NASA CONTRACTOR REPORT

NASA CR-61045

N65 22972
(ACCESSION NUMBER)

(THRU)

44
(PAGES)

1
(CODE)

(NASA CR OR TMX OR AD NUMBER)

07
(CATEGORY)

FACILITY FORM 602

NASA CR-61045

APOLLO LOGISTICS SUPPORT SYSTEMS MOLAB STUDIES

TASK ORDER N-19 REPORT ON GROUND WAVE PROPAGATION ON THE LUNAR SURFACE FOR A LUNAR MOBILE LABORATORY

Prepared under Contract No. NAS8-11096 by

J. D. Hughlett, Jr.

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GPO PRICE $ ________

OTS PRICE(S) $ ________

Hard copy (HC) 2.00

Microfiche (MF) .50

For

NASA - GEORGE C. MARSHALL SPACE FLIGHT CENTER
Huntsville, Alabama

June 1964

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6025 Technology Drive
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For

ASTRIONICS LABORATORY

NASA-GEORGE C. MARSHALL SPACE FLIGHT CENTER

PREFACE

This report was prepared by the Northrop Space Laboratories, Huntsville Department for the George C. Marshall Space Flight Center. The NASA Technical Liaison Representative was Mr. E. C. Hamilton of the Advanced Studies Office, Astrionics Laboratory. The work was started on 29 February 1964, and completed 1 July 1964.

This particular task was one of the current series assigned to the Huntsville Department of NSL for study of the various aspects associated with the preliminary consideration of the Apollo Logistic Support System utilizing the MOLAB Payload.

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SECTION 1

SUMMARY

This document presents the results of a Ground Wave Propagation Study for an Over-the-Lunar Horizon Communication System. It will be applicable to the manned Mobile Laboratory (MOLAB) mission -- now under consideration by the National Aeronautics and Space Administration as a Logistic Support System for the Project Apollo.

Findings of this study indicate that a frequency in the medium-frequency range vertically polarized, offers the best application to over-the-horizon type lunar surface communication systems. This polarization was chosen because the moon could have a short-circuiting affect on the electric intensity of the horizontal polarized wave which would offer resistance to this component of the vertical wave. This effect is comparable to that found on earth and reported by several authors.

The ground currents of the vertically polarized surface wave do not short-circuit a given electric field but rather serve to restore part of the energy used in the electrical field. The ground wave induces charges in the moon which travels with the wave and so constitutes a current. In carrying this induced current, the moon would behave similar to a leaky capacitor and, therefore, can be represented by a resistance shunted by a capacitive reactance.

The characteristics of the moon as a conductor can be described in terms of conductivity (σ) and dielectric constant (ϵ). There are no experimental data available on lunar soil characteristics. However, the values of conductivity and dielectric constants from Reference 1 are considered to be closely related to the soil characteristics of the moon.

The approach to the ground wave propagation problem was to select a set of parameters based on experimental data and extrapolate earth data to determine the feasibility of an over-the-horizon type of communication system. These selected parameters need to be confirmed or updated as the findings of lunar probes or later experiments become available.

SECTION 2

INTRODUCTION

This report is the result of an investigation of specified problems pertinent to the communications area of the lunar surface Mobile Laboratory (MOLAB) - a candidate system to be used as part of the Apollo Logistic Support System (ALSS). It represents only one assignment in the area of lunar communications, that being ground wave propagation on the lunar surface. This work was done under authorization of MSFC Task Order N-19 assigned to NSL as part of Contract No. NAS8-11096. The Task Order is titled "Ground Wave Propagation on the Lunar Surface for a Lunar Mobile Laboratory".

This report is essentially divided into four (4) sections. Results of the first and second section arrive at an optimum frequency for use in the third section. The first section discusses the R. F. power requirements for range and frequency for the outlined parameters. The second section gives the antenna efficiency for a short vertical monopole base loaded and tuned to resonance at the given frequencies. By combination of these two, the optimum frequency results are shown in Section 3. Section 4 discusses briefly the expected weight in developing a transmitter for use on the lunar surface.

2.1 GUIDELINES AND ASSUMPTIONS

The guidelines and assumptions applicable to the overall constants of the Task Order are given below. The detailed guidelines and assumptions to which each Task item was directed are presented in the various Report Sections.

2.1.1 Guidelines

- Voice baseband width to be 2.5 kc.
- Navigation Aid (Direction Finding) application is considered for continuous wave modulation.

- Man-portable equipment including power supply not to exceed 100 earth pounds.
- Remote control of the MOLAB over the surface wave link is not considered during this study.

2.1.2 Assumptions

- Moon is in a complete vacuum
- The surface conductivity is in the range of 10^{-3} to 10^{-4} mhos per meter.
- Lunar surface has a dielectric constant of 2.

SECTION 3

R. F. POWER REQUIREMENTS

The R. F. power requirements for a medium-frequency R. F. system were considered for study by presenting the power requirements as the effective radiated power for distance versus frequency. Point designs of 10, 25, 100, and 1000 nautical miles were considered for possible transmission distances on the lunar surface with soil conductivities in the range of 10^{-3} to 10^{-4} mhos per meter and a dielectric constant of 2.

The curves for Distance versus Frequency with Effective Radiated Power as the parameter were derived from Voglers equation:

(1) $P_t = L_b + (L_t - G_t) - G_r + R + F + B - 204$ (Reference 2)

In rewriting equation 1 in the form of effective radiated power,

(2) $ERP = L_b + (L_r - G_r) + R + F + B - 204$ (Reference 3)

where

ERP = effective radiatred power in dbw

L_b = received power

$(L_r - G_r)$ = loss on the receiver

R = received power

F = information bandwidth

204 = constant from 10 log (kt.)

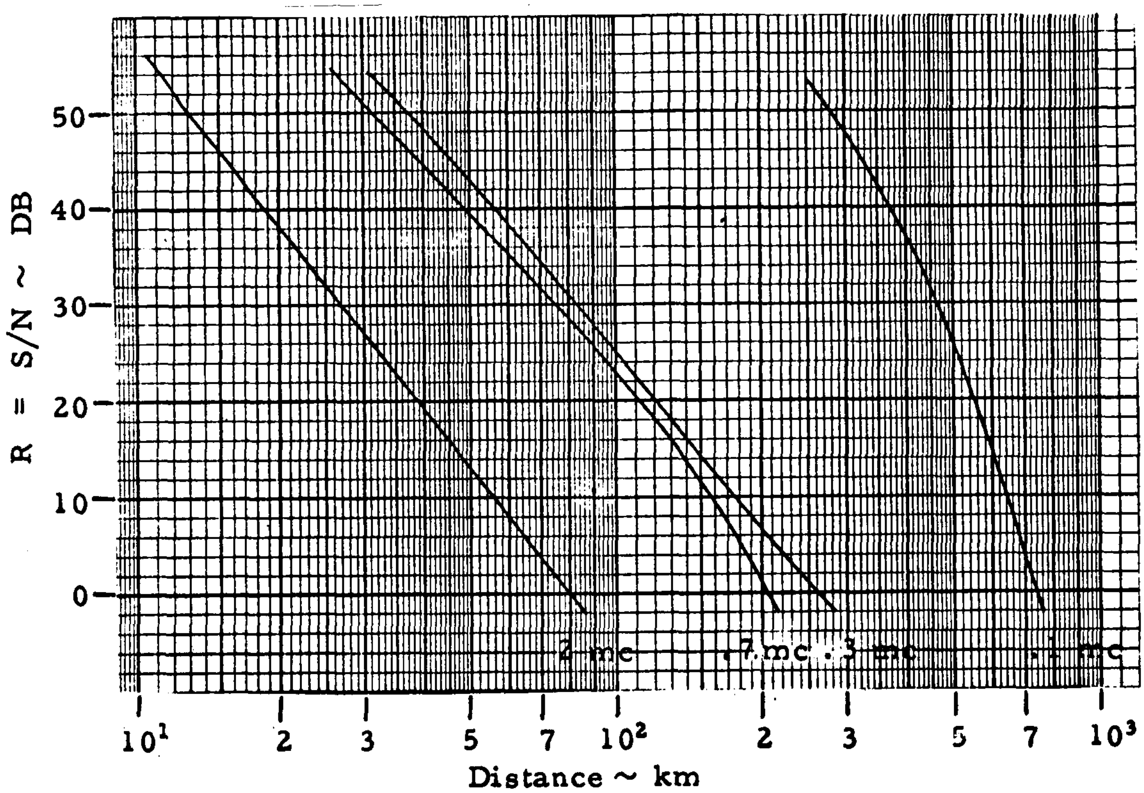
a series of output signal-to-noise ratio (transmitted signal-to-noise ratio) curves versus distance at various fixed frequencies result in the frequency as the parameter. From the data generated from the signal-to-noise ratio curves versus distance, the curves of effective radiated power results for a varying distance and frequency. The effective radiated power, as illustrated by these curves, is expressed in dbw, which can readily be stated in results by the equation

$$(3) \quad DBW = Log_{10} \frac{P_1}{P_2}$$

where the ratio of P_1 and P_2 are expressed in watts.

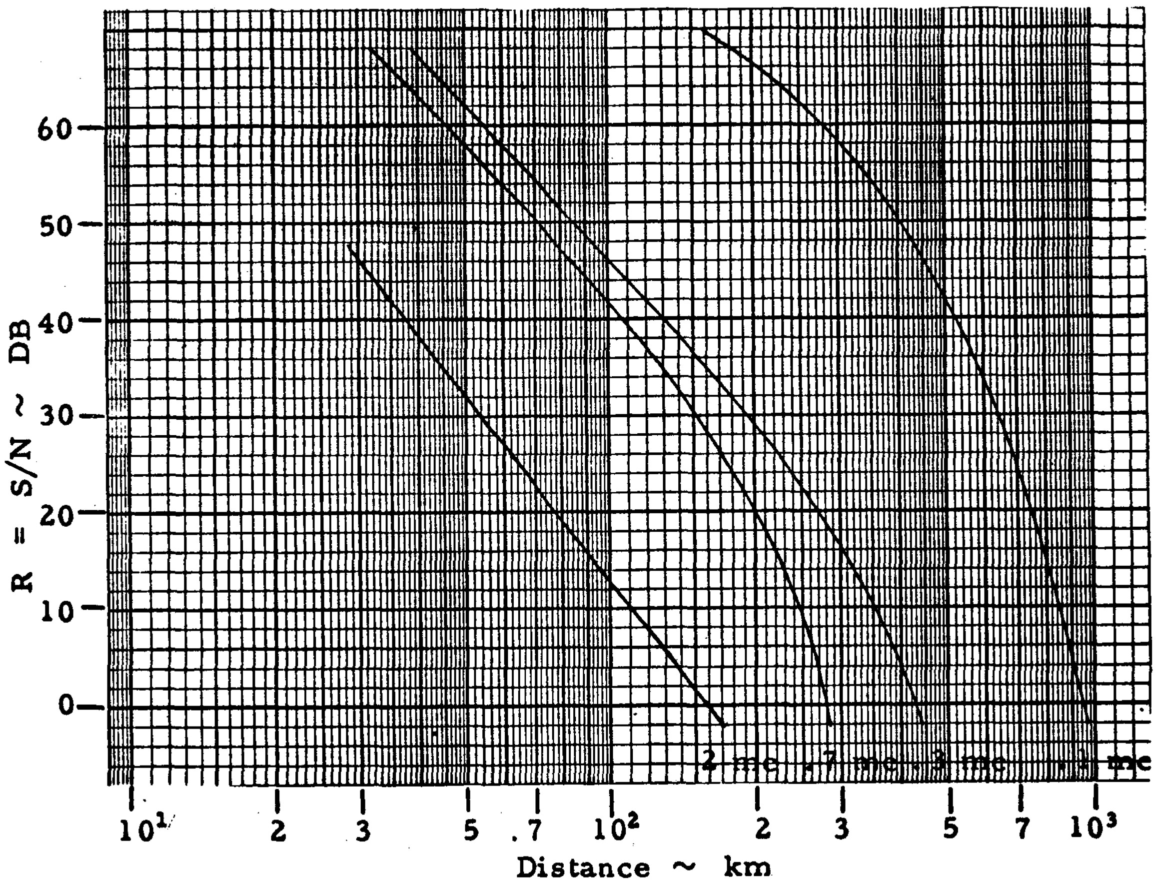
The following illustrations are shown for a soil conductivity of 10^{-3} and 10^{-4} mhos per meter and a dielectric constant of 2. The dielectric constant of 2 is taken for ease in calculations, since, previous calculations have indicated that the dielectric constant does not affect the transmission characteristics to any great degree. The first three figures are illustrated so that the data may be collected to plot distance versus frequency with effective radiated power as the parameter. To demonstrate the method of deriving this information, Figures 3-1, 3-2, and 3-3 of SNR versus distance must be used. After careful consideration has been given to the expected transmitted signal-to-noise ratio and fixing ERP to some value in dbw, a line drawn parallel to the abscissa will represent the transmitted signal-to-noise ratio. Where this assumed SNR line intersects with the frequency curves and then reading the distance from the graph, this data may then be plotted as Distance versus Frequency, with the Effective Radiated Power as the parameter (Figure 3-4). This figure intends to illustrate the power requirements at 10, 1000, and 10, 000 watts of transmitter output.

Figures 3-1 through 3-8 refer to voice communications at a bandwidth of 2. 5 kilocycles. It will be noted that for a range of 100 and 1000 nautical miles (1, 852 and 18, 520 kilometers respectively) the frequency required for ground wave propagation is in the Very Low Frequency range and the R. F. power requirements are not feasible as seen from Figures 3-1 through 3-12. A second series of figures (Figures 3-13 through 3-16) are given for Navigation Aid (Direction Finding) utilizing the technique of continuous wave modulation with no information modulation on the carrier. A bandwidth of 100 cycles per second is assumed as the receiver drift establishes this narrow band. From Figure 3-16 for Direction Finding a 10 watt transmitter should prove sufficient, assuming the lunar conductivity is within the range of 10^{-3} to 10^{-4} mhos per meter. This indicates that the radio direction finder for LEM and MOLAB will function when voice capability of the circuit is impractical.



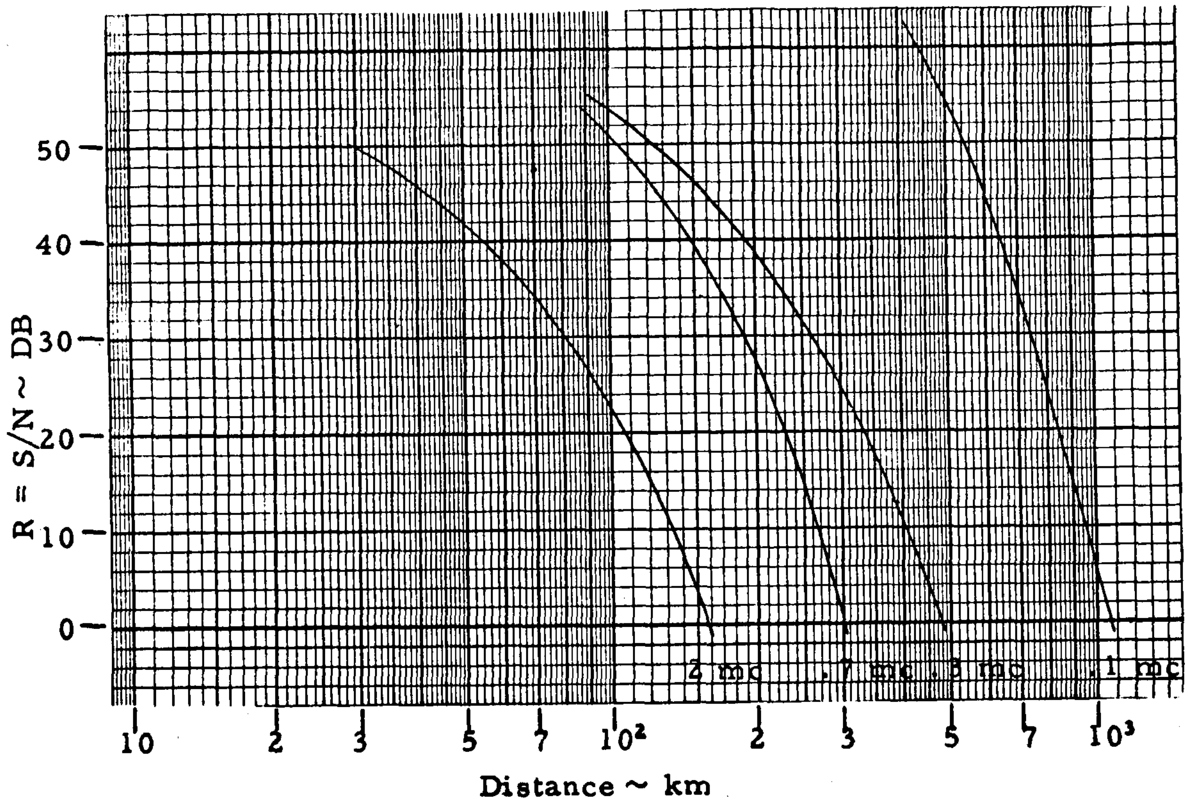
ERP = 10 dbw
Bandwidth 2.5 kc
$\sigma = 10^{-3}$
$\epsilon_r = 2$

FIGURE 3-1. SNR VERSUS DISTANCE FOR $\sigma = 10^{-3}$ AT 10 WATTS



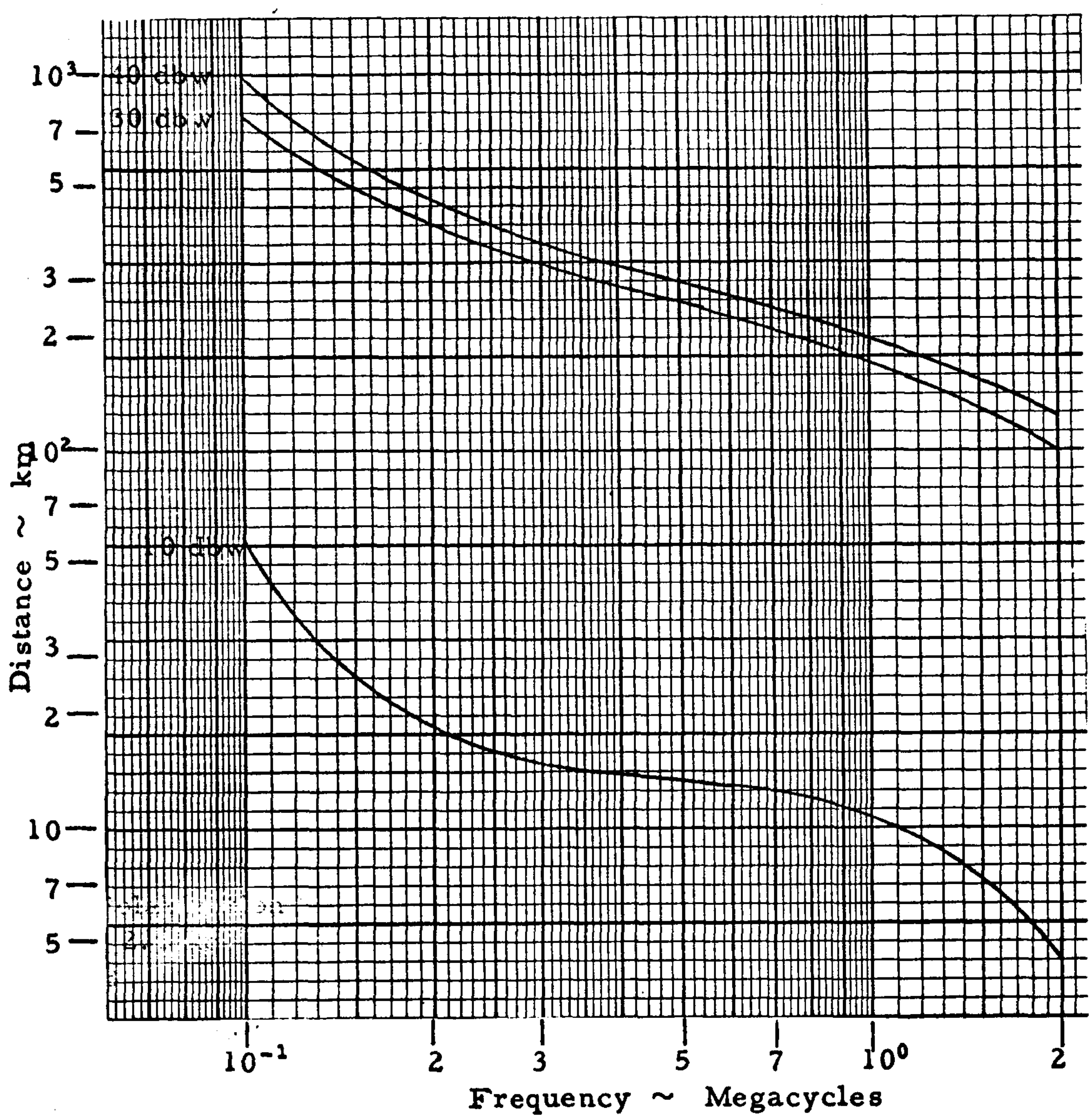
ERP = 30 dbw
Bandwidth 2.5 kc
$\sigma = 10^{-3}$
$\epsilon_r = 2$

FIGURE 3-2. SNR VERSUS DISTANCE FOR $\sigma = 10^{-3}$ AT 1000 WATTS



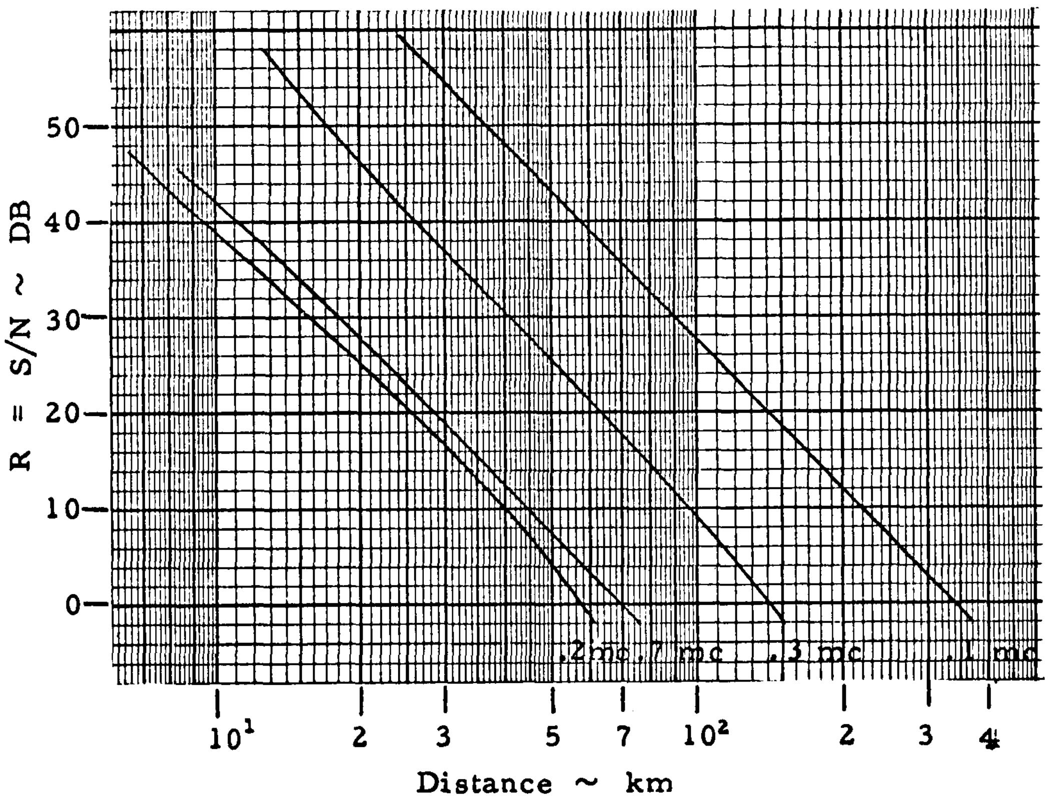
ERP = 40 dbw
Bandwidth 2.5 kc
$\sigma = 10^{-3}$ $\epsilon_r = 2$

FIGURE 3-3. SNR VERSUS DISTANCE FOR $\sigma = 10^{-3}$ AT 10,000 WATTS



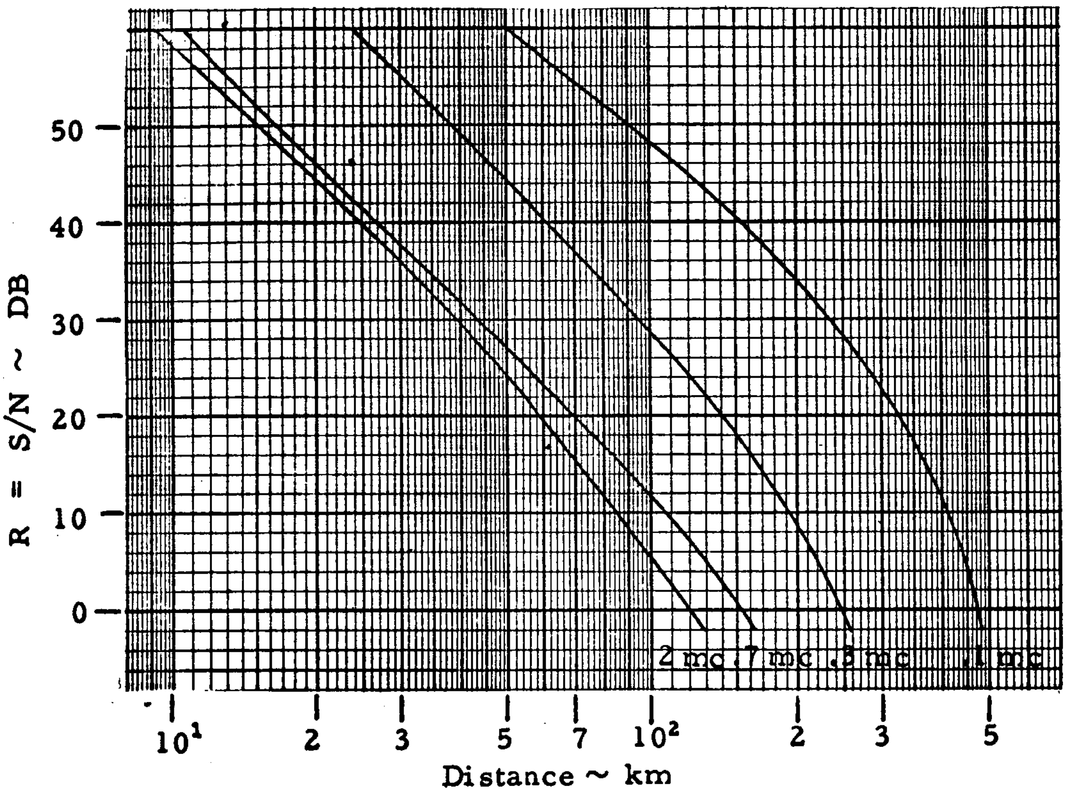
Vertical Polarization
Bandwidth 2. 5 kc
SNR 15 DB
ϵ_r = 2
σ = 10^{-3}

FIGURE 3-4. EFFECTIVE RADIATED POWER FOR 10^{-3} MHOS/METER



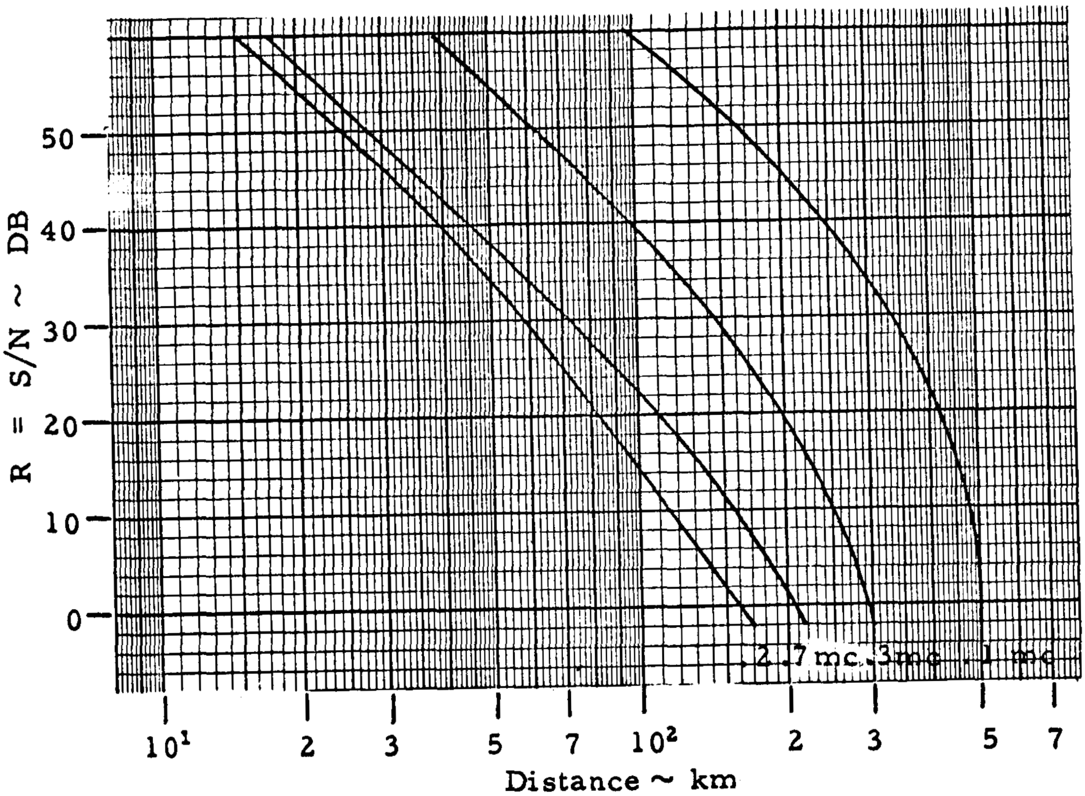
ERP = 10 dbw
Bandwidth 2. 5 kc
σ = 10^{-4}
ϵ_r = 2

FIGURE 3-5. SNR VERSUS DISTANCE FOR $\sigma = 10^{-4}$ AT 10 WATTS



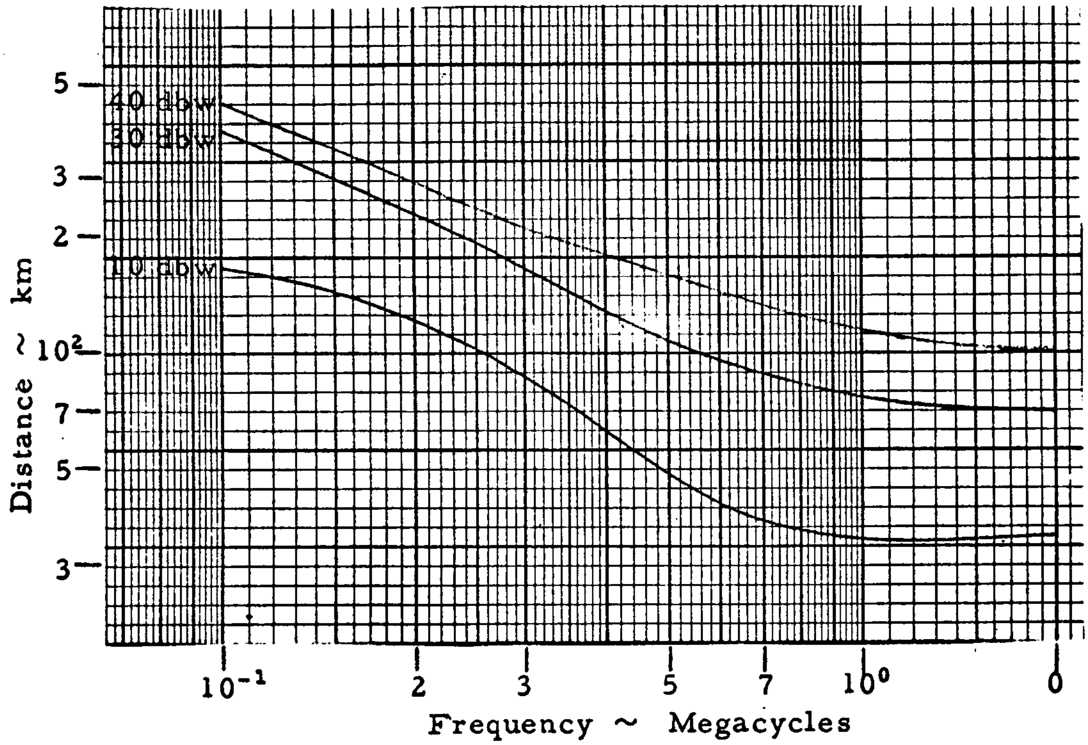
ERP = 30 dbw
Bandwidth 2.5 kc
σ = 10^{-4}
ϵ_r = 2

FIGURE 3-6. SNR VERSUS DISTANCE FOR $\sigma = 10^{-4}$ AT 1000 WATTS



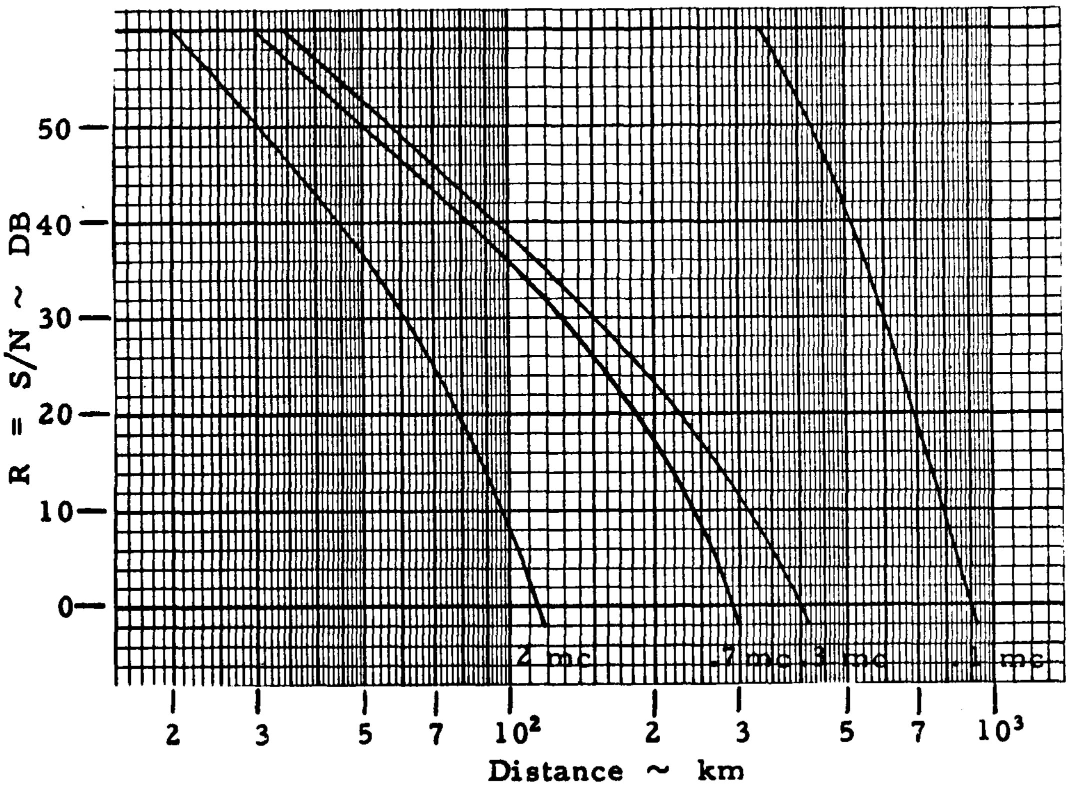
ERP = 40 dbw
Bandwidth 2.5 kc
σ = 10^{-4}
ϵ_r = 2

FIGURE 3-7. SNR VERSUS DISTANCE FOR $\sigma = 10^{-4}$ AT 10,000 WATTS



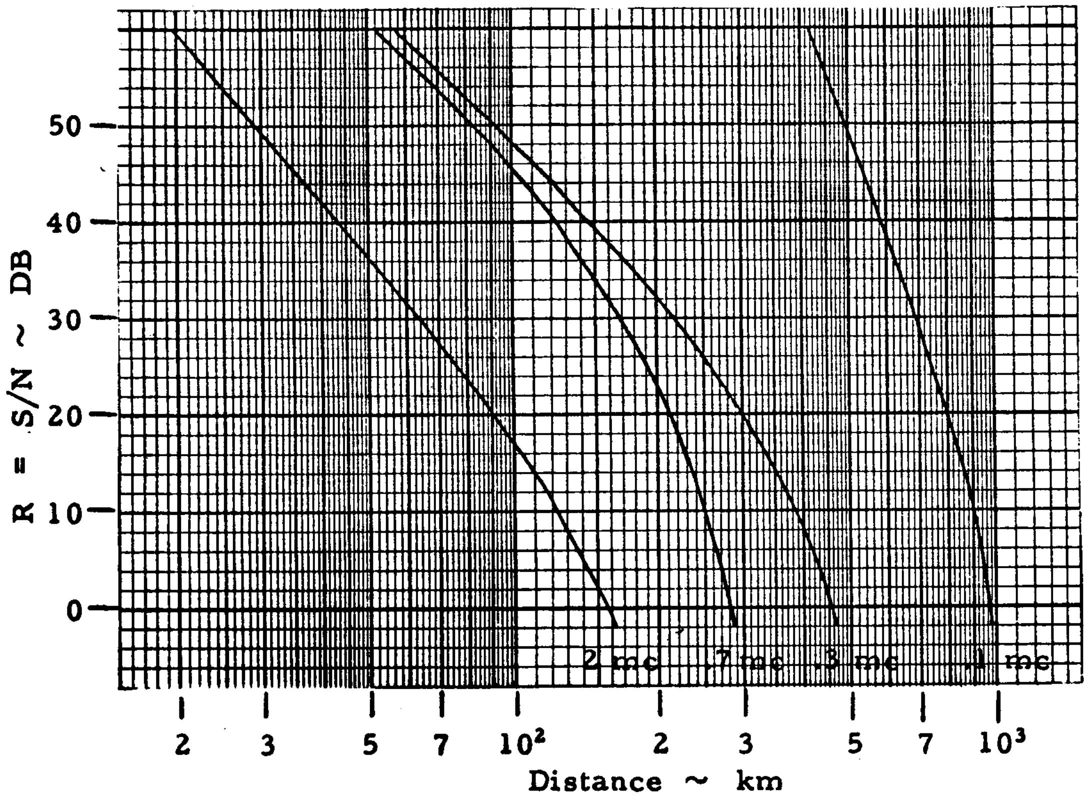
Vertical Polarization
Bandwidth 2. 5 kc
$\epsilon_r = 2$
$\sigma = 10^{-4}$
SNR 15 DB

FIGURE 3-8. EFFECTIVE RADIATED POWER FOR 10^{-4} MHOS/METER



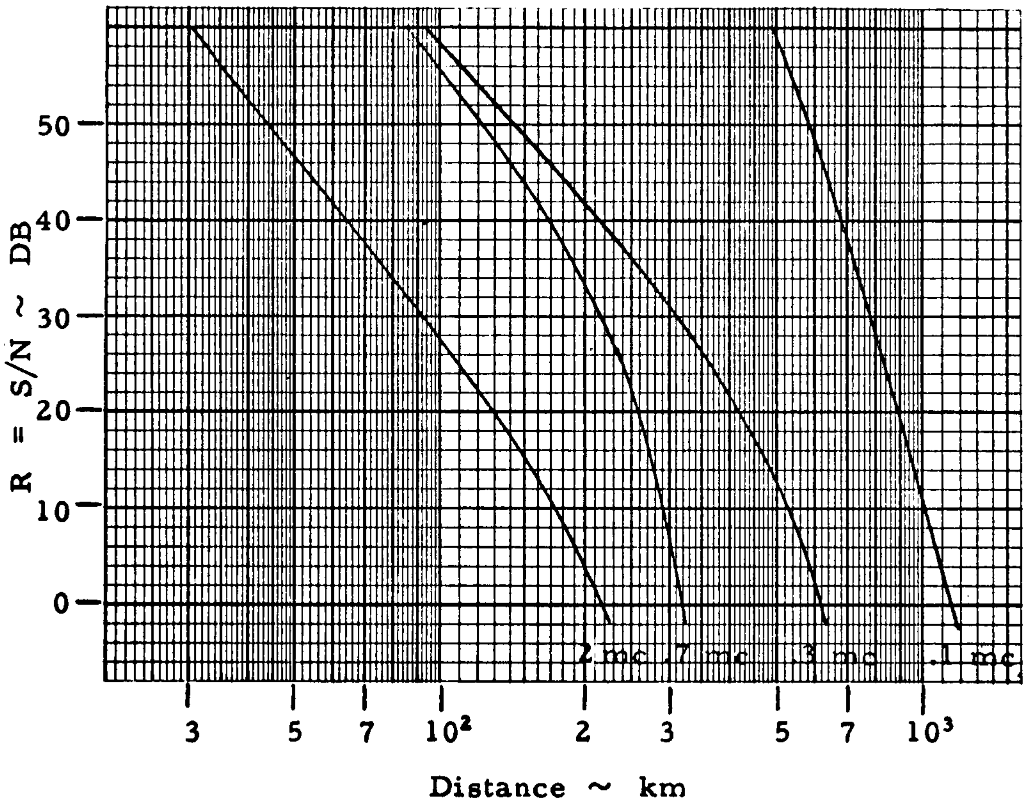
ERP = 10 dbw
Bandwidth 100 cps
$\sigma = 10^{-3}$
$\epsilon_r = 2$

FIGURE 3-9. SNR VERSUS DISTANCE FOR BW = 100 CPS AT 10 WATTS



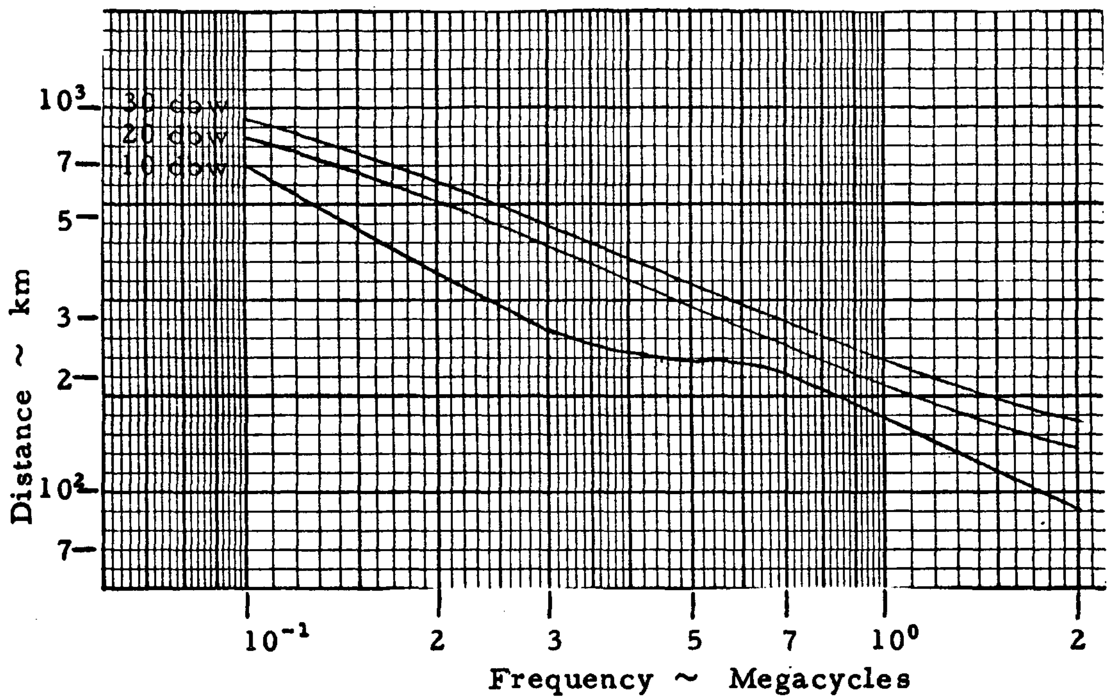
EPR = 20
Bandwidth 100 cps
$\sigma = 10^{-3}$
$\epsilon_r = 2$

FIGURE 3-10. SNR VERSUS DISTANCE FOR BW = 100 CPS AT 100 WATTS



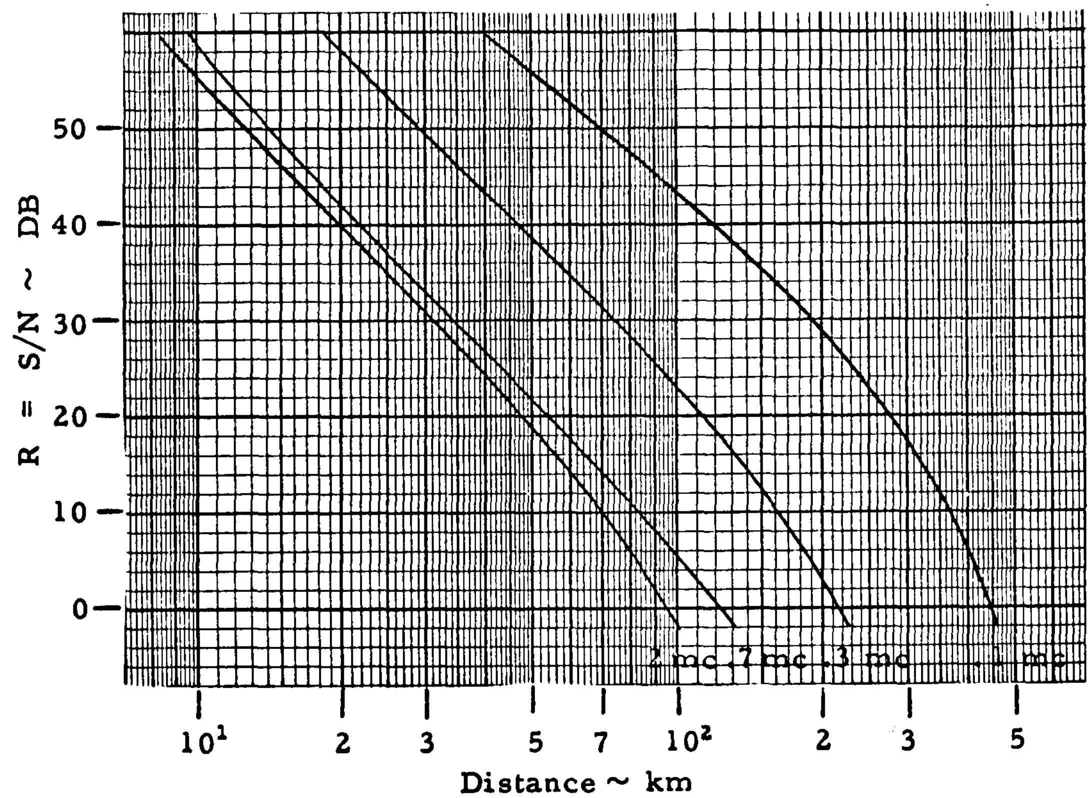
ERP = 30 dbw
Bandwidth 100 cps
$\sigma = 10^{-3}$
$\epsilon_r = 2$

FIGURE 3-11. SNR VERSUS DISTANCE FOR BW = 100 CPS AT 1000 WATTS



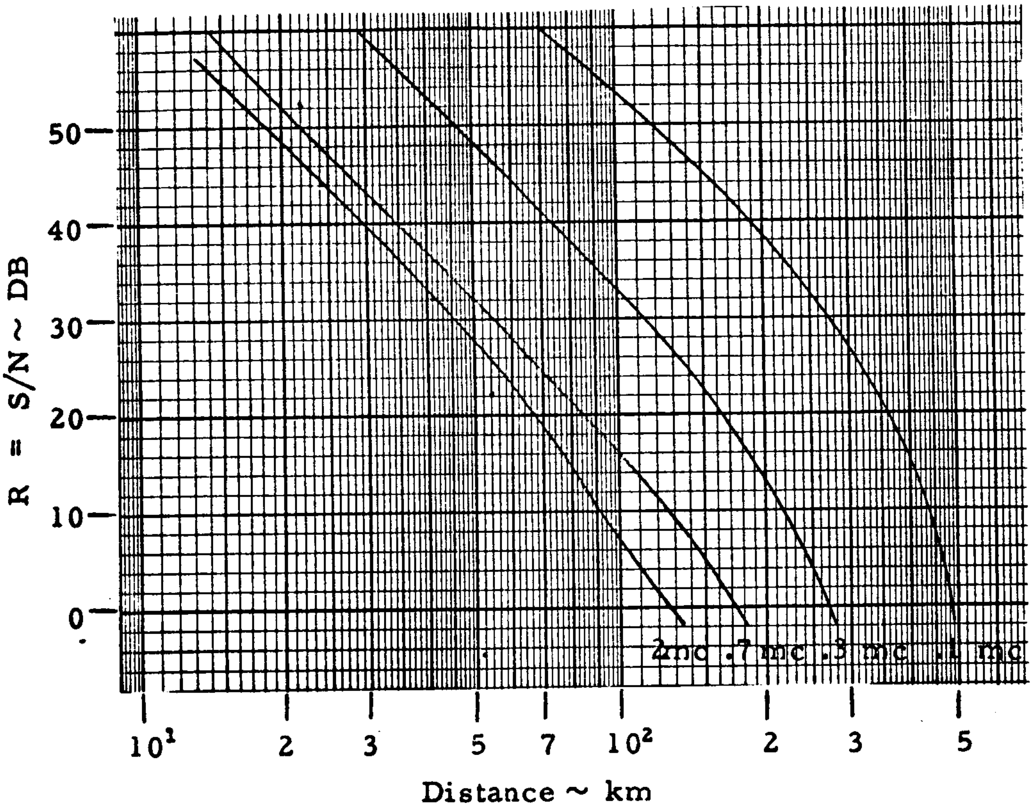
Vertical Polarization
CW Narrow - Band Signaling
SNR 15 DB
$\sigma = 10^{-3}$
$\epsilon_r = 2$

FIGURE 3-12. EFFECTIVE RADIATED POWER FOR NARROW-BAND SIGNALING



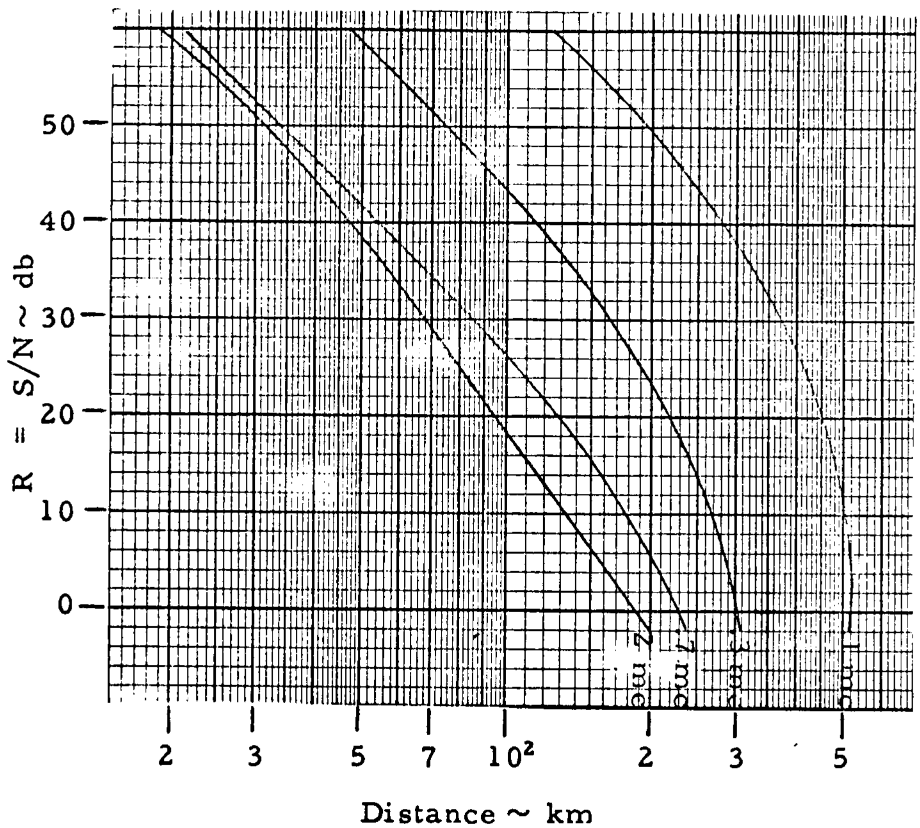
ERP = 10 dbw
Bandwidth 100 cps
$\sigma = 10^{-4}$
$\epsilon_r = 2$

FIGURE 3-13. SNR VERSUS DISTANCE FOR BW = 100 CPS AT 10 WATTS



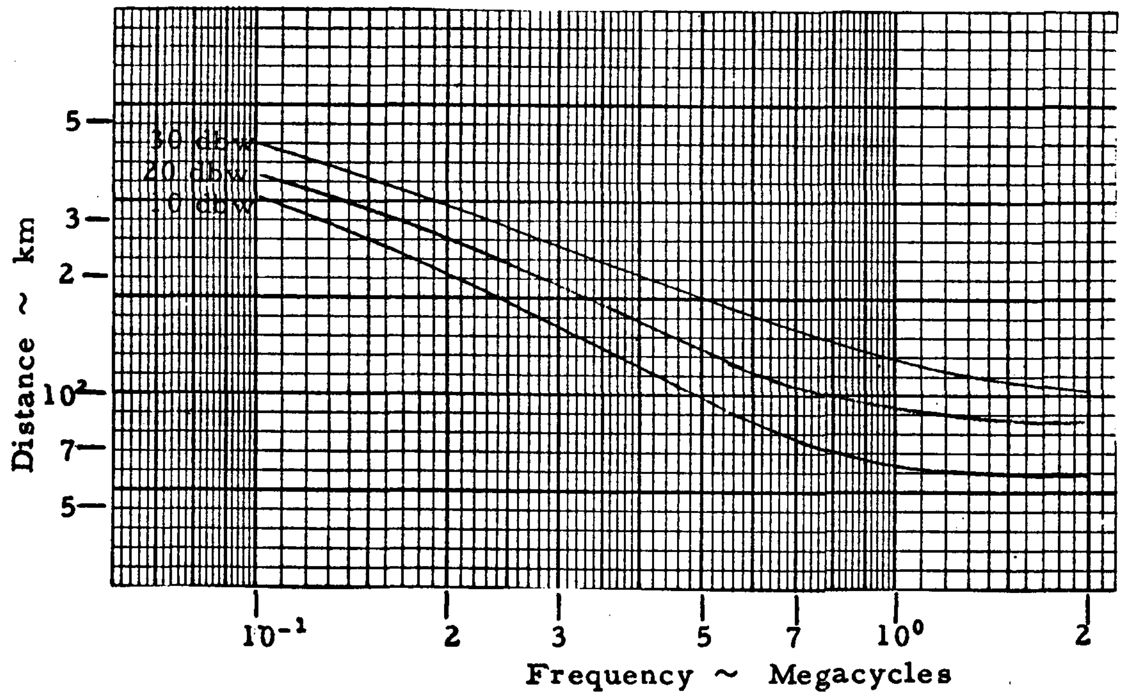
ERP = 20 dbw
Bandwidth 100 cps
$\sigma = 10^{-4}$
$\epsilon_r = 2$

FIGURE 3-14. SNR VERSUS DISTANCE FOR BW = 100 CPS AT 100 WATTS



ERP = 30 dbw
Bandwidth 100 cps
σ = 10^{-4}
ϵ_r = 2

FIGURE 3-15. SNR VERSUS DISTANCE FOR BW = 100 CPS AT 1000 WATTS



Vertical Polarization
Bandwidth 100 cps
SNR 15 DB
$\sigma = 10^{-4}$
$\epsilon_r = 2$

FIGURE 3-16. EFFECTIVE RADIATED POWER FOR NARROW-BAND SIGNALING

SECTION 4

MONOPOLE ANTENNA

The propagation of R. F. energy at medium-frequency is characterized by a high degree of stability and by the long range of useful signal transmission. One limitation that deters greater usage is the antenna length necessary to efficiently radiate power. The figures presented herein show a parametric analysis of all pertinent aspects encountered in the vertical radiator design.

Due to extensive length of antenna required for a quarter-wavelength at the frequencies in the medium-frequency band as illustrated in Figure 4-1, shorter antennas of less than a quarter-wavelength will be considered for practical application to the MOLAB. An omni-directional antenna (one producing essentially constant field strength in azimuth and direction radiation pattern in elevation) at lengths equal to and less than 0. 1 wavelength long was assumed for this study. Calculations made from fundamental equations (see appendix 4) were utilized in presenting this data. All equations are given in a chronological fashion in order that future use might be made of them.

4. 1 ANTENNA EFFICIENCY

As previously stated, presently designed medium-frequency antennas have greatly reduced transmission and receiving efficiencies when physically sized for mobile operations. However, the techniques of top loading, center loading, and tuning of whip antennas improve the capabilities. In the case of center loading the antenna efficiency remains approximately the same, but the gain is improved.

Antenna loading is assumed in all the following calculations to resonate the antenna because of the short length. The purpose of resonating either the antenna or the system as a whole is simply to facilitate feeding power to the antenna. Such resonating or tuning does not affect the antennas radiating properties. The various techniques, as stated earlier, employed in tuning are those of base, center, and top loading. For the purpose of this study base loading was chosen for investigation. The curves (Figures 4-2 through 4-7) show the characteristics for a base loaded whip antenna.

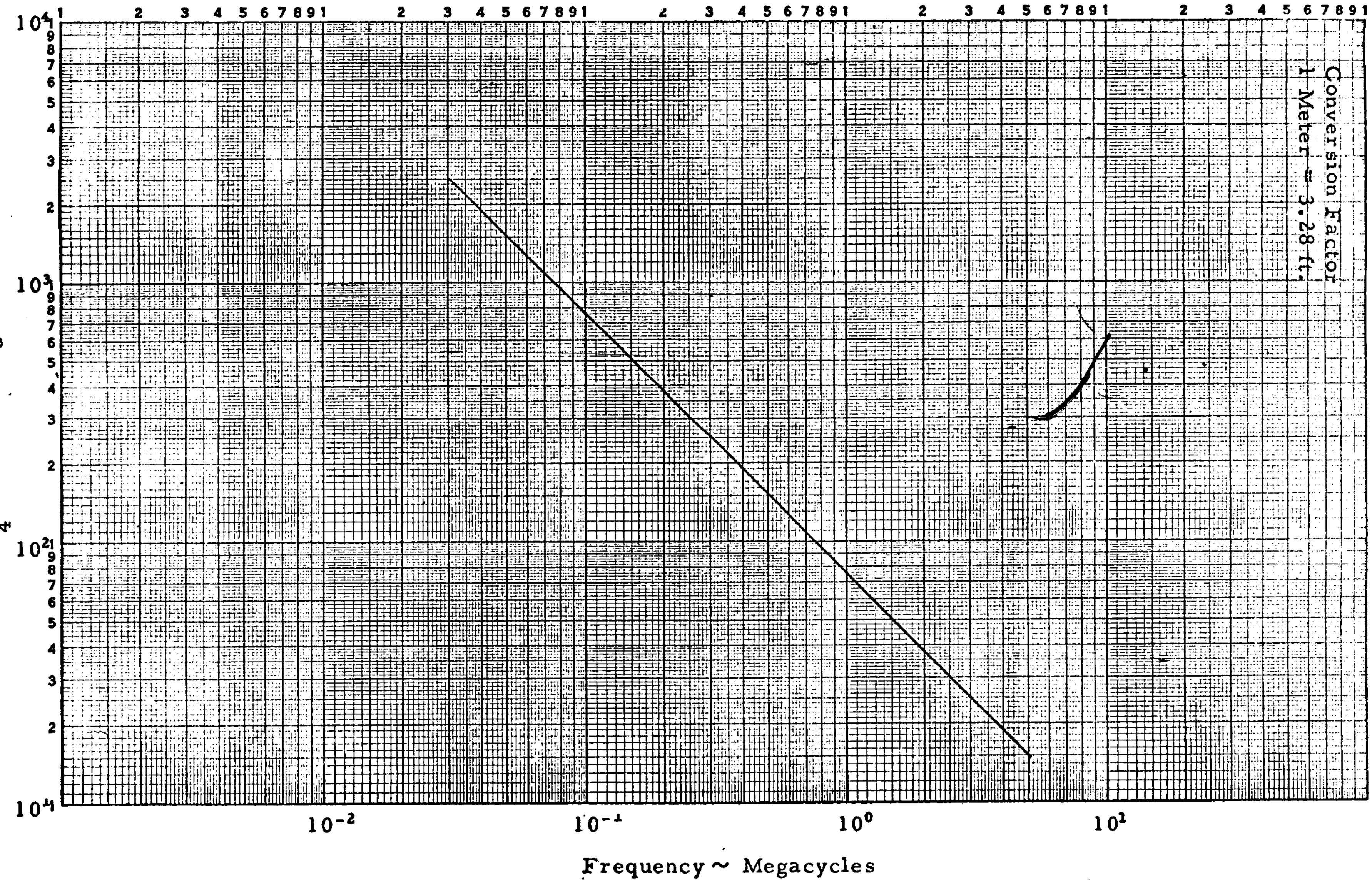


FIGURE 4-1. $\frac{\lambda}{4}$ WHIP ANTENNA VERSUS FREQUENCY

If center loading is utilized, the radiation resistance of the whip antenna can be approximately doubled at the lower frequencies which results from the ground loss having remained the same while the increased radiation resistance becomes a longer portion of the total circuit resistance. That is, the center-fed antenna behaves similar to a vertical antenna above a horizontal ground of infinite conductivity (Reference 4). This method was not used so that the poorer condition of base loading could be studied.

A digital computer program was written to investigate antenna efficiencies for grounded whip antennas less than 0.1 wavelength over a broad range under varying conditions. The first program covered range of antenna diameter from .25 to .75 inches in increments of .125 inches. Similarly, the frequency was taken from 1 to 3 mega cycles at increments of 0.5 megacycles, (likewise, the bandwidth of 2.5 to 6 kilocycles at increments of 0.5 kilocycles and the antenna lengths from 10 to 60 feet in increments of 10 feet). Further consideration was given to the program and it was concluded that the data obtained would be large in quantity with limited parameter variations. However, this program would be excellent for a detailed study on the antenna and its characteristics affected by these values. It was felt that a consideration of parameters similar to those previously stated would produce the same, if not better, results for this study. In this program, limits were taken on all the inputs except that of antenna lengths. The lengths ranged from 10 to 60 feet in 10 foot increments, thus allowing to plot length versus antenna efficiency with other data as the parameter. A diameter of .25 and .50 inches was taken as an upper and lower limit of a vertical radiator. A frequency of 1 and 3 megacycles at a bandwidth of 2.5 and 6 kilocycles was also used as upper and lower limits. This represented the best trade-off on the past study. The usefulness of this program is that it presents data in a parametric form.

The following Figure 4-2 represents the calculated efficiencies of a tuned vertical radiator operating in the medium-frequency band. The values were all computed for a vertical radiator equal to or less than 0.1 wavelength long. These values will serve for good approximations of the efficiency that can be expected from a vertical radiator at these frequencies and lengths. Throughout these percentage calculations, a base bandwidth of 2.5 kilocycles was assumed. It will be noted that a higher antenna efficiency is gained by selecting a narrower bandwidth (Figure 4-4). A good approximation of gain in efficiency canbe approximated by closely comparing Figures 4-5 and Figure 4-6.

4.2 ANALYTICAL RESULTS

It was determined that an increase in the diameter of the vertical radiator from 0.25 inches to 0.50 inches does not increase the efficiency of

PERCENT EFFICIENCY						
Freq. / Length	.3 mc	.5 mc	.7 mc	1 mc	2 mc	3 mc
60 feet	0.384	2.921	10.498	33.523	* ———	* ———
50 feet	0.228	1.744	6.446	22.677	84.348	* ———
40 feet	0.120	0.924	3.483	13.226	72.640	* ———
30 feet	0.052	0.407	1.552	6.206	52.583	85.907
20 feet	0.016	0.128	0.491	2.022	25.208	63.850
10 feet	0.002	0.017	0.068	0.286	4.413	19.073

* Antenna exceeds 0.1 λ

FIGURE 4-2. MEDIUM FREQUENCY ANTENNA EFFICIENCY CHART FOR A WHIP ANTENNA $<.1\lambda$ AT A BANDWIDTH OF 2.5 KC ANTENNA DIAMETER OF .25 INCHES the antenna to any measurable value. The resistance of the antenna varies with its length as well as with the ratio of its length to diameter. As the antenna is made thicker, the radiation resistance decreases. It is a known fact that the thicker antennas can be expected to show a lower reactance at a given height and thinner antennas should show more. However, in this case all antennas will have large capacitance reactance. Figure 4-3 illustrates the length versus the efficiency with the diameters of the antenna as the parameter. Behavior of antennas with different length to diameter ratios corresponds with the behavior of ordinary resonant circuit having different Q's. Thick antennas operate well over a comparatively wide band of frequencies. In considering an antenna for MOLAB use, one for only a single frequency, a thin antenna giving a high Q shows to be more profitable. Figure 4-4 illustrates length versus efficiency with the information bandwidth as the parameter. It is to be noted here that as the information bandwidth is increased the efficiency of the antenna is reduced. From this figure, by increasing the bandwidth from 2.5 k.c. to 6 k.c., the efficiency is reduced by approximately 17 percent. Figures 4-5 and 4-6 are the most important with the frequency being the parameter. Two cases are illustrated with an information bandwidth of 2.5 kilocycles and 6 kilocycles. As the frequency is increased, the efficiency of the antenna is increased. This is due to the fact that by increasing the frequency there is a corresponding increase in the radiation resistance, thus, improving the overall efficiency of the antenna. It must be remembered that at a frequency of 3 megacycles the efficiency of the antenna of Figure 4-6 is not valid above 33 feet. The reason for this is that all the data was computed for an antenna less than 0.1 wavelength long. Figure 4-7 is for the readers convenience. This illustration shows that the higher the Q of the circuit the higher the efficiency of the antenna. The Q of 300 and 600 are both plotted with base bandwidth of 2.5 kilocycles.

The illustrations presented herein are exhibiting some of the parameters affecting communications and are means of determining the radiation requirements for utilization in the medium-frequency. These illustrations are presented in order that the reader may fix parameters, use the curves and determine needed values for remaining parameters within the medium-frequency band. With these given illustrations and the efficiency chart of Figure 4-2, the reader is able to determine, with a reasonable degree of accuracy, most any power requirement or radiation efficiency. It must be kept in mind that much of the available data pertaining to Lunar communications have been derived from earth experiments and have, in turn, been analyzed using techniques employed for earth communications. Uncertainties concerning the Lunar ionosphere, troposphere, magnetic fields, noise temperatures and, most important, the soil conductivities (whose earth counterpart play such an

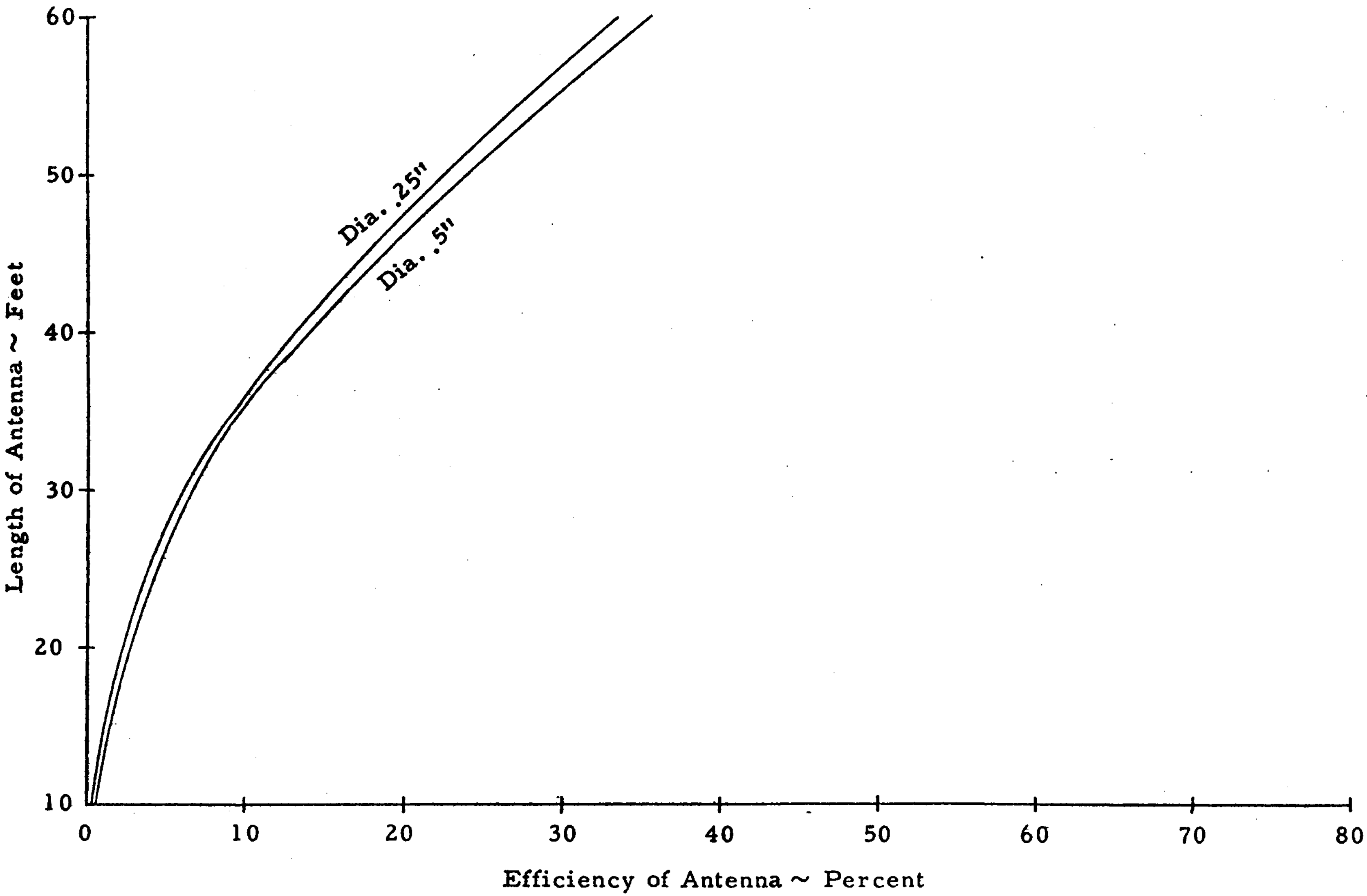


FIGURE 4-3. LENGTH VERSUS EFFICIENCY FOR WHIP ANTENNA WITH DIAMETERS OF ANTENNA AS THE PARAMETER

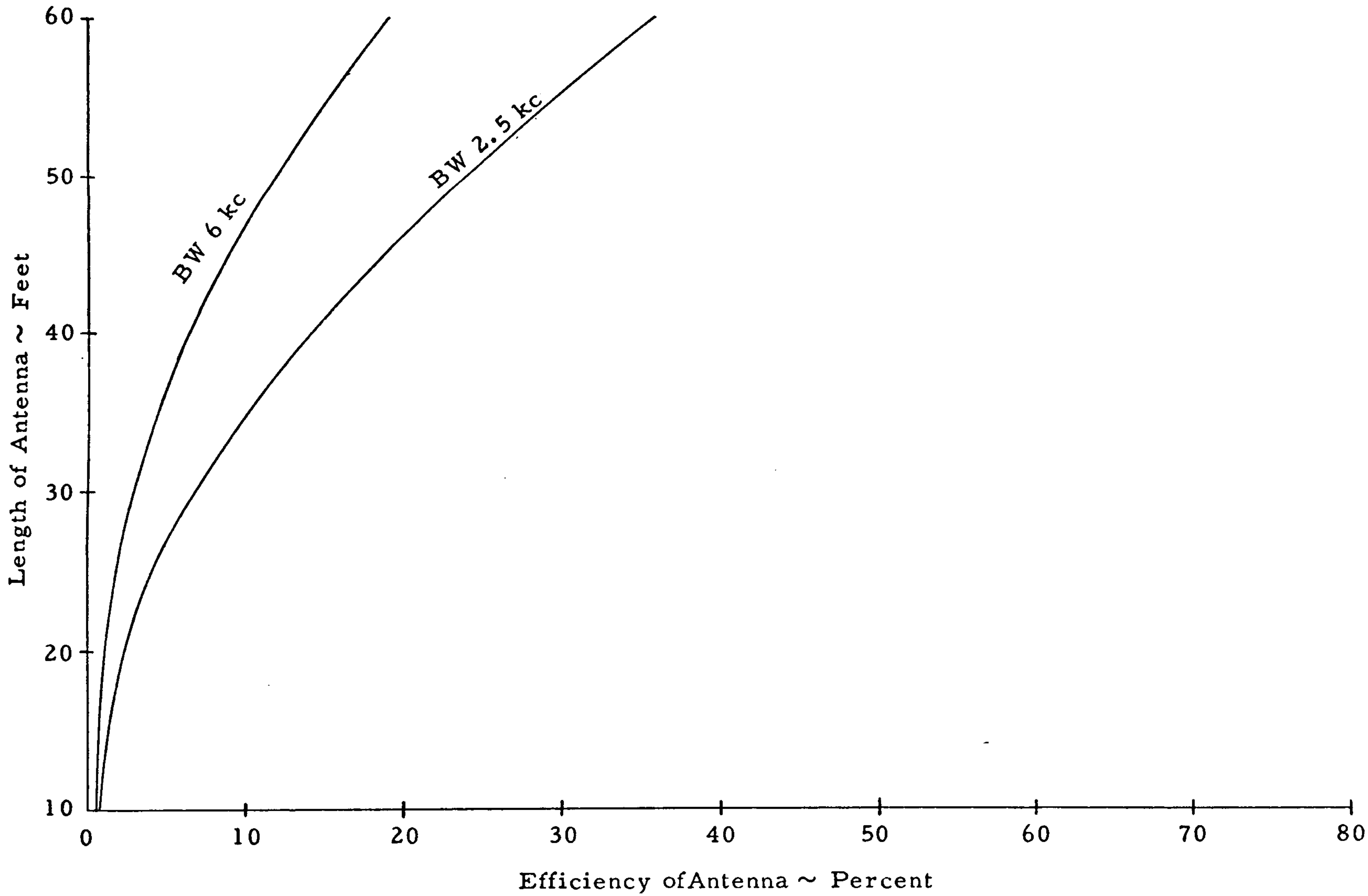


FIGURE 4-4. LENGTH VERSUS EFFICIENCY FOR WHIP ANTENNA WITH THE BANDWIDTH AS THE PARAMETER

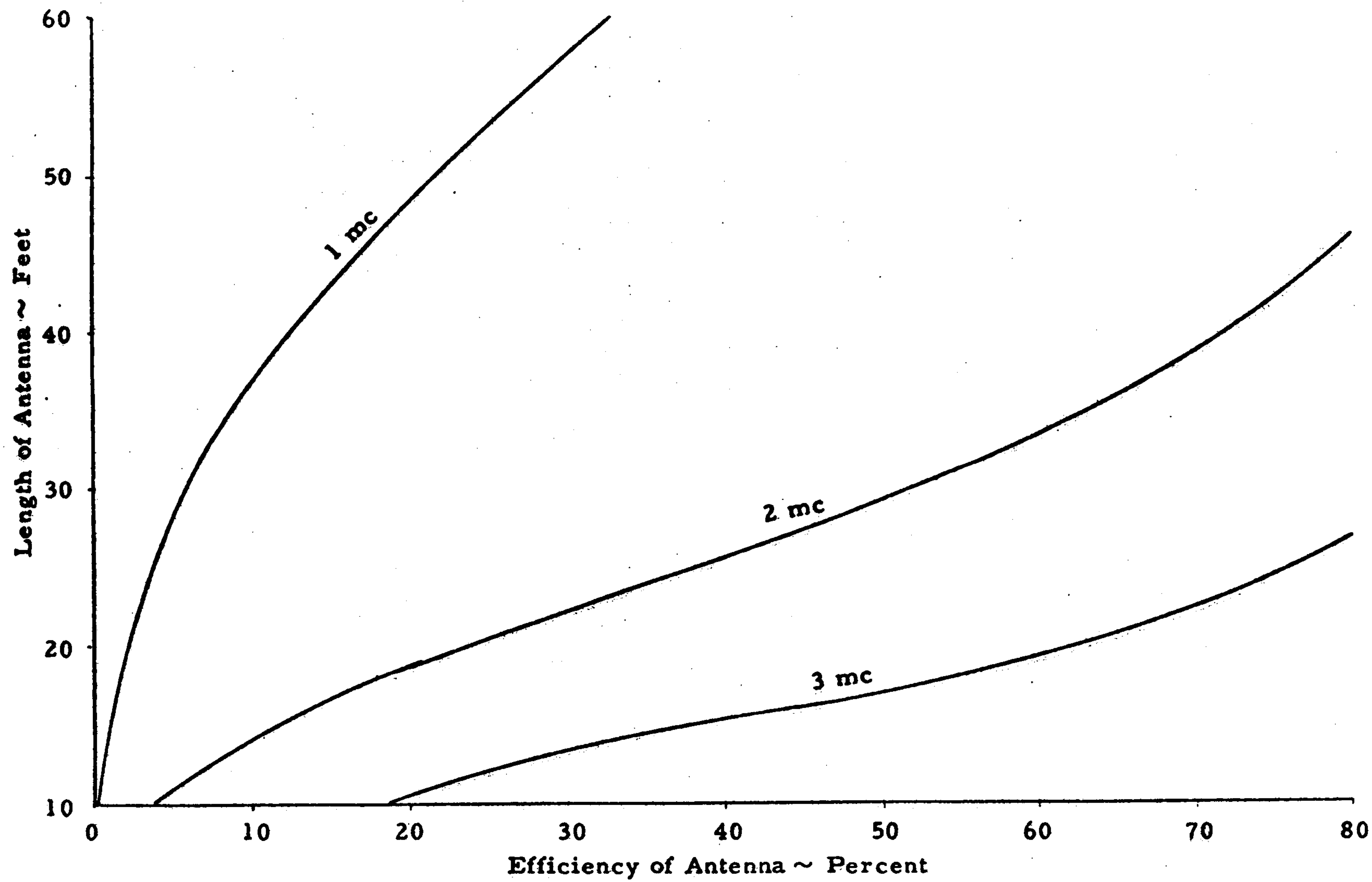


FIGURE 4-5. LENGTH VERSUS EFFICIENCY OF WHIP ANTENNA WITH THE FREQUENCY AS THE PARAMETER FOR AN INFORMATION BW OF 2.5 KC

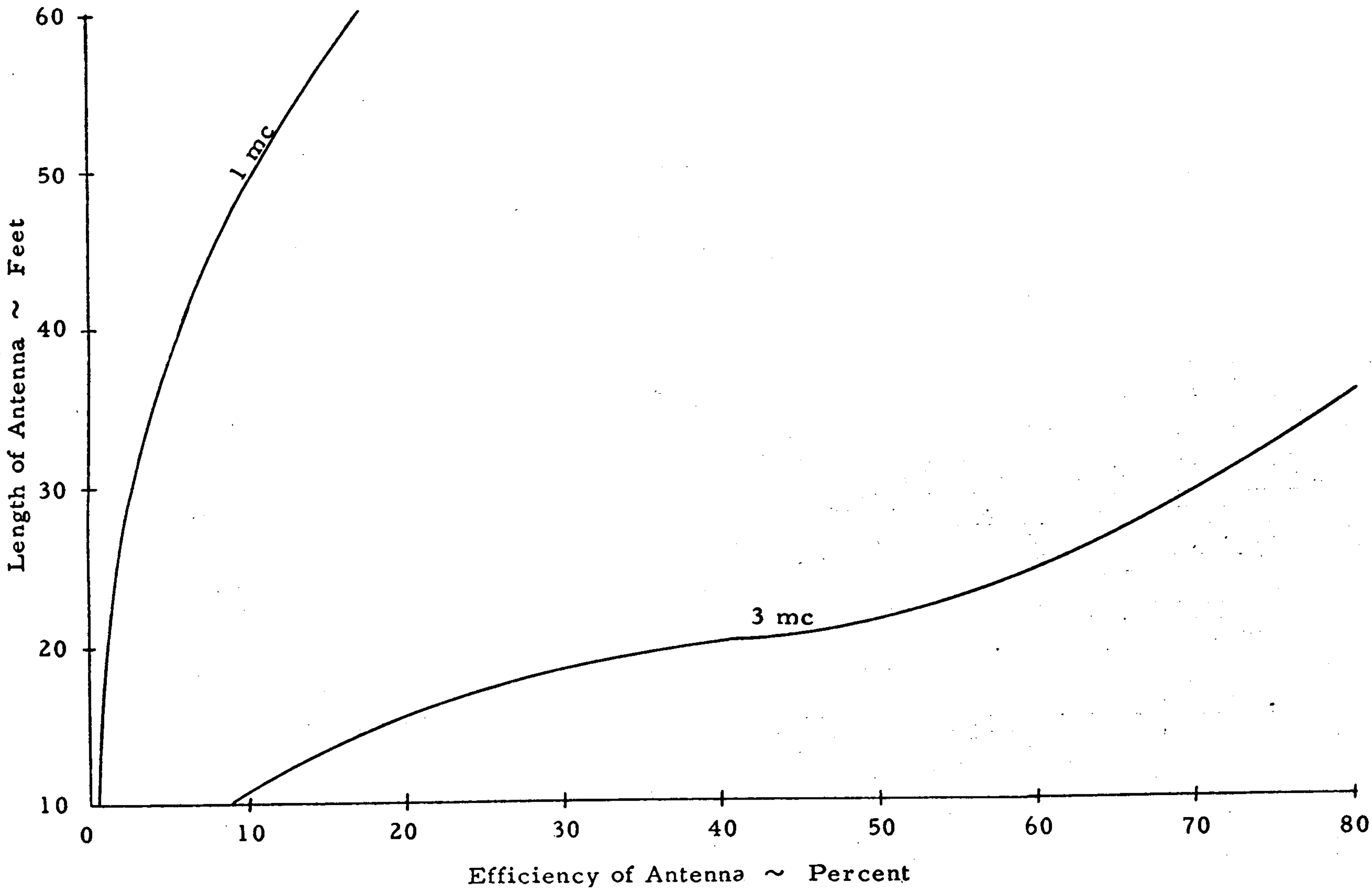


FIGURE 4-6. LENGTH VERSUS EFFICIENCY OF WHIP ANTENNA WITH THE FREQUENCY AS THE PARAMETER FOR AN INFORMATION BW OF 6 KC

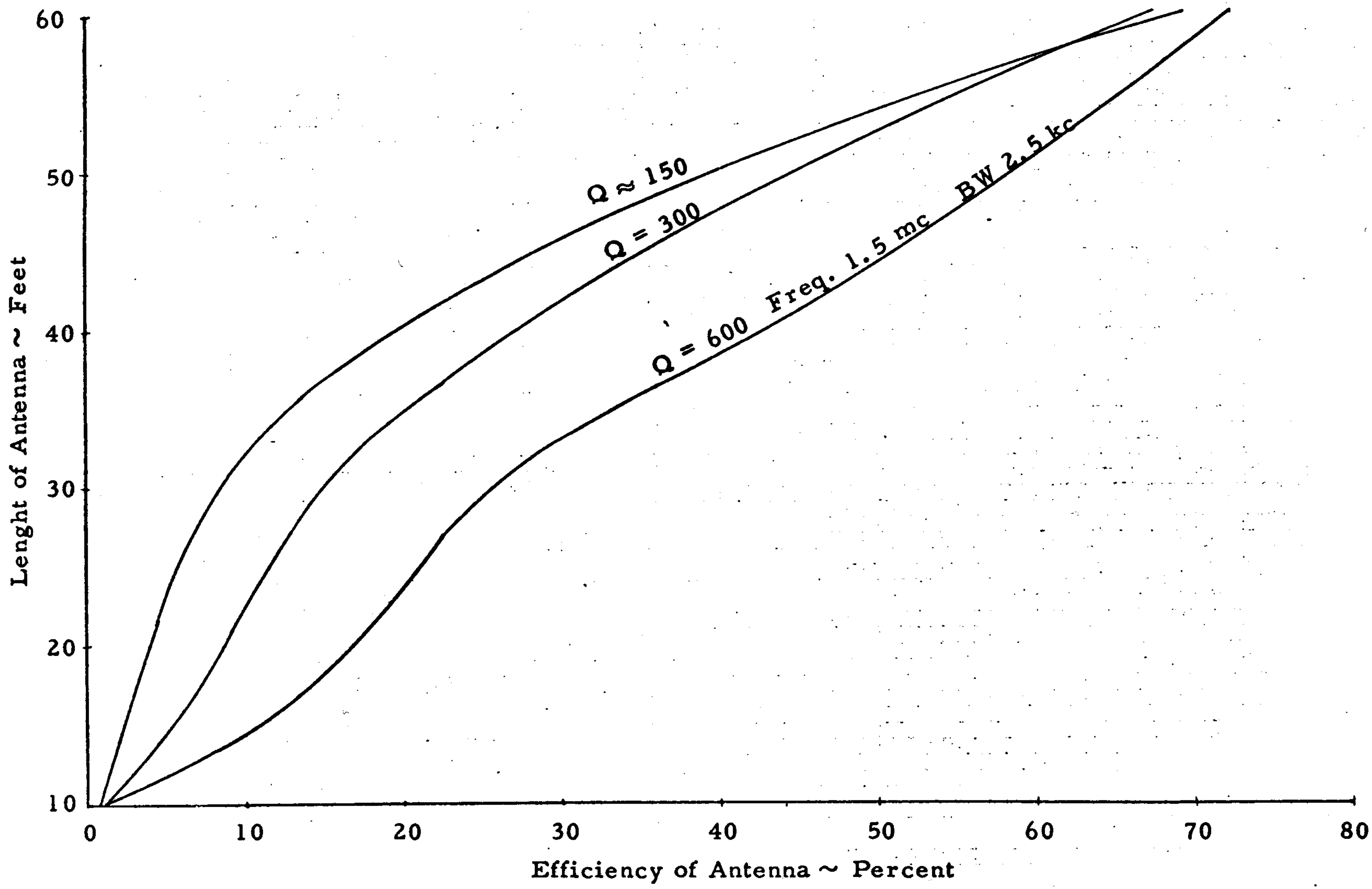


FIGURE 4-7. LENGTH VERSUS EFFICIENCY FOR WHIP ANTENNA <. 1λ WITH THE Q AS THE PARAMETER

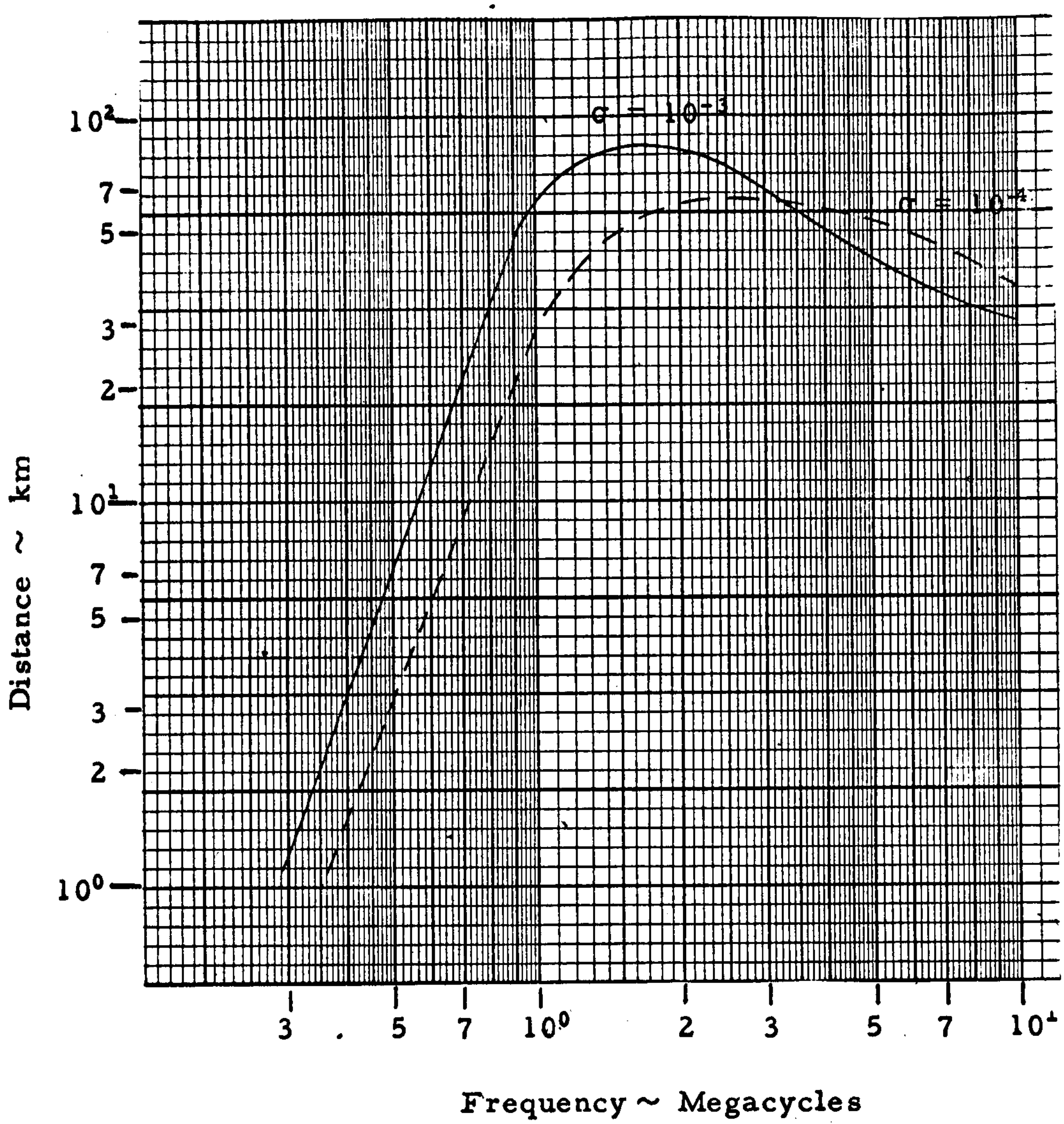
important role in designing earth communication systems), make precise design of Lunar communications dependent on how closely the assumed design parameters match those found on the moon. Senior and Siegel (Reference 1) have made calculations of the lunar soil by use of their theory of radar scattering by the moon and have found it to be within the region of 10^{-3} to 10^{-4} mhos per meter. Their values have been taken and used throughout this report as it represents the best estimate to date of the soil conductivity.

SECTION 5

OPTIMUM FREQUENCY

A 60 foot antenna was established as a reasonable length for the MOLAB. At this length and the low frequencies required to propagate over-the-horizon, the .1 wavelength is the most desirable from the length standpoint. Figure 5-1 illustrates the Optimum Transmitting Frequency for over-the-horizon Lunar communications. This curve is derived from Figures 3-2, 3-4, 3-6, and 3-8 of the primary power requirements, and Figure 4-2 of the efficiency chart for .1 λ (less than 60 feet) base loaded turned to resonance for an effective radiated power of 1 kilowatt. A bandwidth of 2.5 kilocycles at an assumed 15 db threshold requirement for AM utility is utilized. The positive slope of the curve represents that of a 60 foot antenna tuned to resonance while the negative slope of the curve represents exactly 0.1 wavelength tuned to resonance.

The figure shows distance versus frequency illustrating the optimum frequency for a conductivity of 10^{-3} and 10^{-4} mhos per meter. Attention is called to the curve of 10^{-3} mhos per meter where the optimum frequency is approximately 1.7 megacycles and 2.7 megacycles for a conductivity of 10^{-4} mhos per meter. For a one kilowatt radiated power, the maximum transmission range for the given parameters are 84 kilometers (52 miles) and 59.5 kilometers (37 miles) respectively. It is noted that the lower conductivities gives a reduced range which can be seen from Figures 3-4 and 3-8.



Vertical Monopole $\leq .1\,\lambda$
Effective Radiated Power 1 kW
Bandwidth 2.5 kc
SNR 15 DB
$\epsilon_r = 2$

FIGURE 5-1. OPTIMUM TRANSMITTING FREQUENCY

SECTION 6

SYSTEM WEIGHT ANALYSIS

A basic ground rule of 100 earth pounds was set for a medium-frequency system. After careful consideration and study had been given to the problem, it was determined that an MF system could be designed and built for the MOLAB within this rule. The radio transmitter and receiver should not exceed 75 pounds depending on how closely the designer selects his components. This estimate does not include any allowable weights for a power supply as it is assumed all power will be taken from fuel cells. Approximately 3 KVA will be needed for 1KVA output. It is believed, at this time, that heaviest component of the transceiver will be that of the power transformer. This item will most probably compose about half or more of the entire weight of the system. The modulator weight can be reduced somewhat by utilizing grid modulation, however, this technique produces a reduced audio quality with voice still being intelligible.

Figure 6-1 is an estimated weight for a medium-frequency power amplifier. This figure represents the best estimate to date of hardware of this type for aerospace application. Attention is called to the curve between the points of 100 watts. It will be noted that the curve rises sharply above 100 watts, indicating that the weight of a system becomes increasingly high at 1000 watts output. The points used in plotting this curve were taken from data furnished by Collins Radio and Hughes Aircraft. All the points do not fall on the illustrated curve as can be seen from the figure. It is believed that if a system were designed it would have the characteristic curve as shown in Figure 6-1.

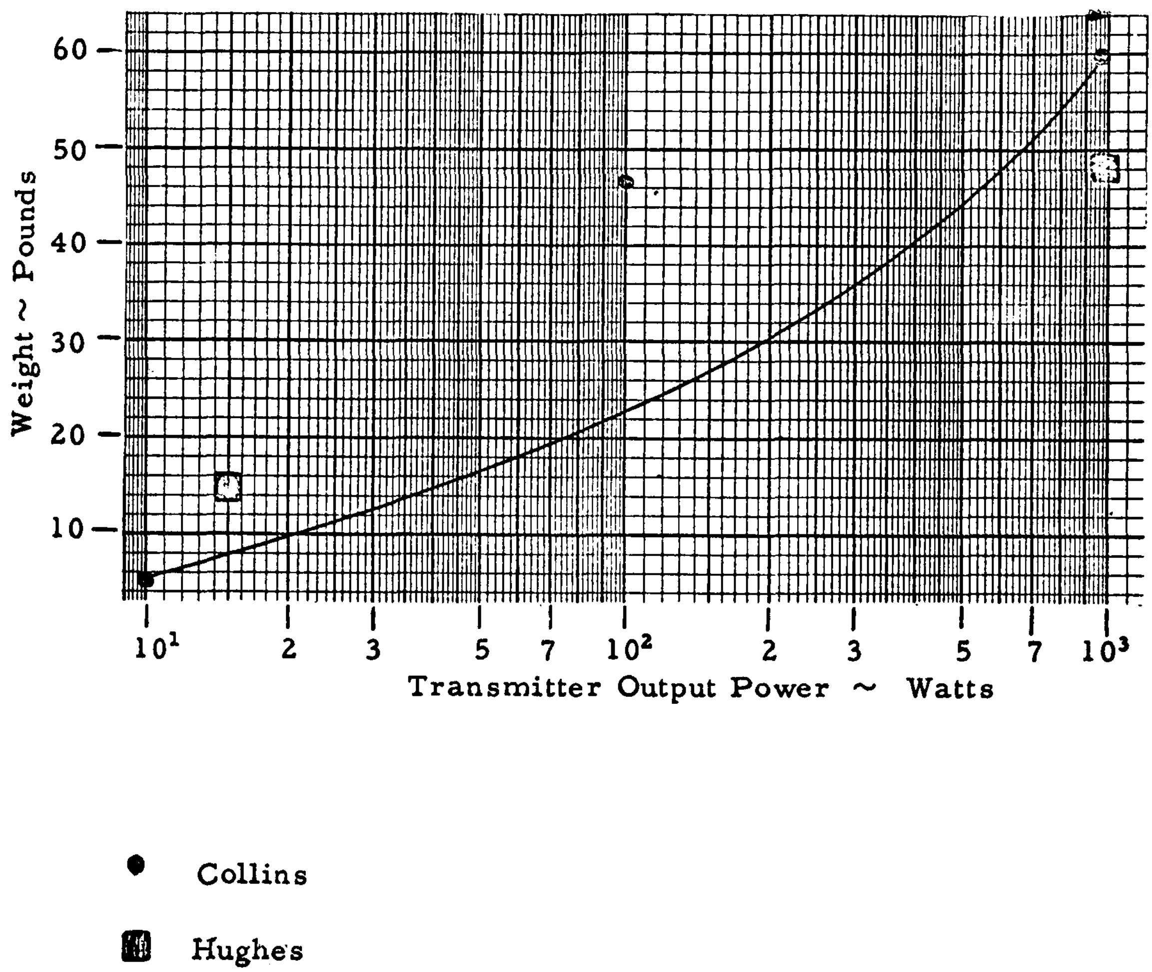


FIGURE 6-1. ESTIMATED WEIGHT FOR MF TRANSCEIVER

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3. "Page Communications Engineers, Inc., No. PCE-R-4541-0001A", "Utility of Lunar Groundwave Propagation", 30 November 1962.

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APPENDIX 4

The following equations were used in making the calculations. The capacitance of a vertical antenna shorter than a quarter wavelength is given by

$$C_A = \frac{17\,L}{\left[2.3\log_{10}\left(\frac{24\,L}{D}\right) - 1\right]\left[1 - \left(\frac{fL}{246}\right)^2\right]}$$

where C_A = capacitance of antenna in $\mu\mu f$

L = antenna height in feet

D = diameter of radiator in inches

f = operating frequency in MC

The approximate radiation resistance for an antenna less than 0.1 wavelength long was determined from

$$R_r = 273\,(lf)^2 \times 10^{-8}$$

where l is the length of the whip in inches, and f is the frequency in megacycles.

The inductance in henries is determined from the equation

$$L = \frac{1}{C\,\omega^2}$$

where C = capacitance in $\mu\mu f$

$\omega^2 = (2\pi f)^2$ with f in cycles per second.

The Q of the antenna is

$$Q = \frac{f_0}{B\,W}$$

where fo = operating frequency in cycles per second

BW = the circuit bandwidth in cycles per second.

The total resistance in the circuit is found from the equation

$$R = \frac{\omega L}{Q}$$

where R = $2\pi f$

L = inductance in henries

Q = resenance of circuit.

The efficiency of the antenna is defined as the ratio of the radiation resistance to the total resistance of the system. The total resistance includes radiation resistance, resistance in conductors and dielectrics (including the resistance of loading coils if used) and the resistance of the ground system, usually referred to as the ground resistance. For the purposeof this study, the ground resistance has been assumed to be negligible therefore, the equation for the efficiency is

$$\text{Efficiency} = \frac{R_r}{R_t}$$

where R_r = radiation resistance

R_t = total resistance of the circuit.

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