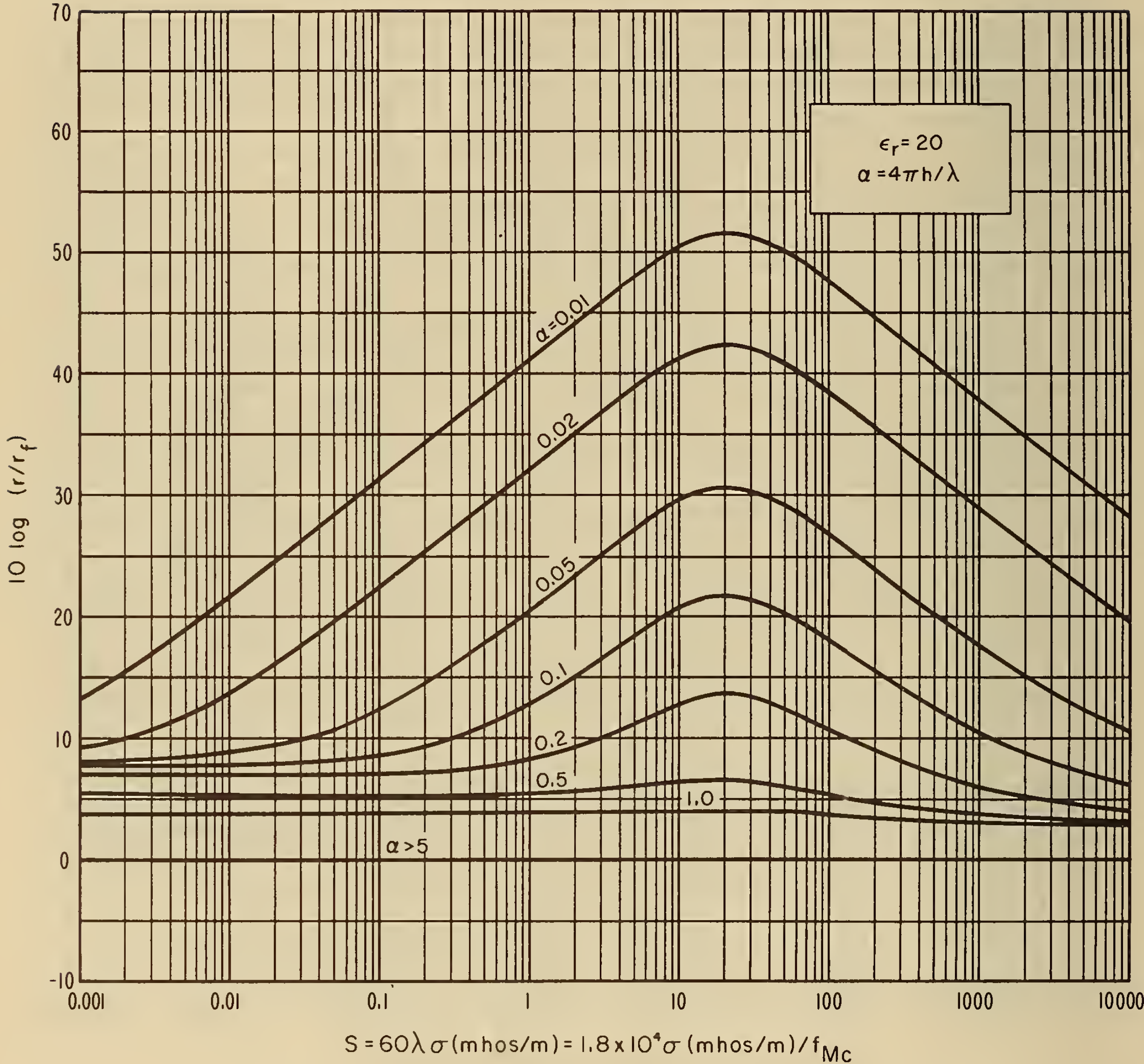


$S = 60\lambda\sigma$(mhos/m)= $1.8 \times 10^4\sigma$(mhos/m)/f_{Mc}

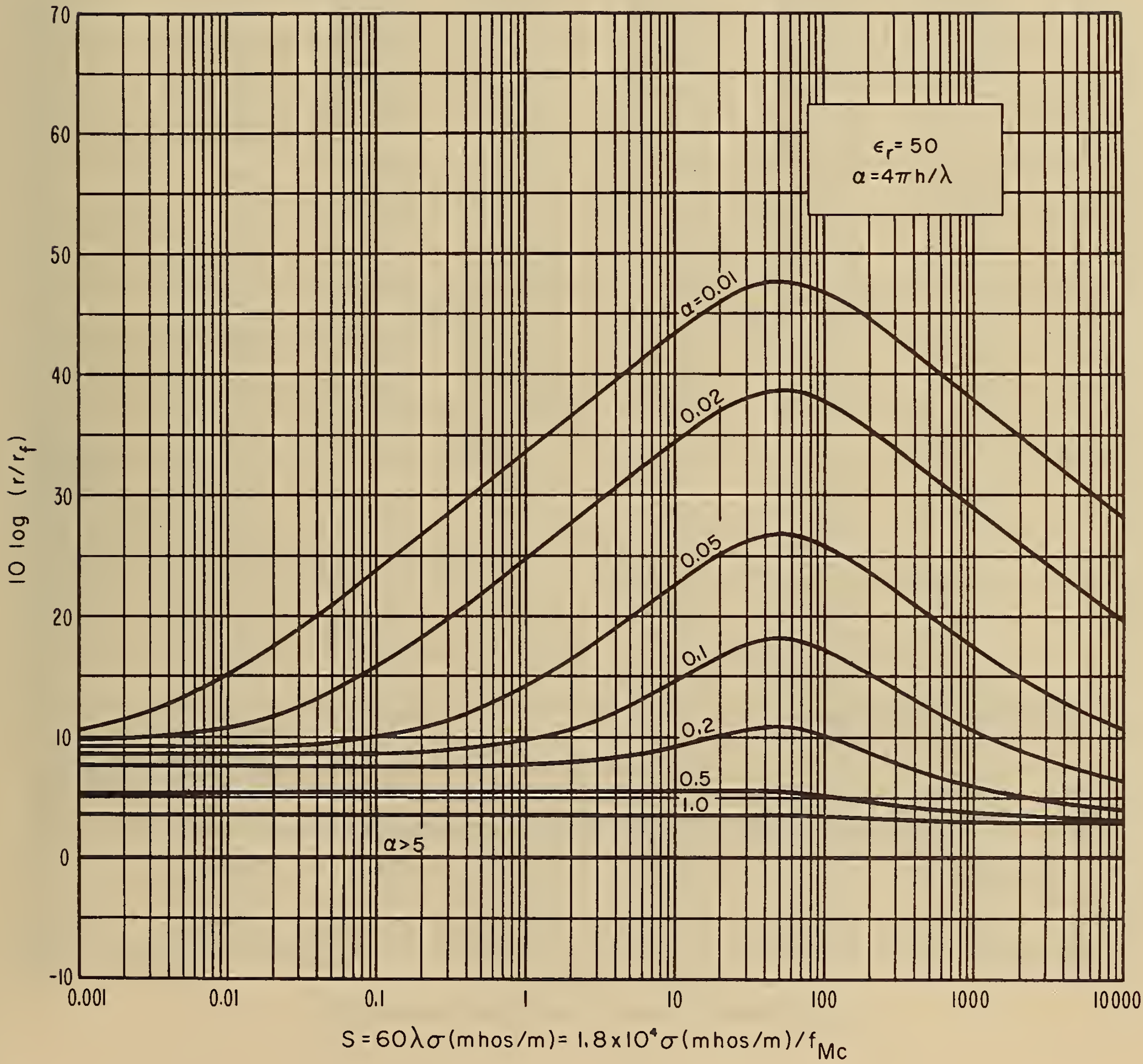
GROUND PROXIMITY LOSS FOR VED, $\epsilon_r = 10$



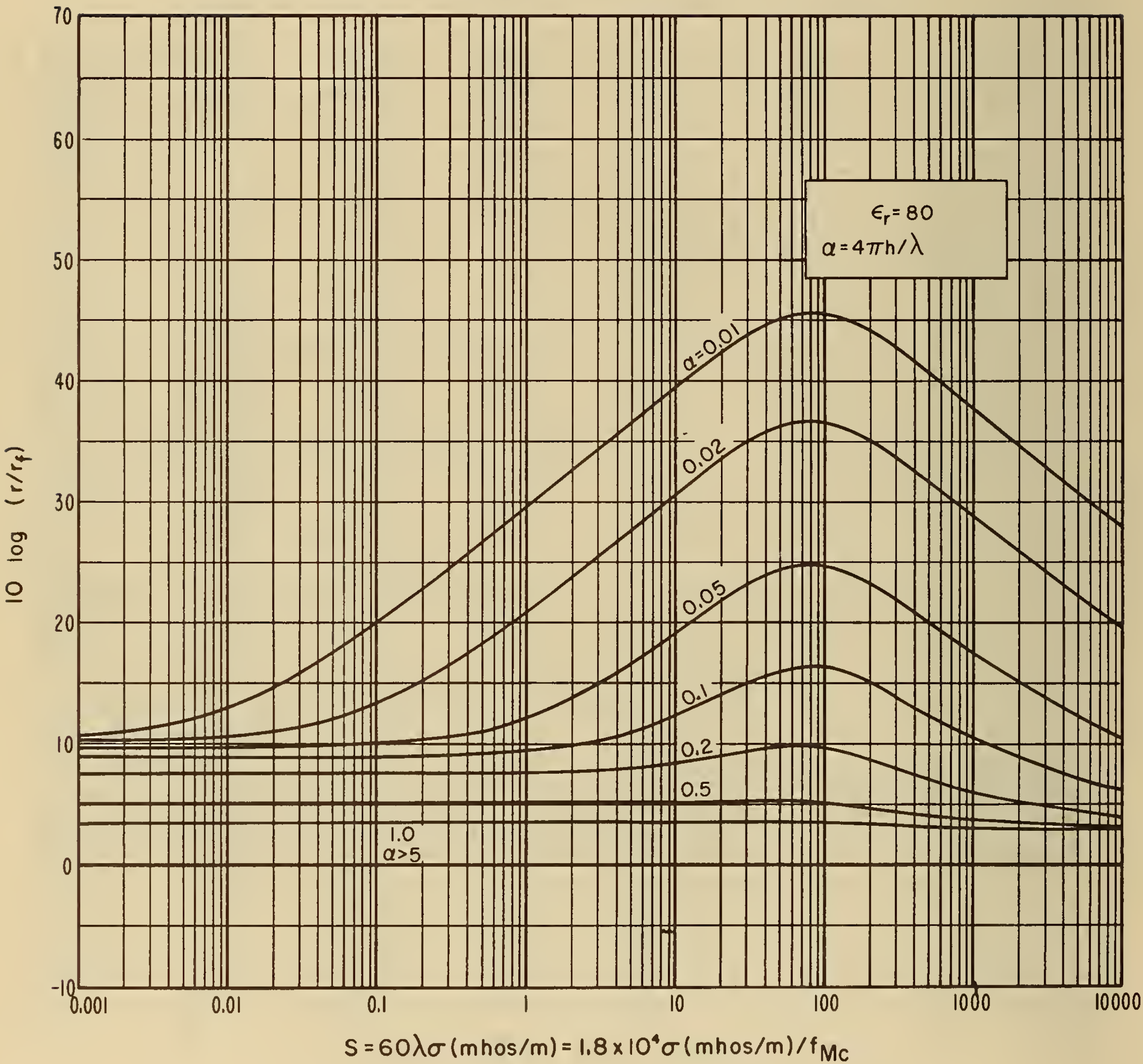
GROUND PROXIMITY LOSS FOR VED, $\epsilon_r = 20$



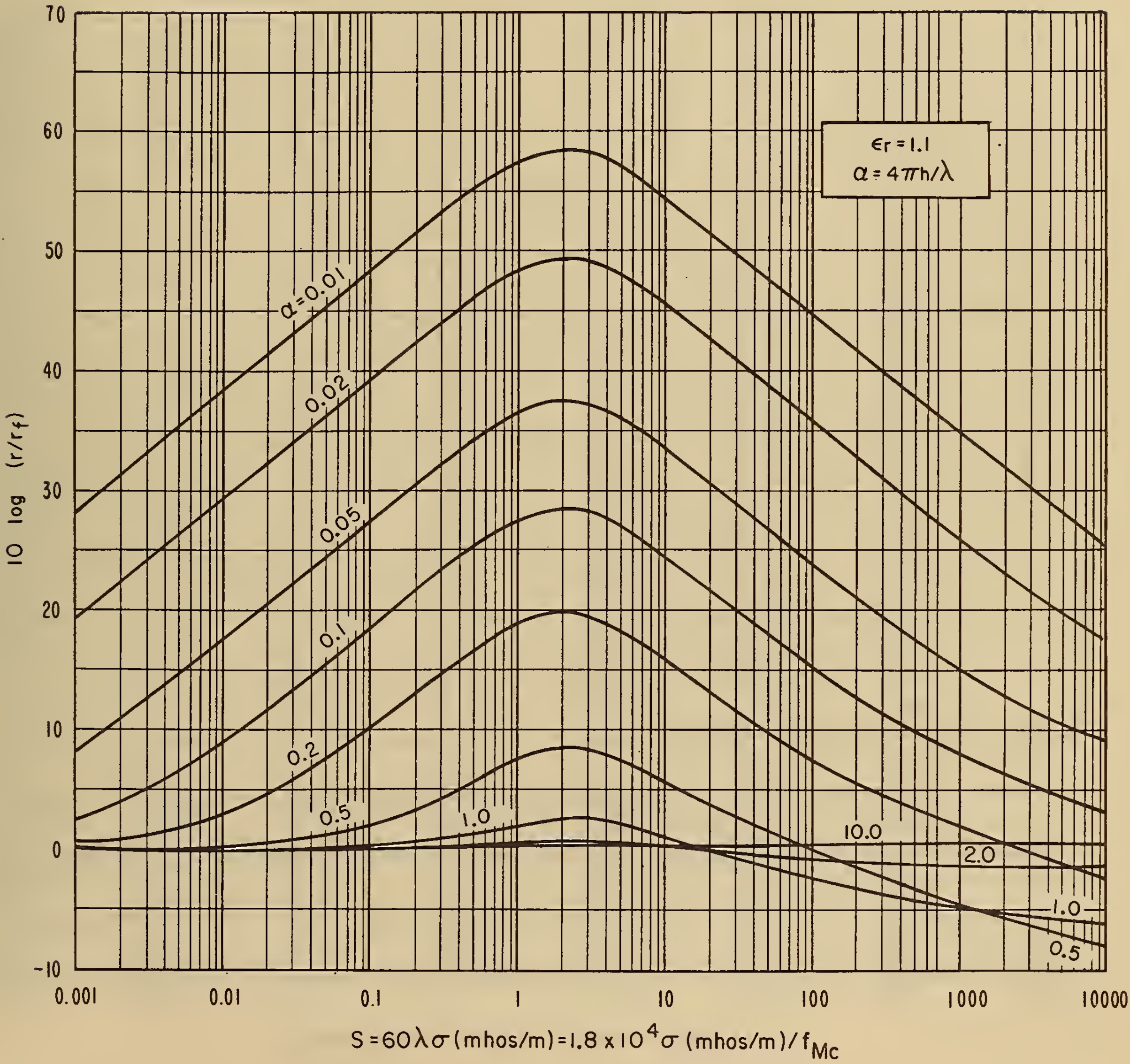
GROUND PROXIMITY LOSS FOR VED, $\epsilon_r = 50$



GROUND PROXIMITY LOSS FOR VED, $\epsilon_r = 80$



GROUND PROXIMITY LOSS FOR HED, $\epsilon_r = 1.1$



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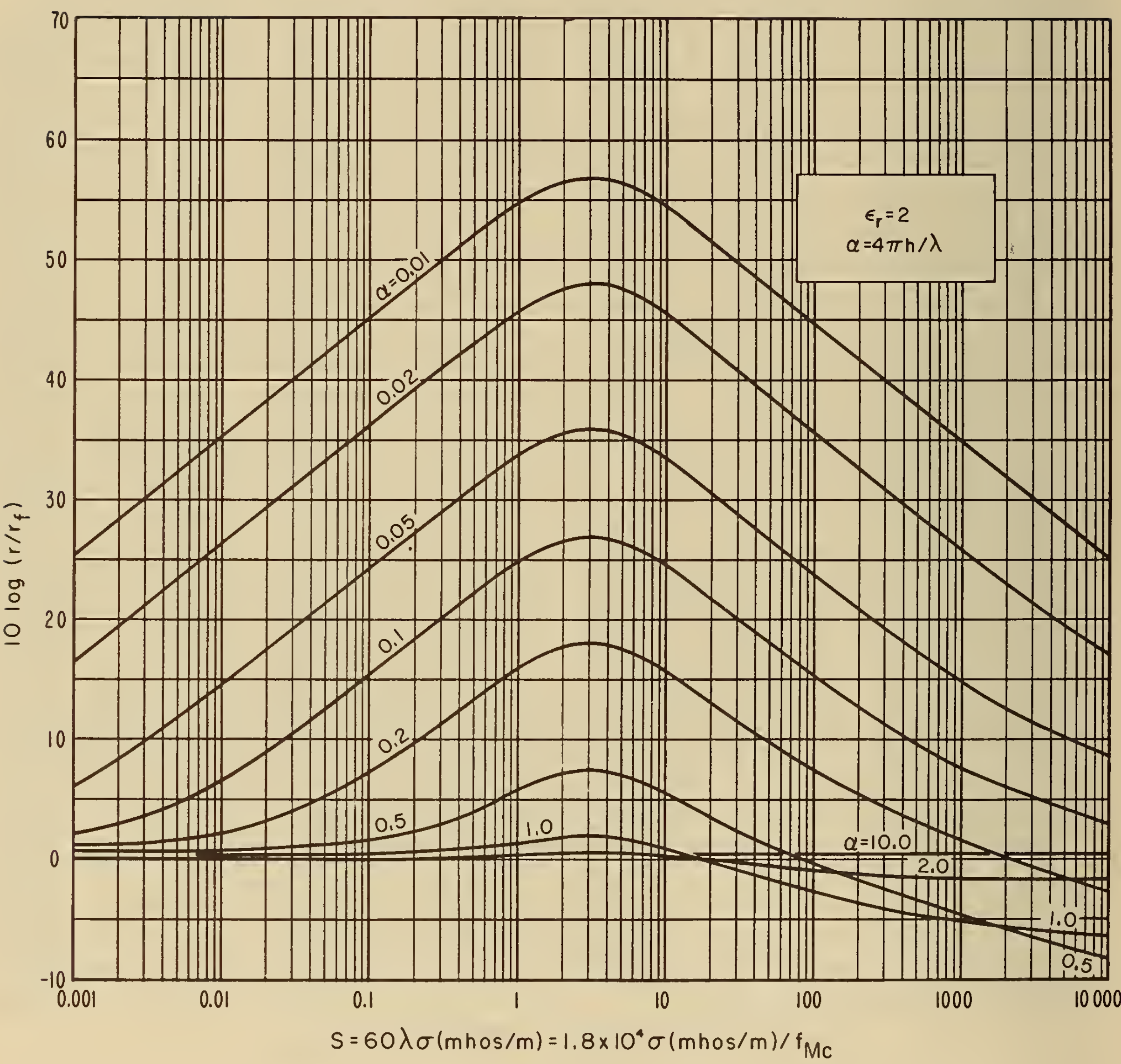

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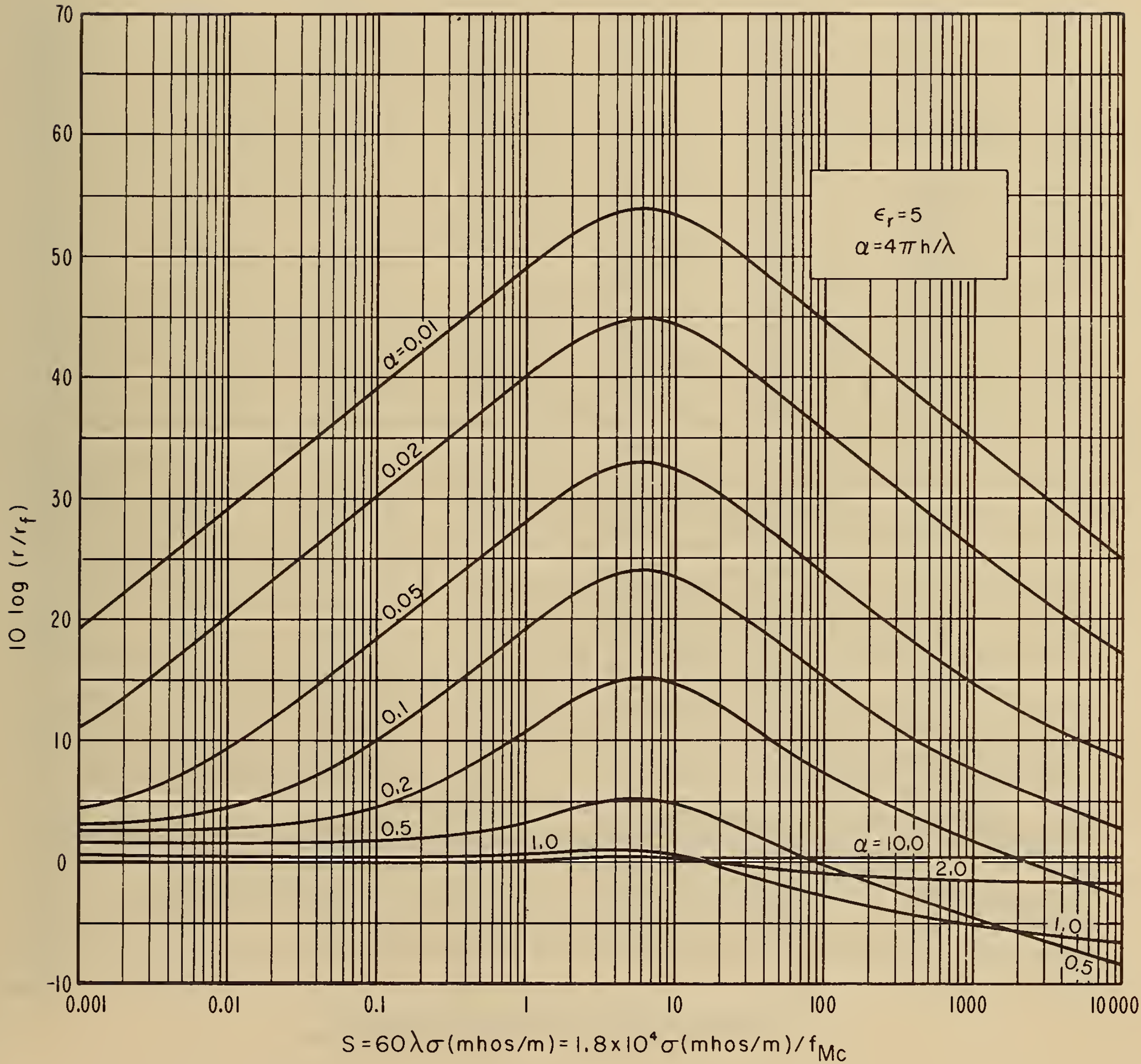

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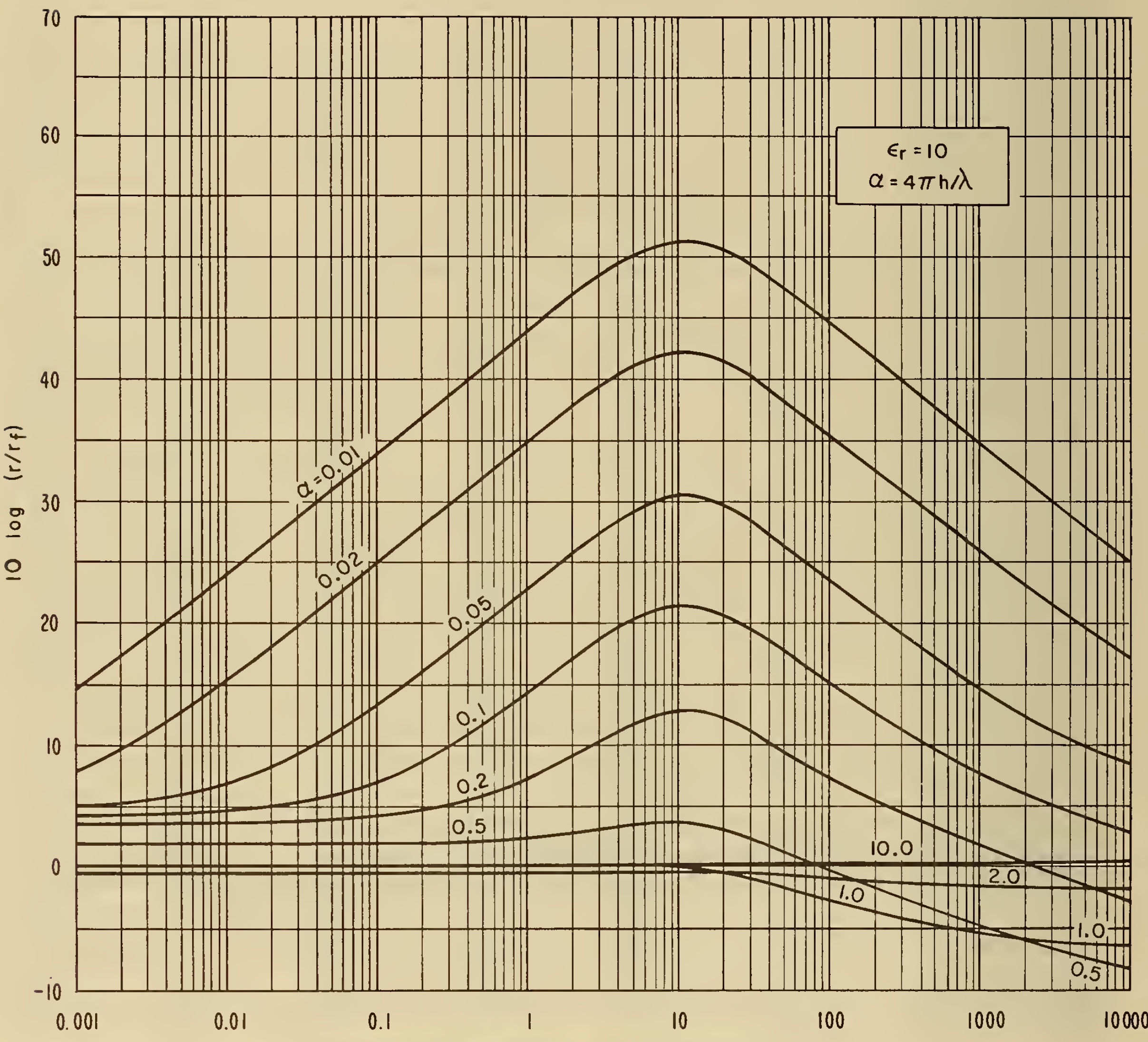
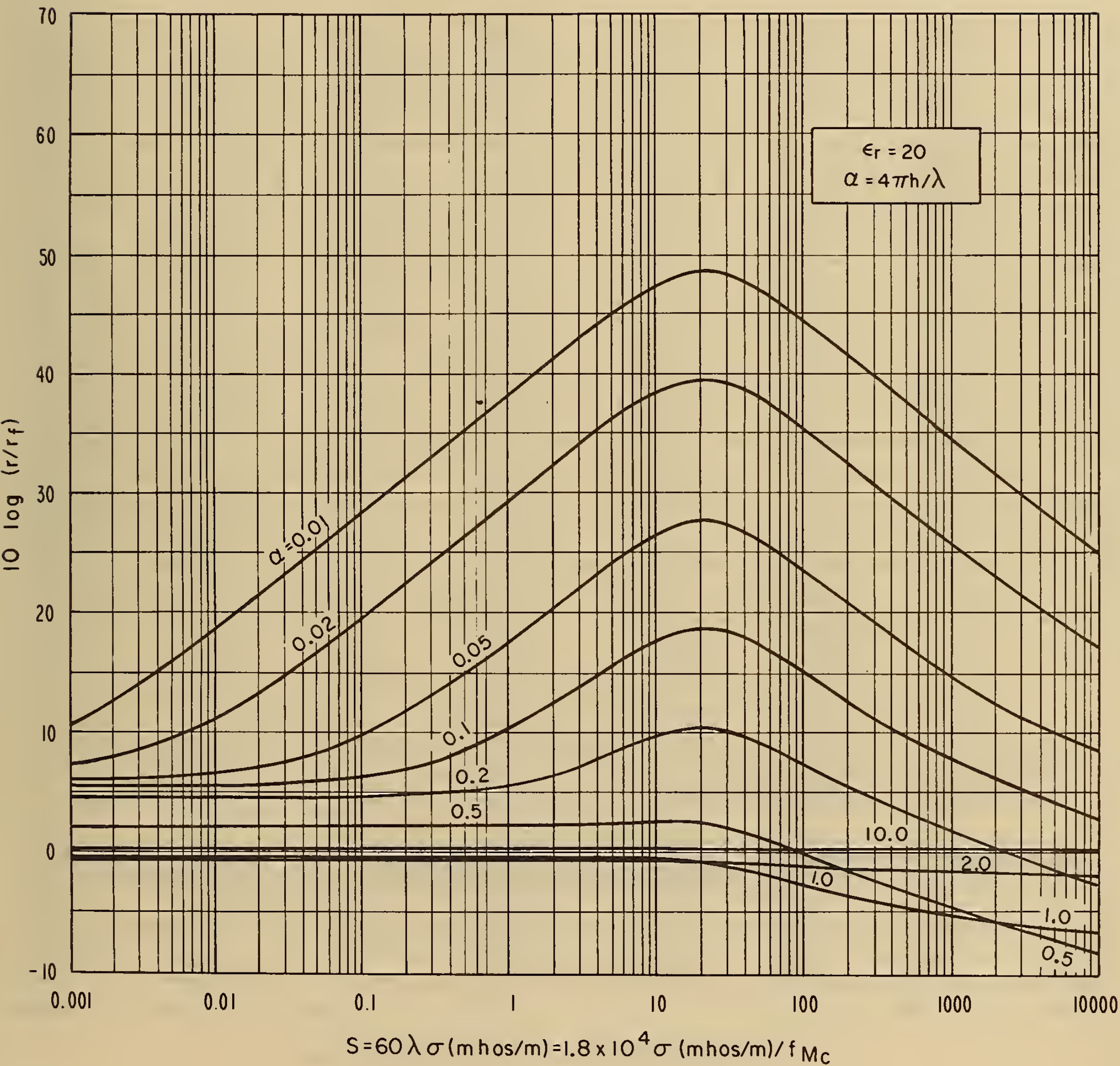
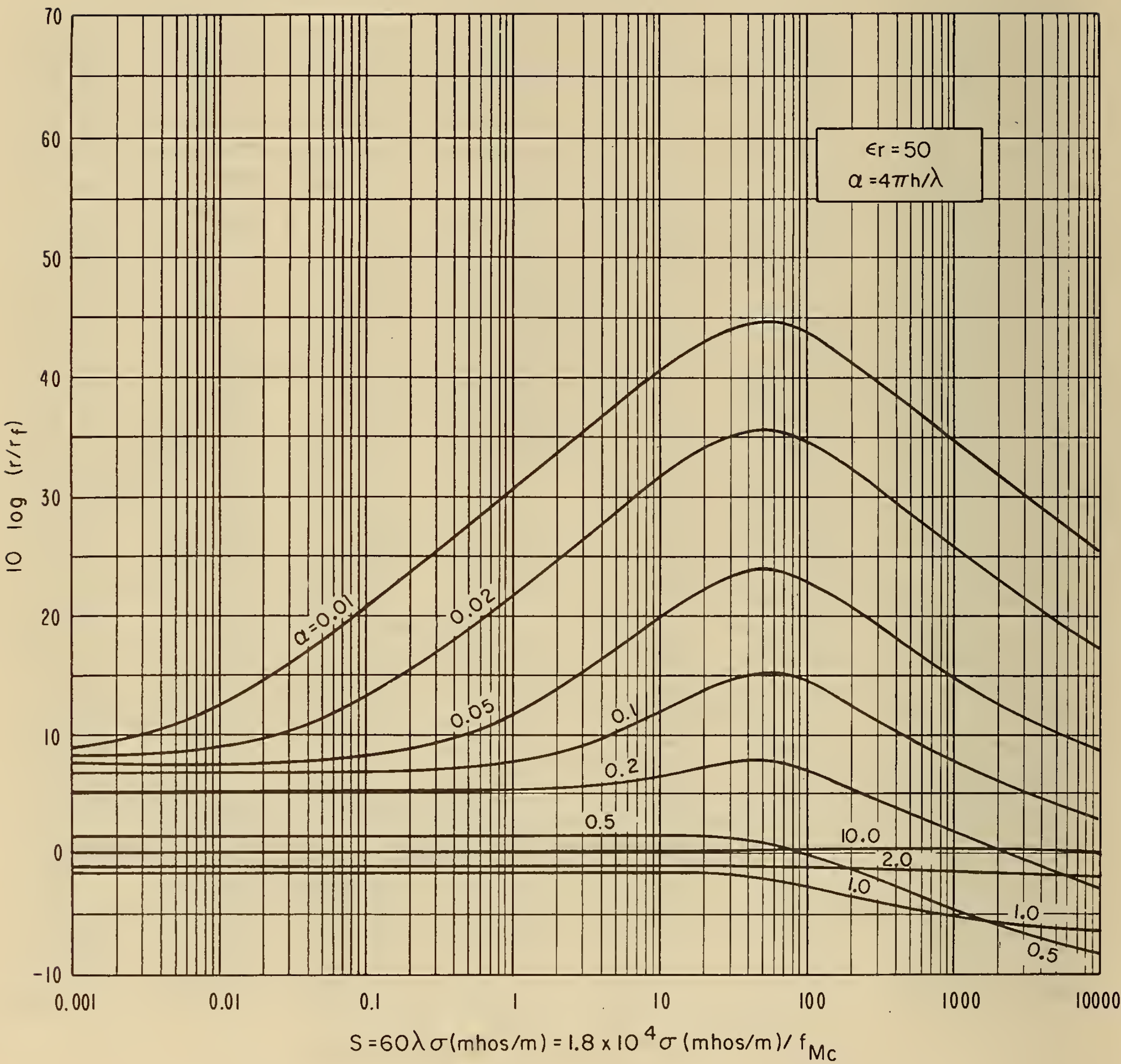


$S = 60\,\lambda\sigma\,(\text{mhos/m}) = 1.8 \times 10^4 \sigma\,(\text{mhos/m}) / f_{Mc}$

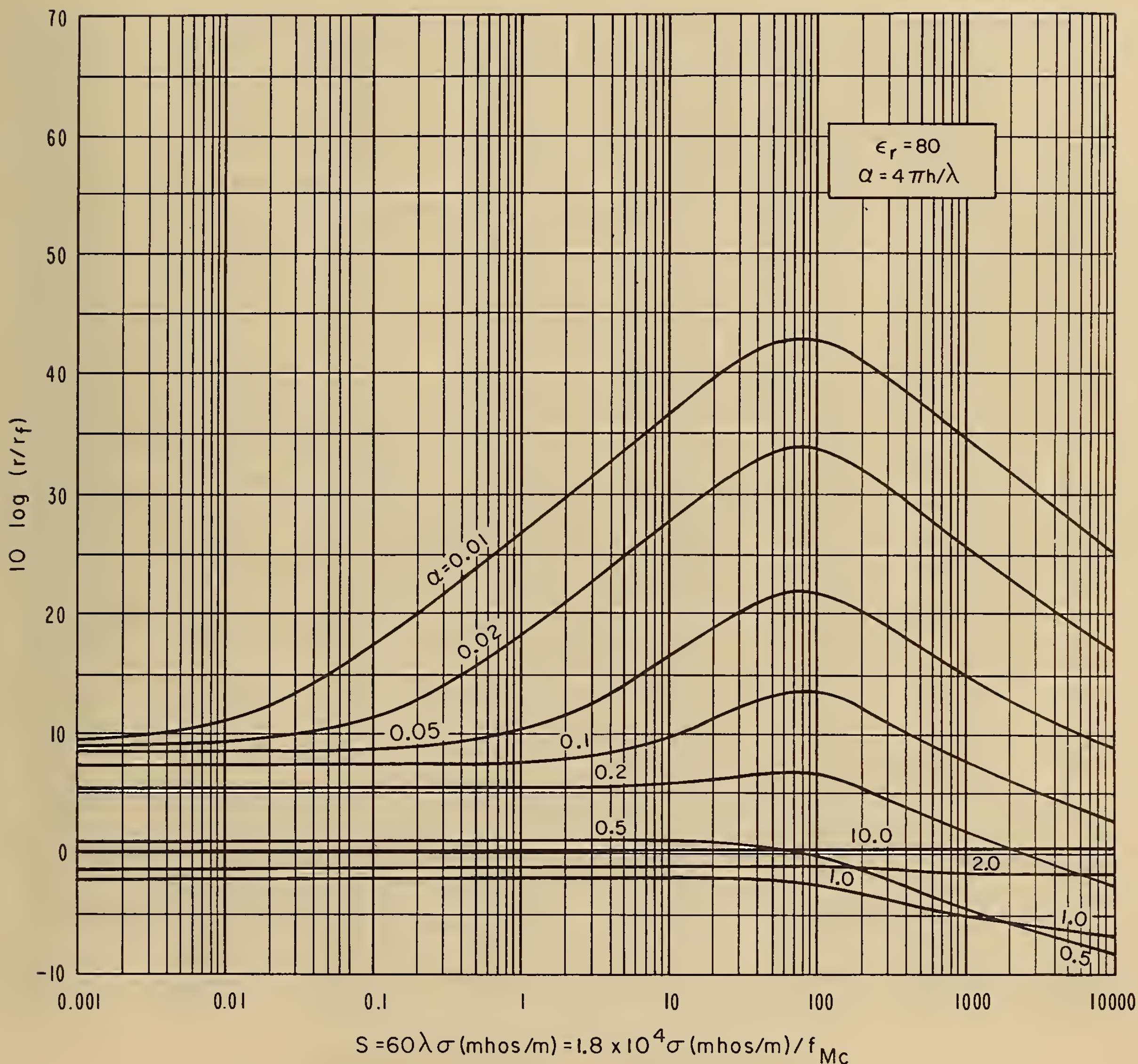
GROUND PROXIMITY LOSS FOR HED, $\epsilon_r = 20$



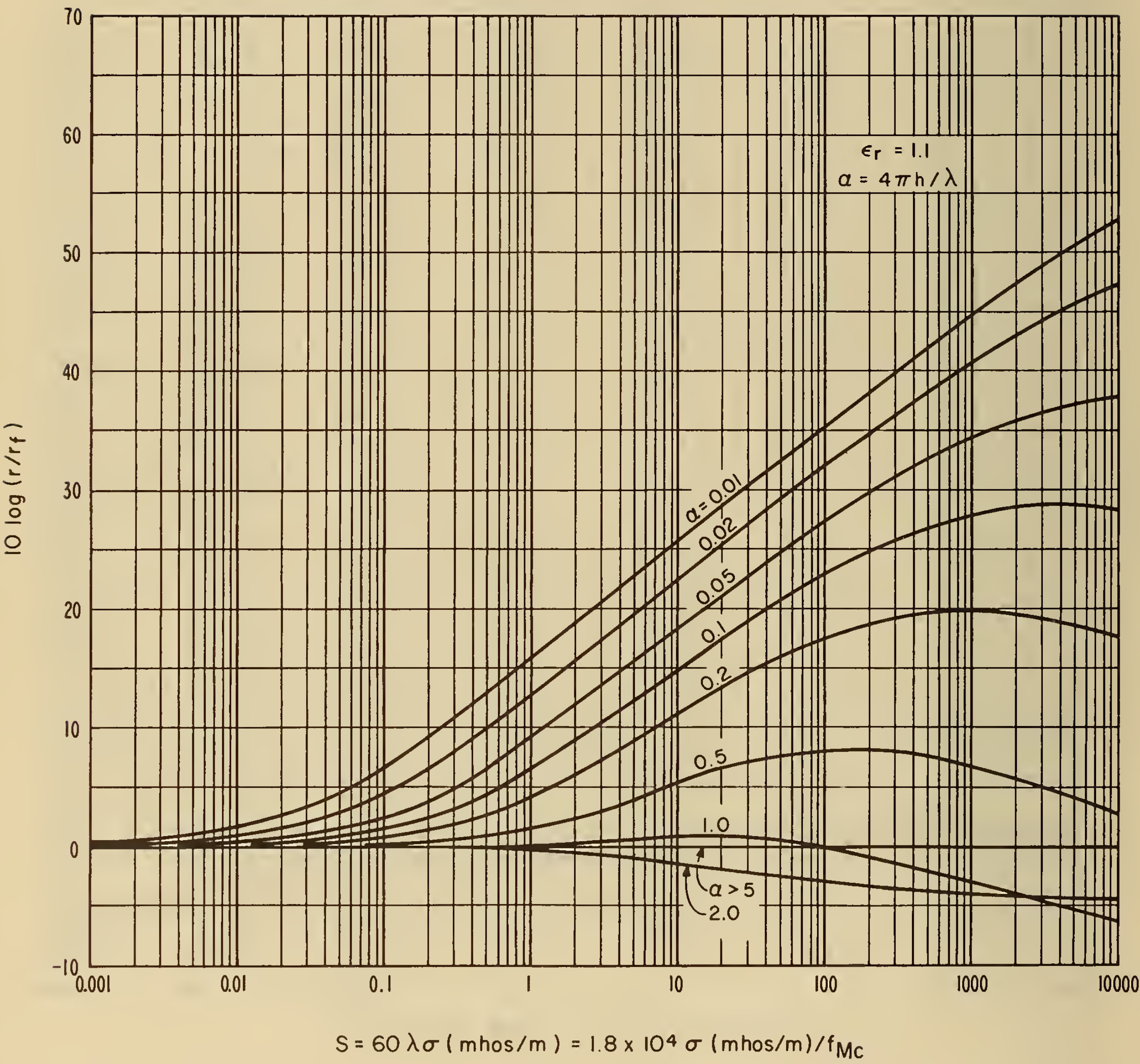
GROUND PROXIMITY LOSS FOR HED, $\epsilon_r = 50$



GROUND PROXIMITY LOSS FOR HED, $\epsilon_r = 80$



GROUND PROXIMITY LOSS FOR VMD, $\epsilon_r = 1.1$



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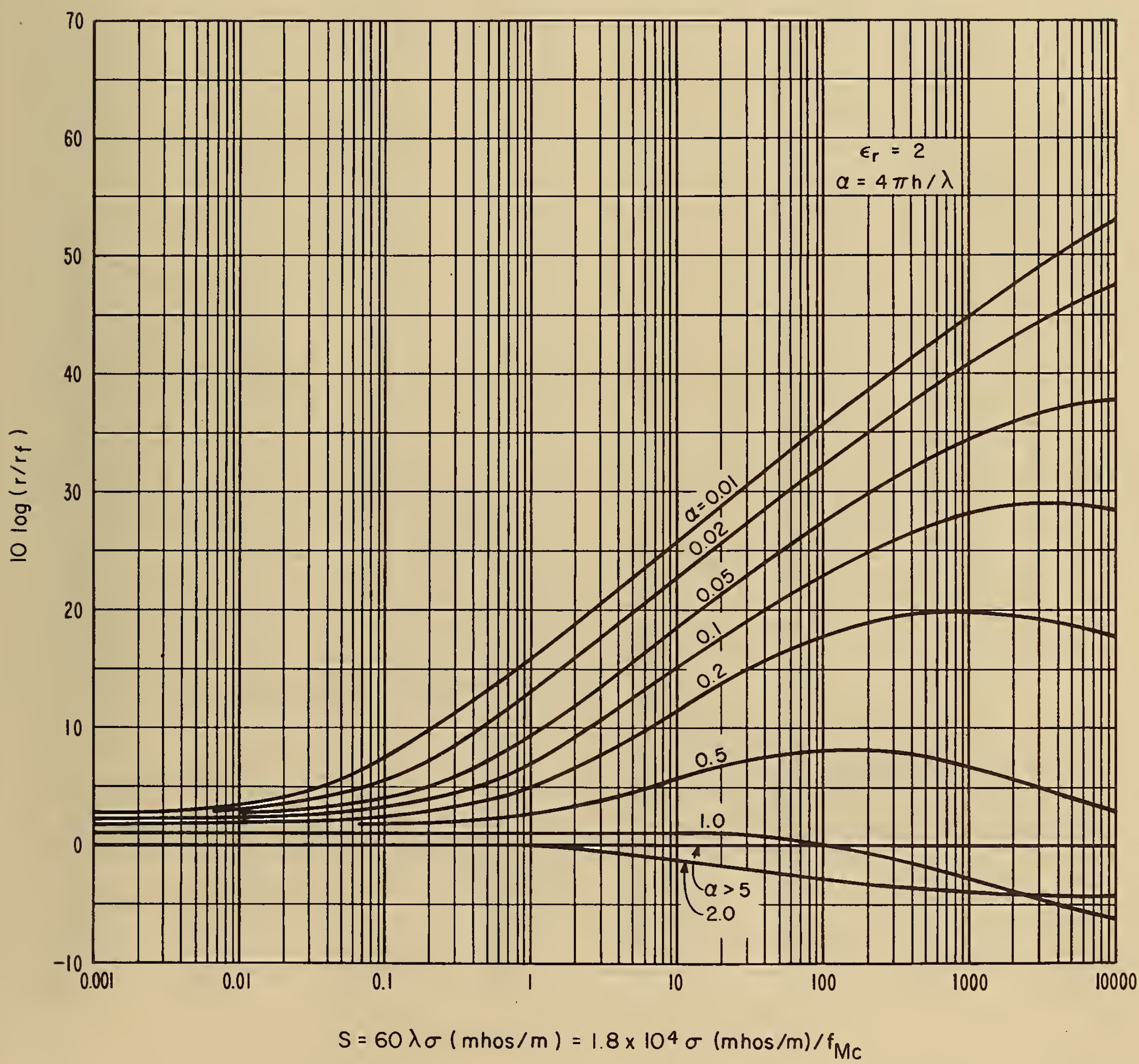
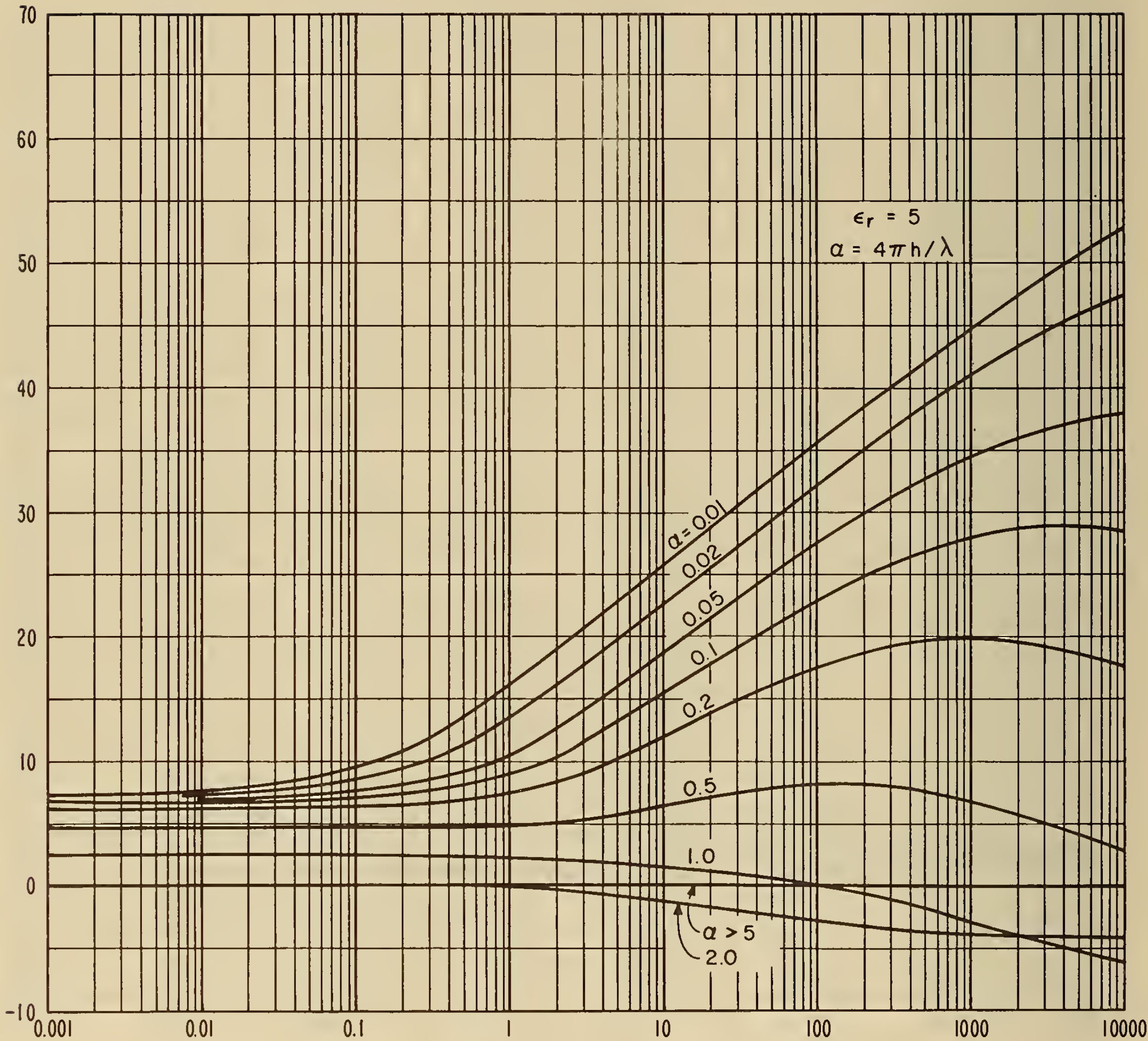
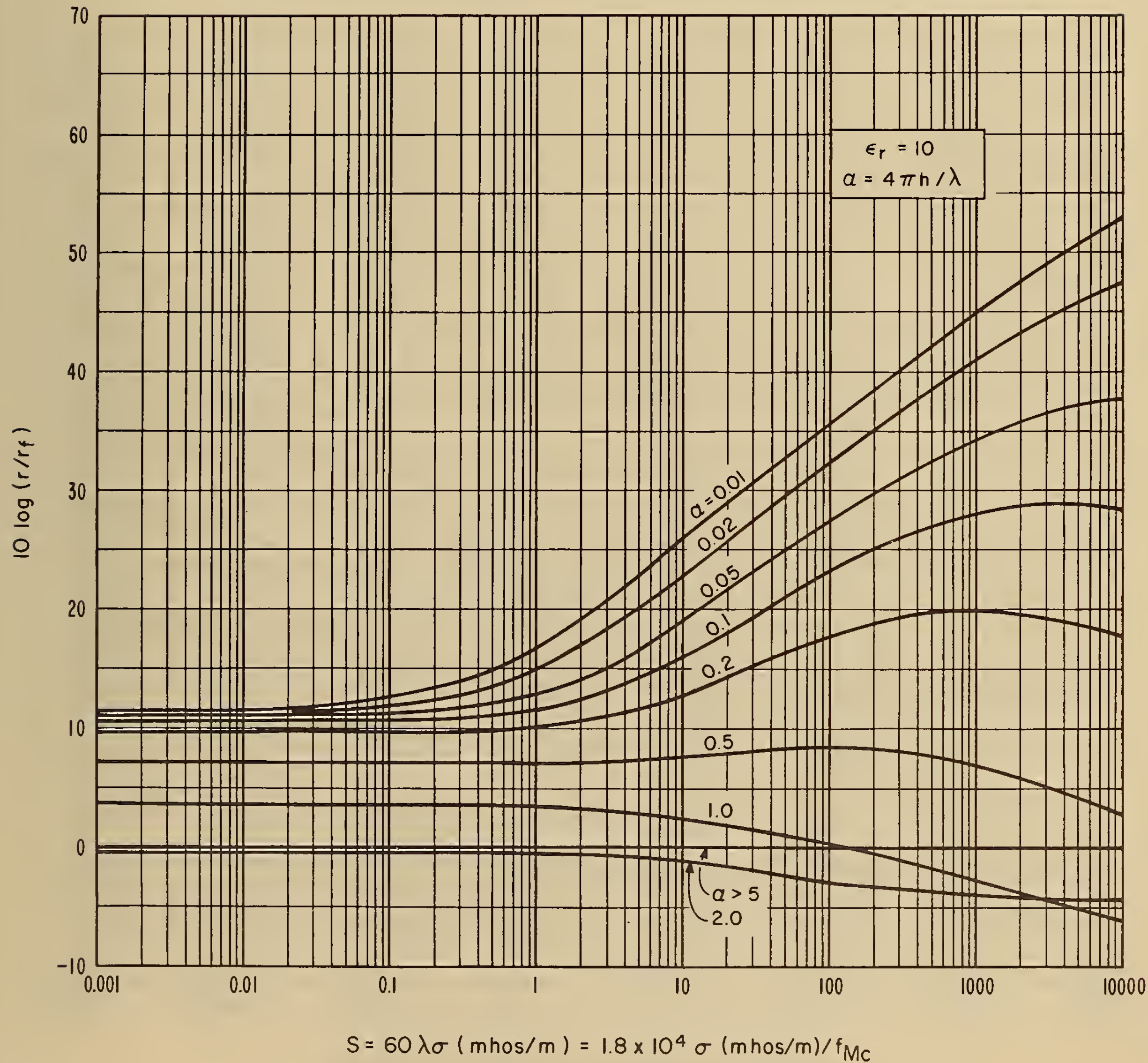


GROUND PROXIMITY LOSS FOR VMD, $\epsilon_r = 5$



$S = 60\,\lambda\sigma$ (mhos/m) $= 1.8 \times 10^4\ \sigma$ (mhos/m)/f_{Mc}

GROUND PROXIMITY LOSS FOR VMD, $\epsilon_r = 10$



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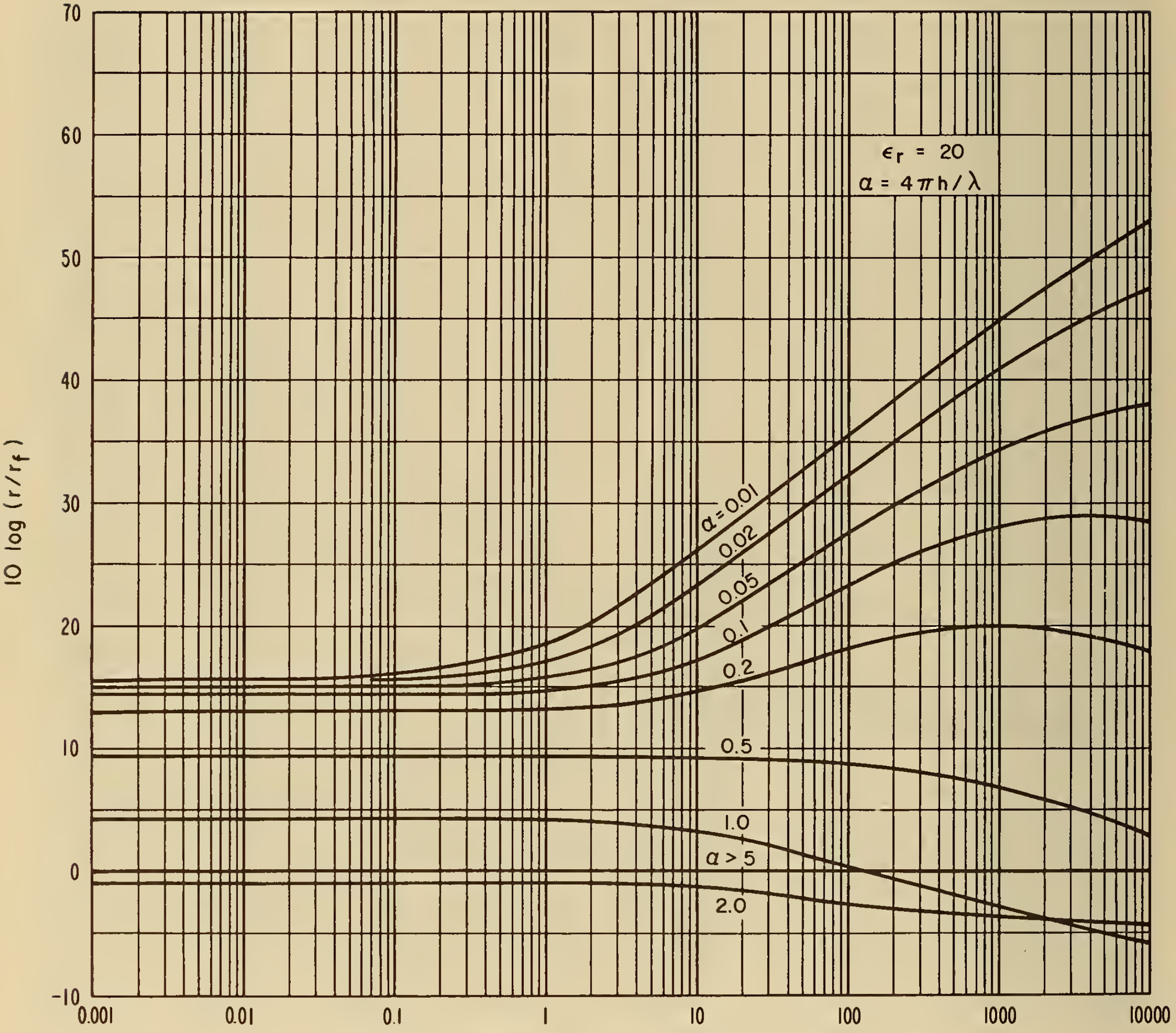
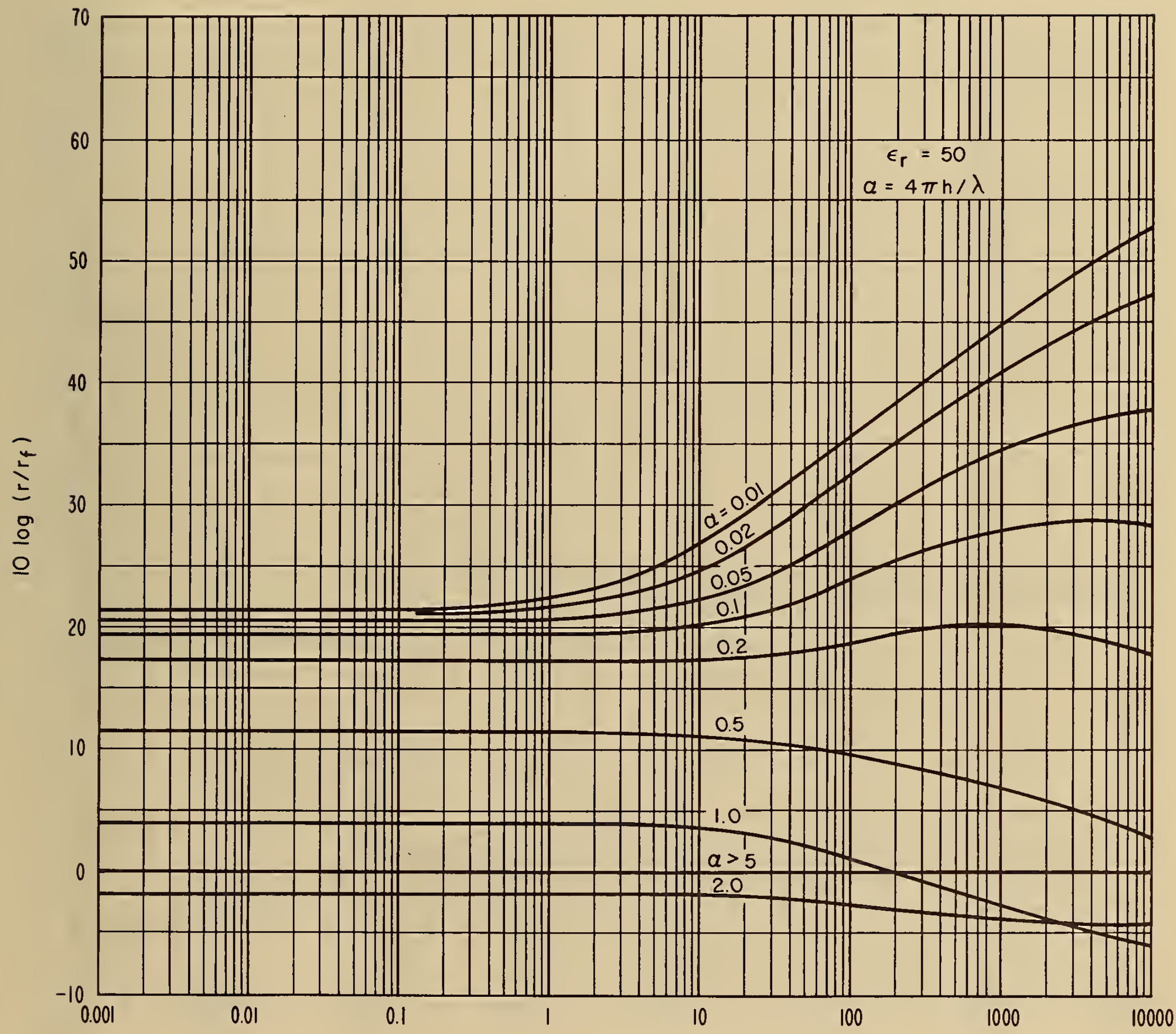


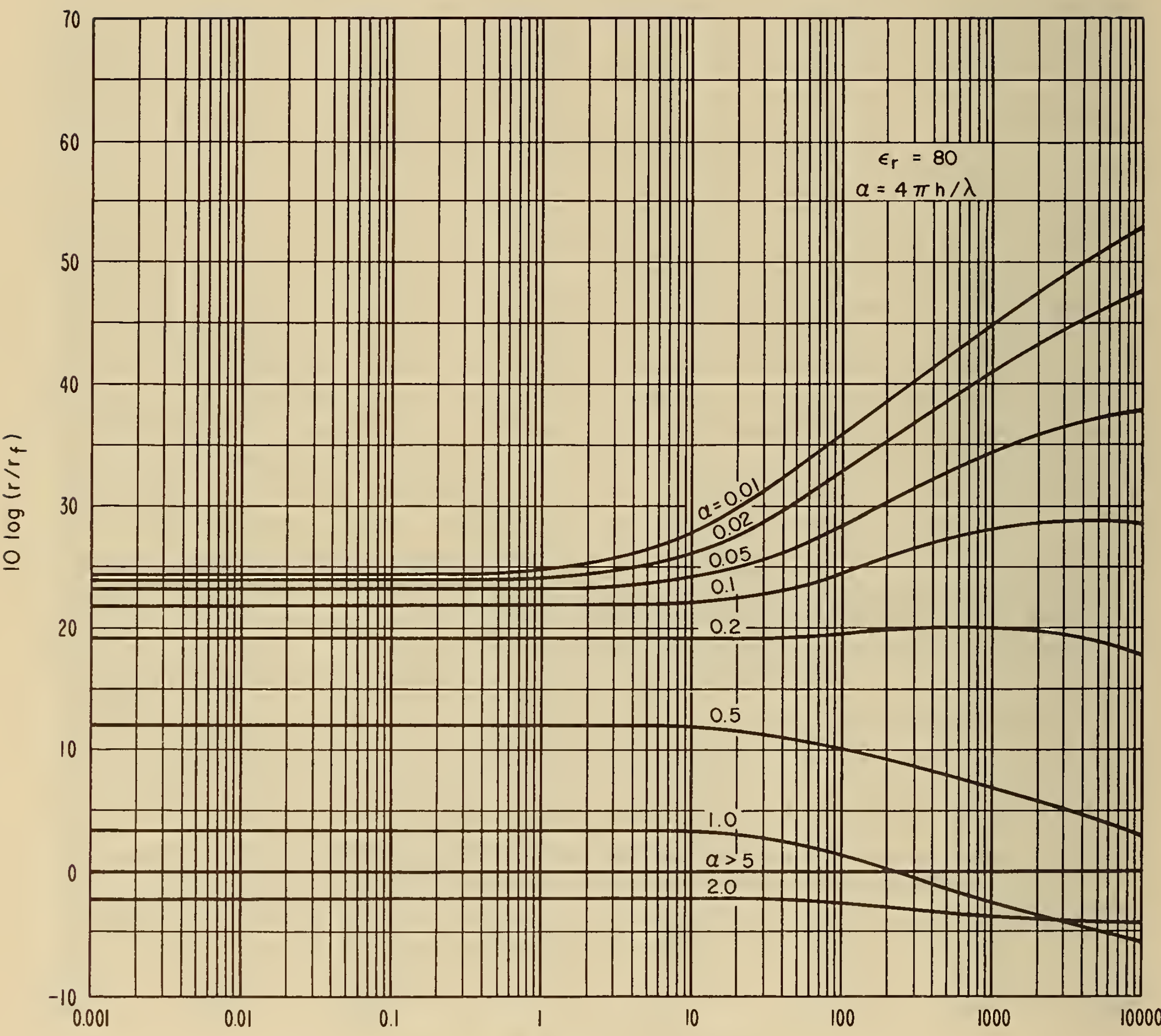
$S = 60\,\lambda\sigma$ (mhos/m) = $1.8 \times 10^4\,\sigma$ (mhos/m)/f_{Mc}

GROUND PROXIMITY LOSS FOR VMD, $\epsilon_r = 50$



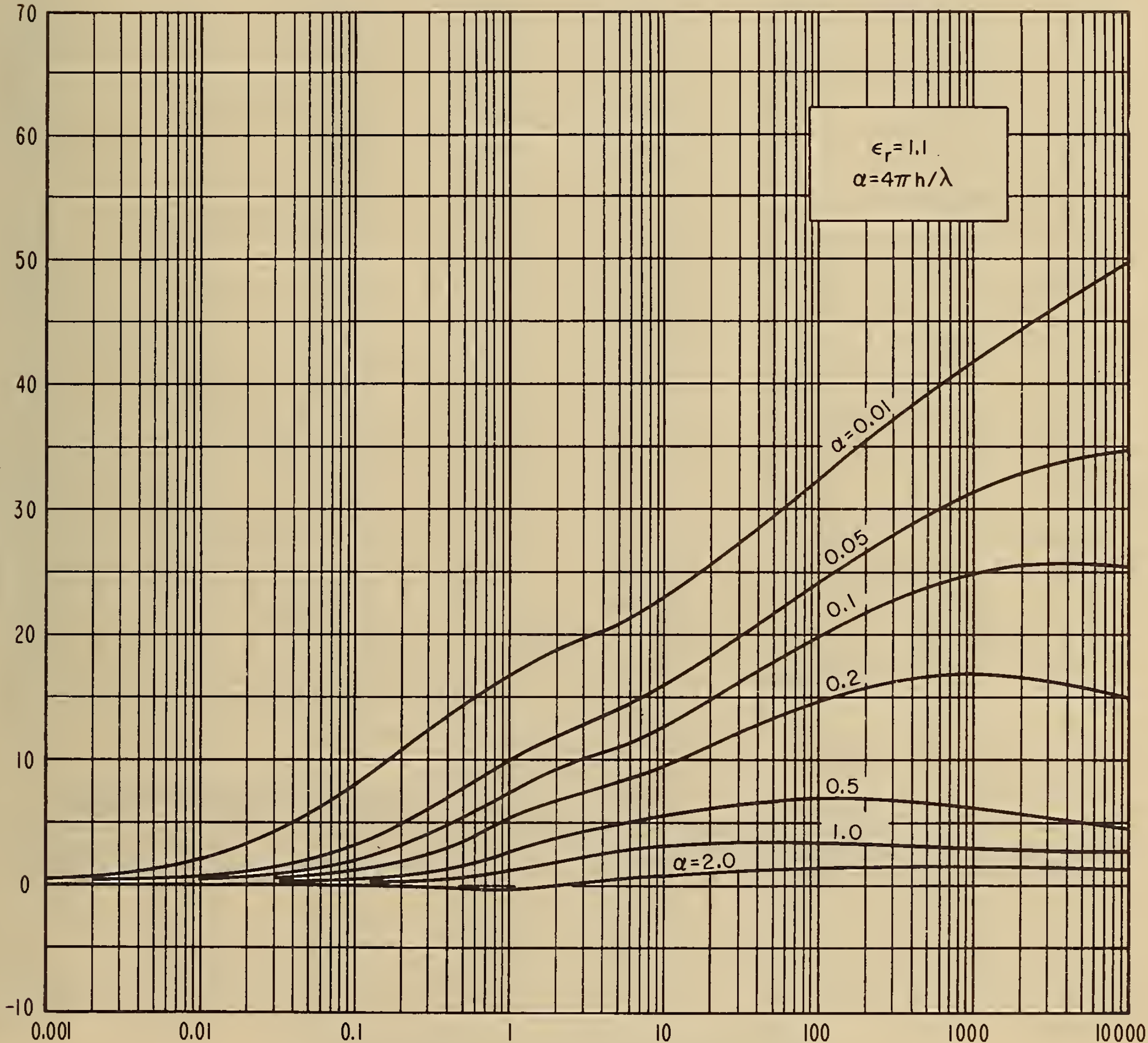
S = 60 $\lambda\sigma$ (mhos/m) = 1.8 x 10^4 σ (mhos/m)/f_{Mc}

GROUND PROXIMITY LOSS FOR VMD, $\epsilon_r = 80$



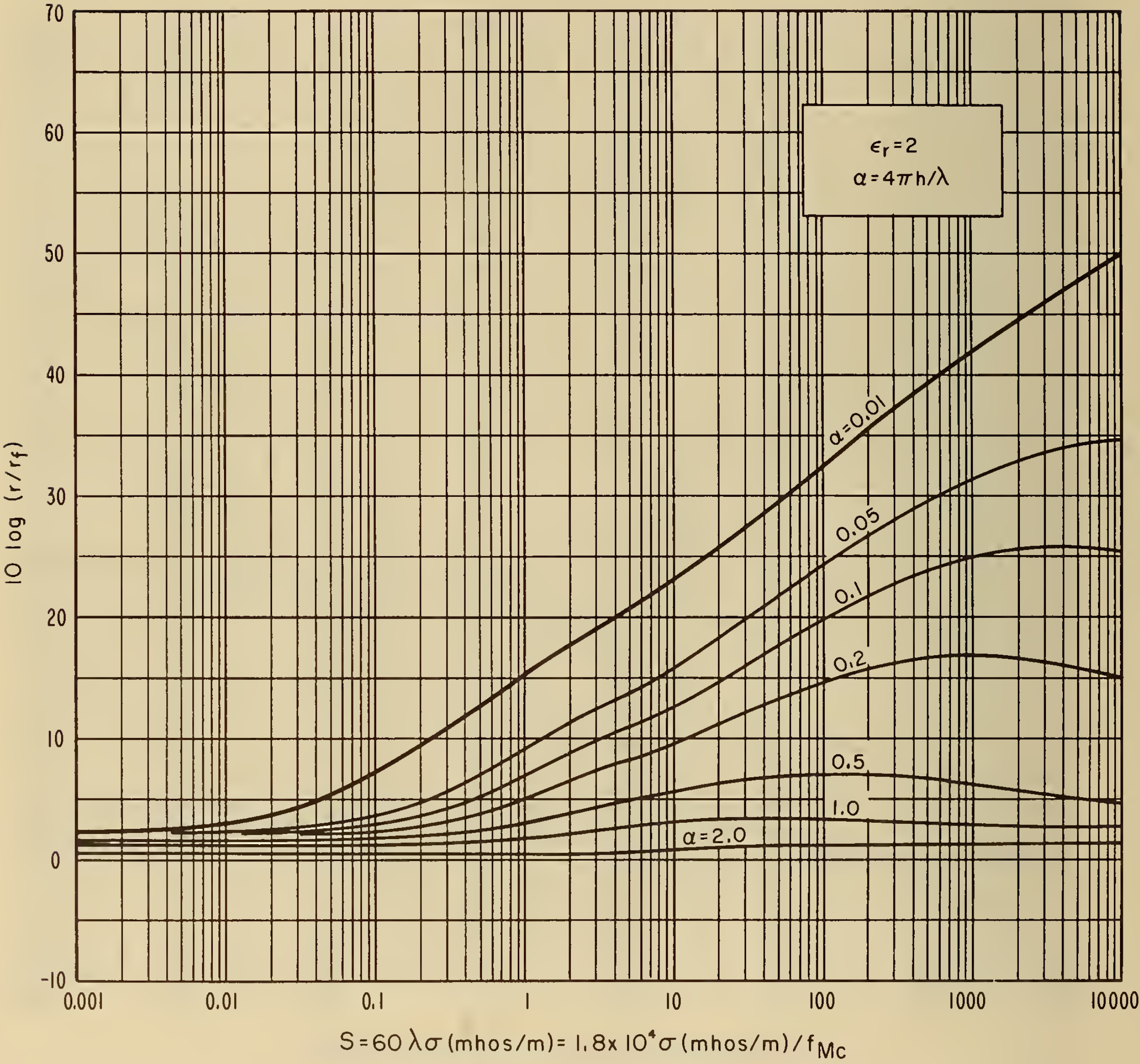
$S = 60\lambda\sigma$ (mhos/m) $= 1.8 \times 10^4\ \sigma$ (mhos/m)$/f_{Mc}$

GROUND PROXIMITY LOSS FOR HMD, $\epsilon_r = 1.1$

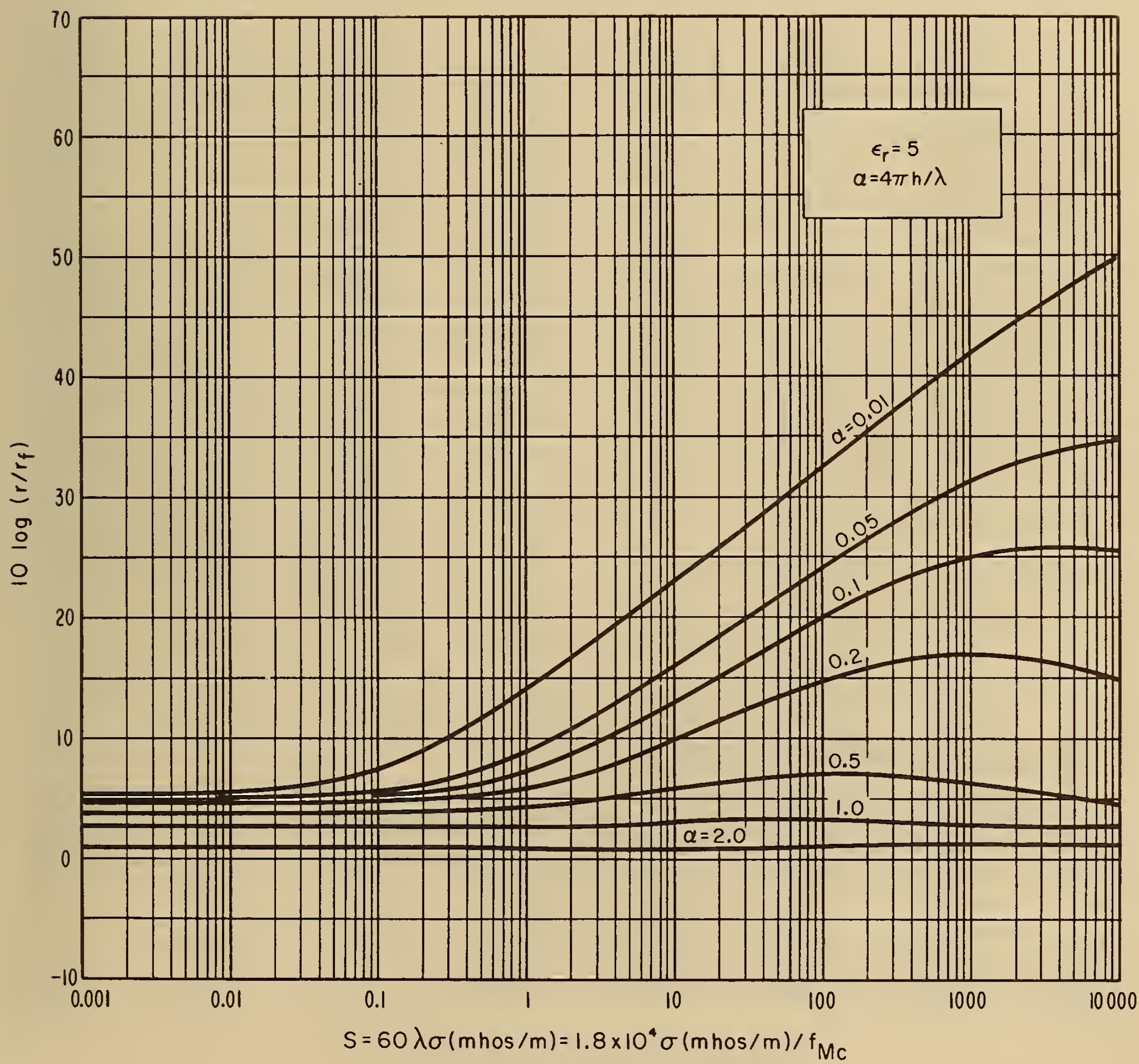


$S = 60\lambda\sigma$ (mhos/m) $= 1.8 \times 10^4 \sigma$ (mhos/m)$/f_{Mc}$

GROUND PROXIMITY LOSS FOR HMD, $\epsilon_r = 2$



GROUND PROXIMITY LOSS FOR HMD, $\epsilon_r = 5$



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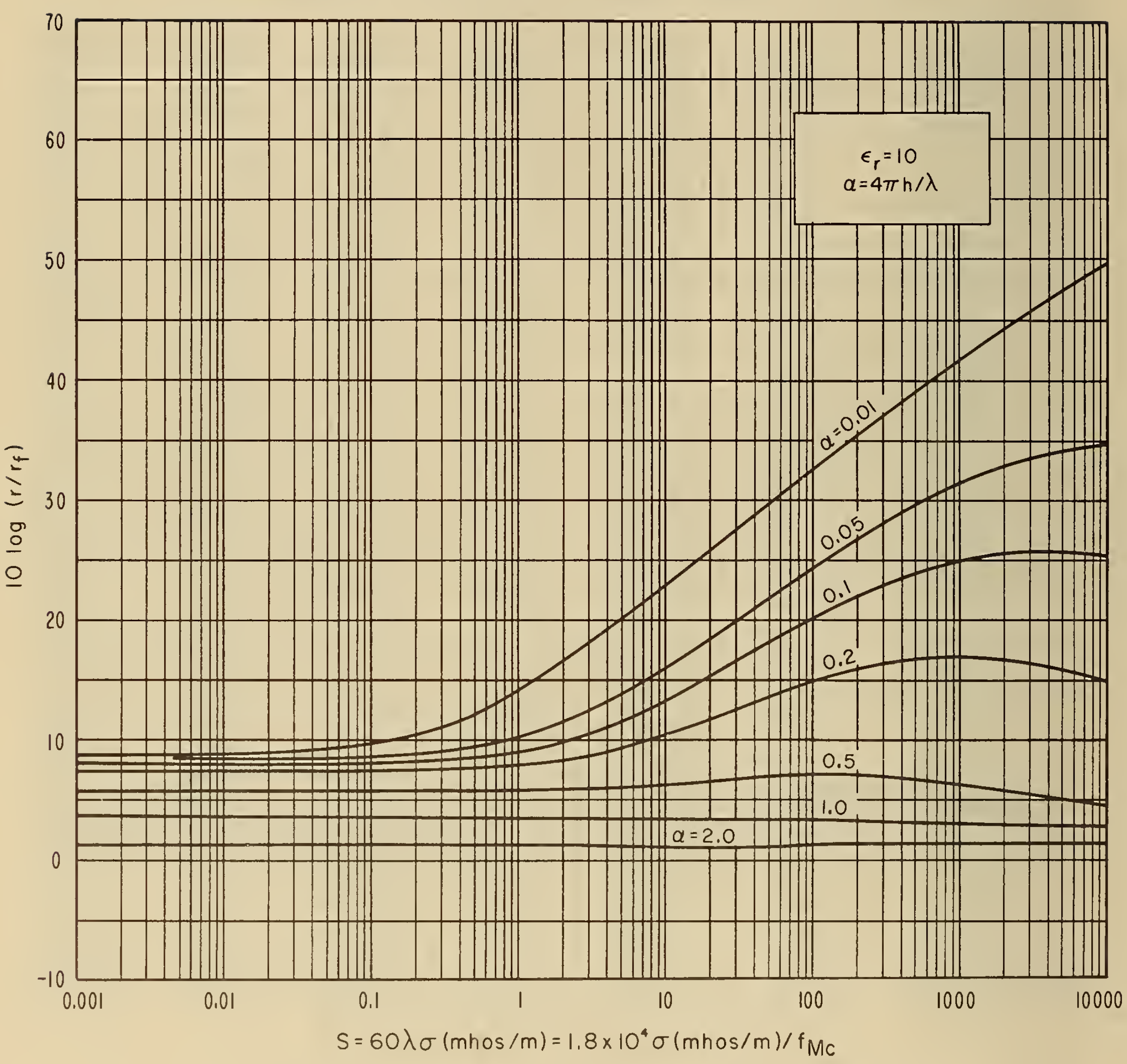

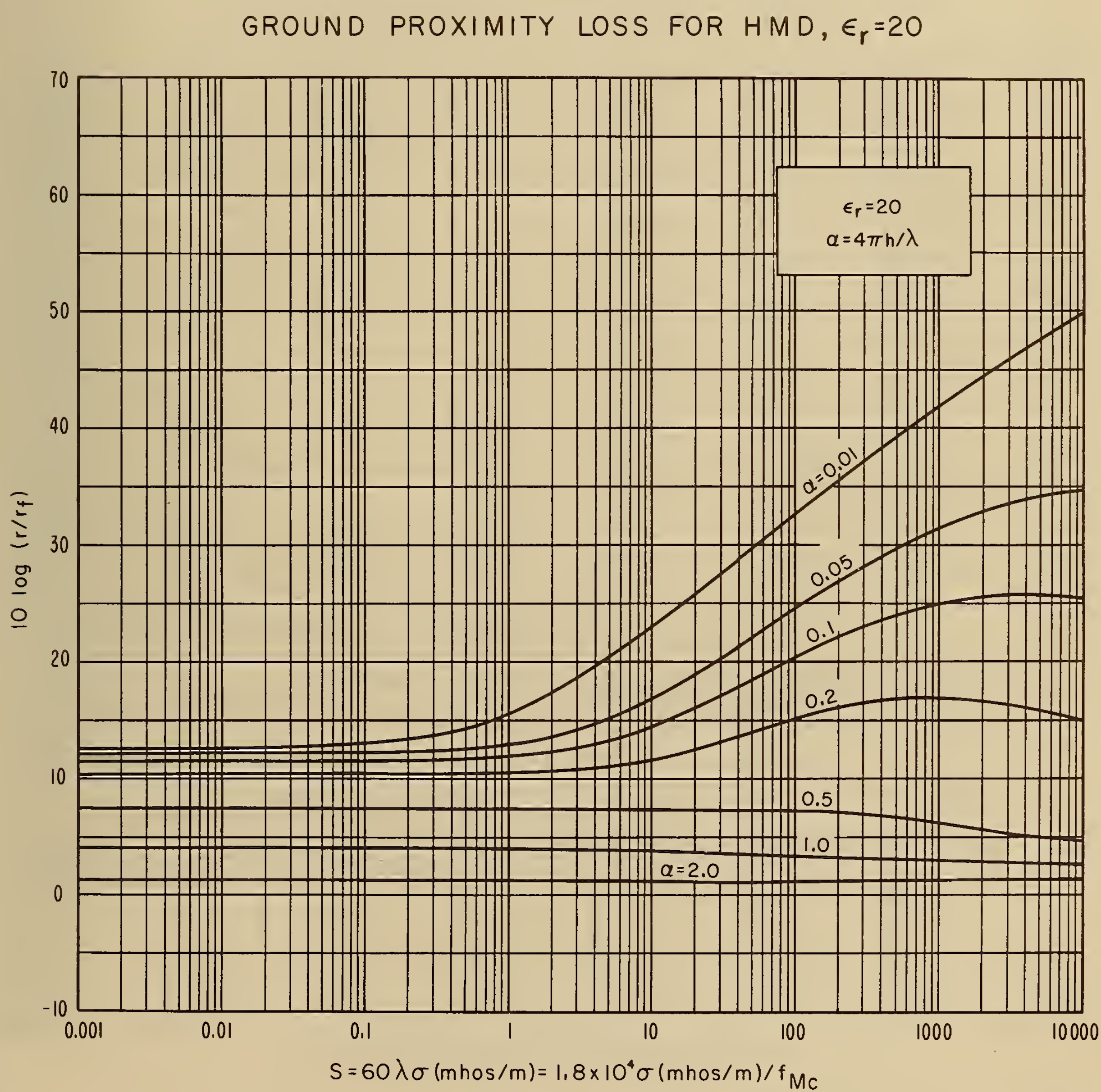
GROUND PROXIMITY LOSS FOR HMD, $\epsilon_r=20$
$\epsilon_r=20$
$\alpha=4\pi h/\lambda$
$\alpha=0.01$
0.05
0.1
0.2
0.5
1.0
$\alpha=2.0$
70
60
50
40
30
20
10
0
-10
0.001
0.01
0.1
1
10
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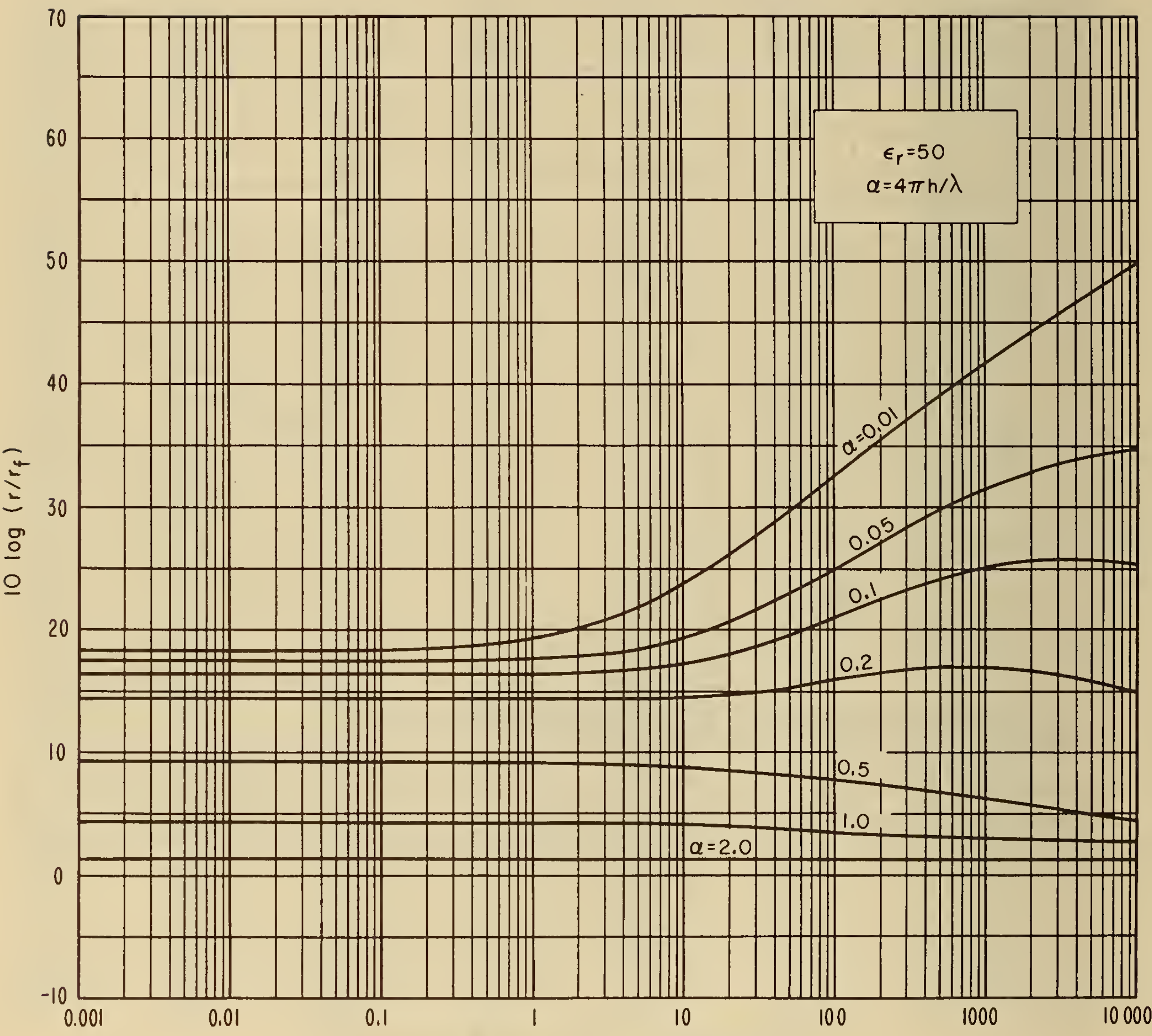
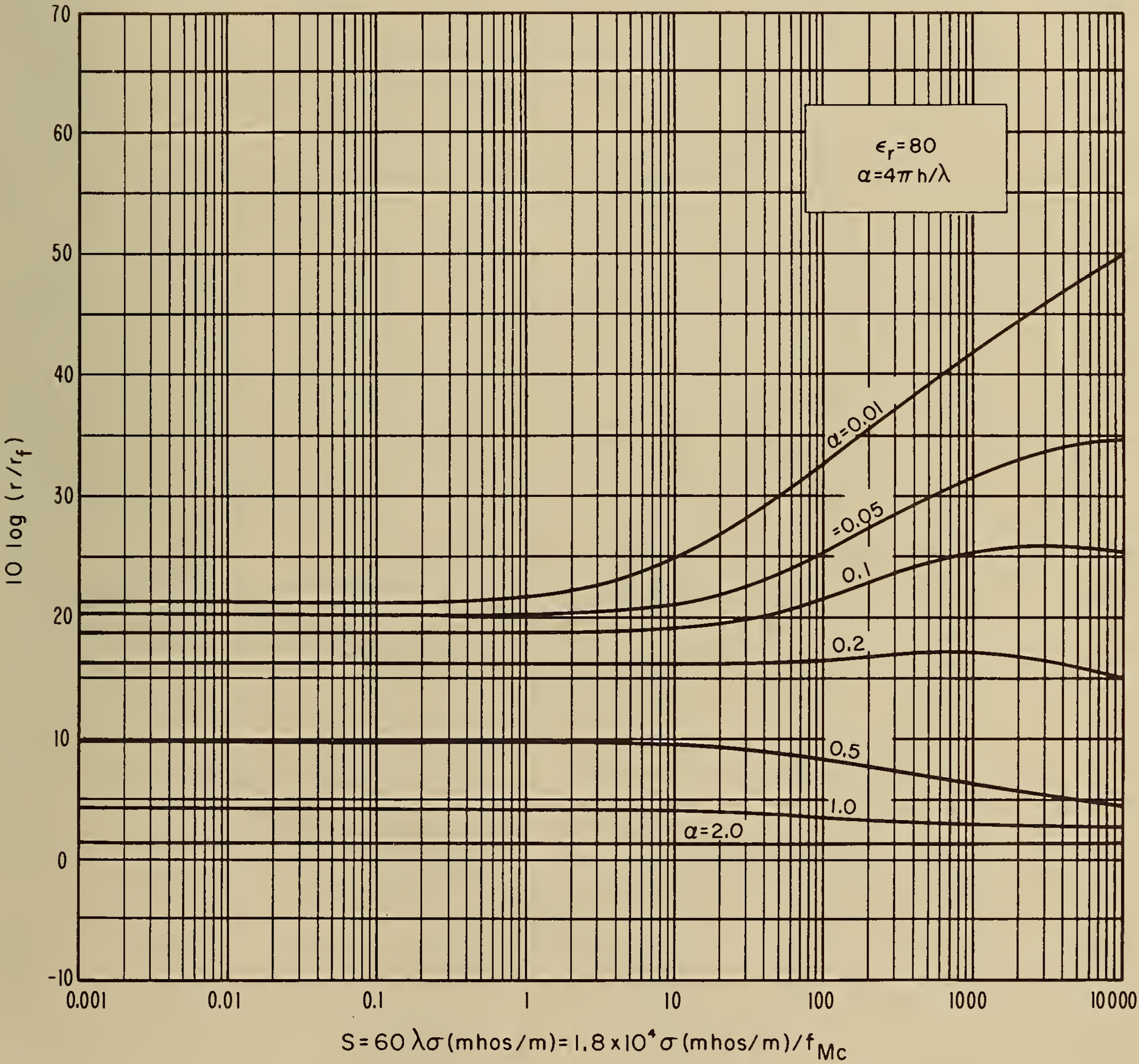
10000
10 log (r/r_f)
$S=60\lambda\sigma$(mhos/m)$=1.8\times10^4\sigma$(mhos/m)$/f_{Mc}$

GROUND PROXIMITY LOSS FOR HMD, $\epsilon_r = 50$



$S = 60\lambda\sigma$ (mhos/m) = $1.8 \times 10^4 \sigma$ (mhos/m) / f_{Mc}

GROUND PROXIMITY LOSS FOR HMD, $\epsilon_r = 80$



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Luther H. Hodges, *Secretary*

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WASHINGTON, D. C.

Electricity. Resistance and Reactance. Electrochemistry. Electrical Instruments. Magnetic Measurements. Dielectrics. High Voltage.

Metrology. Photometry and Colorimetry. Refractometry. Photographic Research. Length. Engineering Metrology. Mass and Scale. Volumetry and Densimetry.

Heat. Temperature Physics. Heat Measurements. Cryogenic Physics. Equation of State. Statistical Physics.

Radiation Physics. X-ray. Radioactivity. Radiation Theory. High Energy Radiation. Radiological Equipment. Nucleonic Instrumentation. Neutron Physics.

Analytical and Inorganic Chemistry. Pure Substances. Spectrochemistry. Solution Chemistry. Standard Reference Materials. Applied Analytical Research. Crystal Chemistry.

Mechanics. Sound. Pressure and Vacuum. Fluid Mechanics. Engineering Mechanics. Rheology. Combustion Controls.

Polymers. Macromolecules: Synthesis and Structure. Polymer Chemistry. Polymer Physics. Polymer Characterization. Polymer Evaluation and Testing. Applied Polymer Standards and Research. Dental Research.

Metallurgy. Engineering Metallurgy. Microscopy and Diffraction. Metal Reactions. Metal Physics. Electrolysis and Metal Deposition.

Inorganic Solids. Engineering Ceramics. Glass. Solid State Chemistry. Crystal Growth. Physical Properties. Crystallography.

Building Research. Structural Engineering. Fire Research. Mechanical Systems. Organic Building Materials. Codes and Safety Standards. Heat Transfer. Inorganic Building Materials. Metallic Building Materials.

Applied Mathematics. Numerical Analysis. Computation. Statistical Engineering. Mathematical Physics. Operations Research.

Data Processing Systems. Components and Techniques. Computer Technology. Measurements Automation. Engineering Applications. Systems Analysis.

Atomic Physics. Spectroscopy. Infrared Spectroscopy. Far Ultraviolet Physics. Solid State Physics. Electron Physics. Atomic Physics. Plasma Spectroscopy.

Instrumentation. Engineering Electronics. Electron Devices. Electronic Instrumentation. Mechanical Instruments. Basic Instrumentation.

Physical Chemistry. Thermochemistry. Surface Chemistry. Organic Chemistry. Molecular Spectroscopy. Elementary Processes. Mass Spectrometry. Photochemistry and Radiation Chemistry.

Office of Weights and Measures.

BOULDER, COLO.

Cryogenic Engineering Laboratory. Cryogenic Equipment. Cryogenic Processes. Properties of Materials. Cryogenic Technical Services.

CENTRAL RADIO PROPAGATION LABORATORY

Ionosphere Research and Propagation. Low Frequency and Very Low Frequency Research. Ionosphere Research. Prediction Services. Sun-Earth Relationships. Field Engineering. Radio Warning Services. Vertical Soundings Research.

Radio Propagation Engineering. Data Reduction Instrumentation. Radio Noise. Tropospheric Measurements. Tropospheric Analysis. Propagation-Terrain Effects. Radio-Meteorology. Lower Atmosphere Physics.

Radio Systems. Applied Electromagnetic Theory. High Frequency and Very High Frequency Research. Frequency Utilization. Modulation Research. Antenna Research. Radiodetermination.

Upper Atmosphere and Space Physics. Upper Atmosphere and Plasma Physics. High Latitude Ionosphere Physics. Ionosphere and Exosphere Scatter. Airglow and Aurora. Ionospheric Radio Astronomy.

RADIO STANDARDS LABORATORY

Radio Physics. Radio Broadcast Service. Radio and Microwave Materials. Atomic Frequency and Time-Interval Standards. Radio Plasma. Millimeter-Wave Research.

Circuit Standards. High Frequency Electrical Standards. High Frequency Calibration Services. High Frequency Impedance Standards. Microwave Calibration Services. Microwave Circuit Standards. Low Frequency Calibration Services.

NBS