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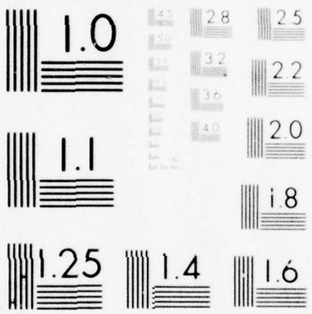
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Electromagnetics Engineering Office
Propagation Engineering Division
Technical Report EMEO-PED-77-5

GROUND-TO-AIR COMMUNICATIONS USING LINE-OF-SIGHT IN THE HIGH FREQUENCY BAND

by
George Lane
and
Charles Mason

March 1977

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GROUND-TO-AIR COMMUNICATIONS USING LINE-OF-SIGHT IN THE HIGH FREQUENCY BAND

Table of Contents

List of Illustrations

1. INTRODUCTION.

Ground-to-air radio communications using the high frequency (HF) band is a topic that has not received sufficient attention. Often times aircraft communications in this band appear to be a hit or miss affair. However, with today's knowledge of high frequency telecommunications, it is possible to provide for reliable HF ground-to-air communications. In order to accomplish this goal, a number of factors not normally considered in conventional point-to-point telecommunication systems must be considered. These factors include changes in elevation, azimuth and range of the aircraft as a function of time. Also it is vitally important for close-in radio contact to consider the skywave/line-of-sight fade region. HF ground-to-air communications using the skywave mode have distinct advantages over the VHF and UHF radio systems in that aircraft flying in the nap of the earth or at ranges well beyond the line-of-sight can be easily reached. Recent tests have shown that ground-to-air contact at ranges of 3000 NM can be consistently obtained using conventional radio equipment when proper frequency selection is used. But, in common practice, ionospheric telecommunications between ground terminals and aircraft are notably unreliable. This dichotomy in performance as shown by common practice and in well-engineered test systems is the stimulating force in the generation of this report. It is the intent of the authors that this series of reports will assist in the design, operation and understanding of ground-to-air communication systems using the HF band. This first report deals exclusively with the propagation engineering of ground-to-air communication links within the line-of-sight region.

2. BACKGROUND.

When possible, it is desirable to establish line-of-sight contact with aircraft. This mode of propagation for ground-to-air radio communications provides a signal that does not tend to fade and, generally, any frequency will propagate. The higher frequencies are more useful since the antennas are usually more efficient, physically smaller, have greater directivity and are easier to rotate for changes in azimuth. Furthermore, higher frequencies will not propagate via the ionosphere which reduces the likelihood of skywave/line-of-sight fading problems. The controlling factor for the mode of propagation is, of course, the distance at which line-of-sight can be maintained. Generally, contact via line-of-sight cannot be attained at ranges much beyond a few hundred nautical miles (NM) even though the aircraft is flying at a great altitude.

3. LOS RANGE FOR GROUND-TO-AIR COMMUNICATION.

3.1 Geometry of the path. The line-of-sight (LOS) range between ground and airborne terminals is determined by the geometry of the earth, the refractivity of the atmosphere which causes a slight bending of the radio waves and the altitude of the aircraft. Other factors, such as terrain clutter, antenna height, antenna pattern, etc., *must also* be considered. From the geometry depicted in Fig. 1, the range versus altitude relationship can be easily derived. From simple geometry, the relationship between arc length and the subtended angle is shown in Eq. (1)

$$D = 2\pi a\left(\frac{\theta}{360}\right) \tag{1}$$

First, the distance from the ground-based antenna to the horizon can be found by evaluating the subtended angle θ_1, such that:

$$\theta_1 = \frac{180 D_1}{\pi a} \tag{2}$$

Using the right triangle theorem,

$$\cos\theta_1 = \frac{a}{a + H_1} \tag{3}$$

Since H_1 is the height of the antenna, the distance to the horizon, D_1 can be obtained by substitution of Eqs. (2) and (3) into Eq. (1).

$$D_1 = \frac{\pi a}{180} \text{ arc cos }\left(\frac{a}{a + H_1}\right) \tag{4}$$

If an aircraft is flying at an altitude of H_2, which also can be defined as at an elevation angle, ψ, with respect to the ground-based antenna, then from the geometry shown in Fig. 1 and the Law of Sines:

$$\frac{H_2 + a}{\sin (90 + \psi + \theta_1} = \frac{H_1 + a}{\sin (90 - \theta_2 - \psi)}$$

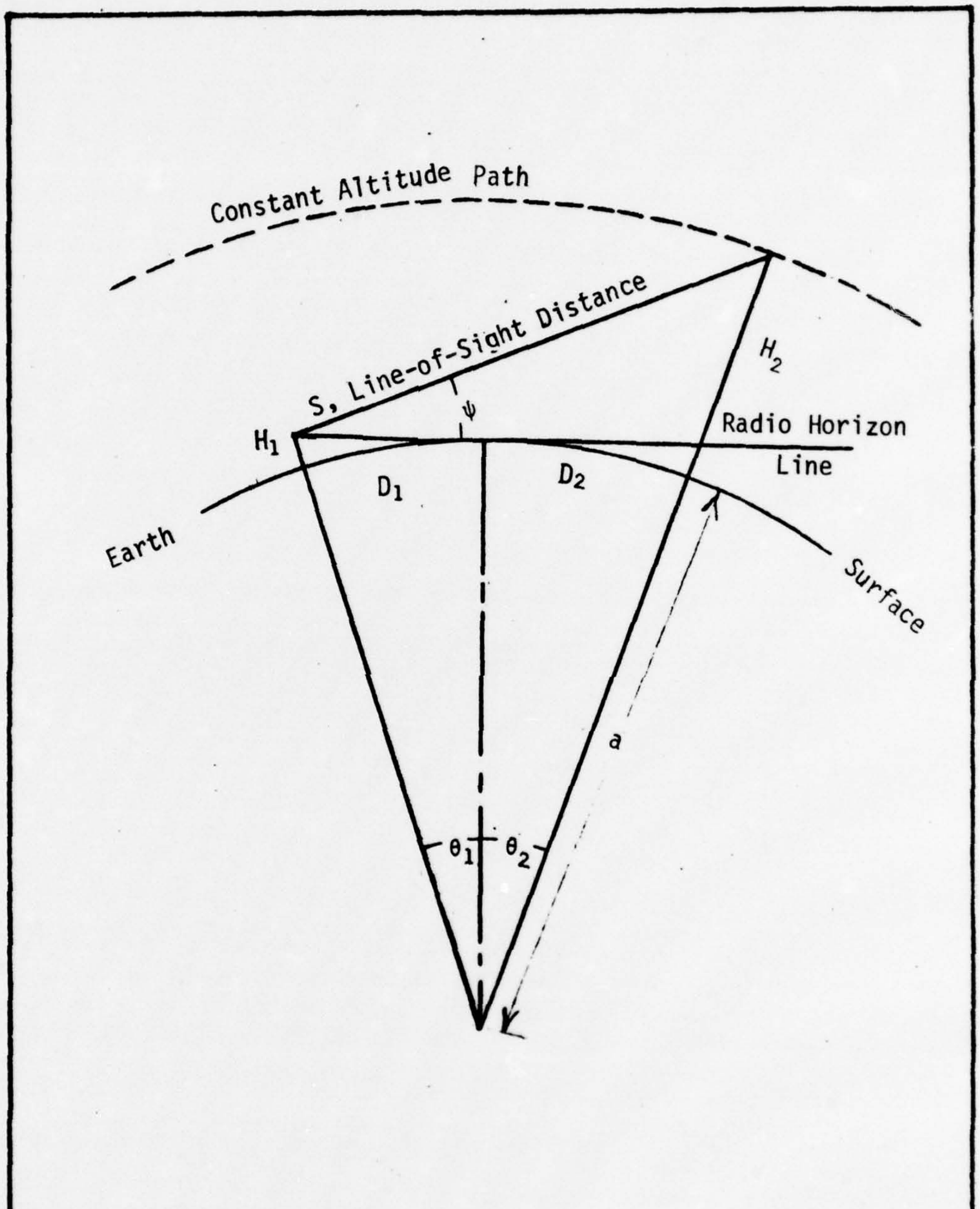

Fig. 1. Sketch showing the geometry for line-of-sight from a ground terminal at height, H_1, to an aircraft at altitude, H_2.

Simplifying yields Eq. (5):

$$H_2 = \frac{(a + H_1)\cos(\psi - \theta_1)}{\cos(\psi + \theta_2)} - a \tag{5}$$

where:

H_2 = altitude of the aircraft

H_1 = height of the ground-based antenna

a = effective radius of the earth

ψ = elevation angle from the ground-based antenna to the aircraft.

Using a similar approach the line-of-sight distance, s, from the ground-based antenna to the aircraft can be equated, as shown in Eq. (6):

$$S = \frac{(a + H_2)\sin(\theta_1 + \theta_2)}{\cos(\psi - \theta_1)} \tag{6}$$

Equation (6) can be solved by assuming either a variable ground range, $D = D_1 + D_2$, or a variable elevation angle. For example, if the separation distance, s, is desired for constant aircraft altitude, H_2, then by rearranging Eq. (5) the angle, θ_2, can be specified as:

$$\theta_2 = (\text{arc cos}\,(\frac{(a + H_1)\cos\theta_1 - \psi)}{a + H_2})) - \psi \tag{7}$$

Substituting Eq. (7) in Eq. (6) yields a solution for the line-of-sight separation distance, S , between the ground-based antenna and the aircraft for a constant value of aircraft altitude (H_2) and a specified elevation angle (ψ).

3.2 Effective Earth's Radius. Radio waves passing through the lower atmosphere tend to be bent by the gradient of the refractive index near the earth's surface. The net effect is that the line-of-sight distance for radio waves is greater than for the visible spectrum. In order to represent radio waves as travelling in straight lines, at least within the first kilometer above the earth's surface, an effective earth's radius has been defined.*[1] Accordingly, the effective earth's radius is given by Eq. (8):

$$a = a_0(1 - 0.04665 \exp(0.005577\,N_s))^{-1} \qquad (8)$$

where:

a_0 = earth's radius (6370 km)

N_s = surface refractivity value

In the work of Bean, et. al.[2], the surface refractivity values throughout the world have been reduced to a common elevation at sea level. These minimum monthly values of refractivity, N_0, at sea level are plotted on a world map in Fig. 2. To adjust the N_0 values for actual elevation, h_s, the following equation may be used:

$$N_s = N_0 \exp(-0.1057\,h_s) \qquad (9)$$

where:

N_0 = refractivity at sea level (obtained from Fig. 2)

h_s = elevation of the ground-based terminal in km

Most of the refraction or bending of the radio waves occurs at the lower altitudes, so it is appropriate to determine N_s for the lowest point on the communications path.[1] Thus h_s should be determined by the elevation of the ground terminal. Substituting N_s in Eq. (8) yields a value of the effective earth's radius generally equal to 1.333 a_0 or 8493 km. However, when the radio waves are directed at high angles or toward high flying aircraft, the total bending of the

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*References are listed numerically in the order of occurrence at the conclusion of this report.

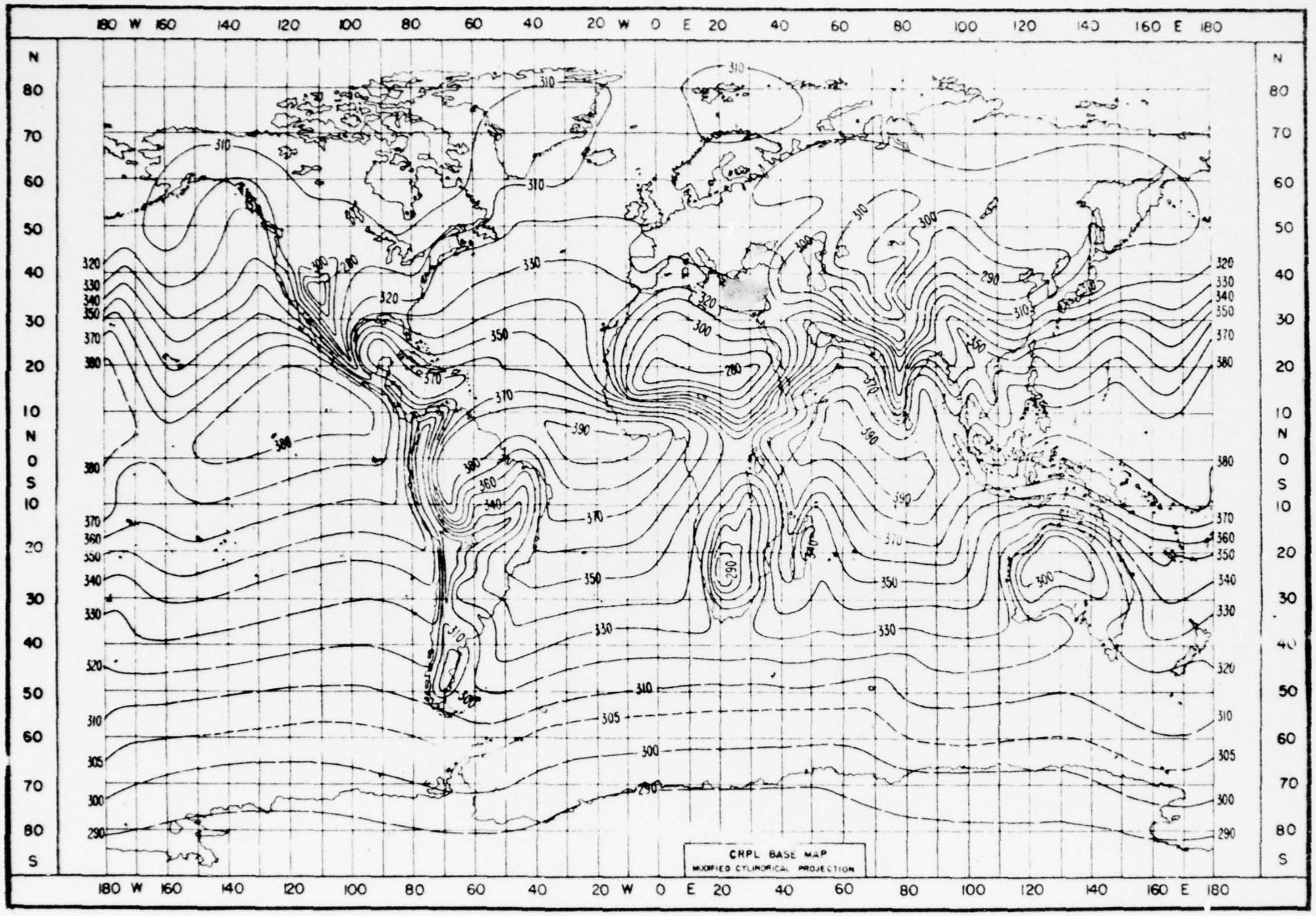

Fig. 2. Minimum Monthly Surface Refractivity Values Referred to mean sea level.[1,2]

ray path may be negligible. Also at frequencies below 10 MHz where the attenuation of radio waves may continue in a nearly constant manner for many kilometers above the earth the use of an effective earth's radius ranging between the limits of 1.3 to 1.0 times a_o is more descriptive.[3] In the lower portion of the HF band, the change in effective earth's radius as a function of frequency is shown from the work of Rotheram.[4] Generally in ground-to-air communications within the line-of-sight region frequencies in the higher portion of the HF band are used in order to avoid interference from the skywave mode. Therefore, in most applications, use of Eq. (8) for the effective earth's radius is recommended unless extremely high angles are encountered, aircraft altitudes of 5 to 15 km are involved and frequencies in the 2 to 4 MHz band are being used. In such exceptional cases the value of the effective earth's radius may be approximated from the values shown in Fig. 3.

3.3 Range Computation. The range and altitude at which an aircraft can be flying with respect to a ground terminal and still maintain radio line-of-sight is computed from Eq. (5) in paragraph 3.1. A computer program for such calculations is given in Appendix I. An example computation is given using this technique with the resulting range versus altitude data shown in Fig. 4. For the example problem, the following parameters are given:

a) Ground-based antenna height: 144 feet

b) Altitude of the ground-based station: 4810 feet above sea level

c) Surface refractivity reduced to sea level, N_o: 300

d) Minimum clearance angle to the horizon, ψ: 3 degrees

The problem is to determine for the given conditions the maximum range at which an aircraft can maintain radio line-of-sight to the ground-based antenna for aircraft elevations ranging from 5000 to 50,000 feet. The results of the evaluation of Eq. (5) using the computer program listed in Appendix I are shown in Fig. 4. As may be seen, the aircraft at 50,000 feet elevation can maintain line-of-sight radio contact with the ground terminal for a radius of 125 NM.

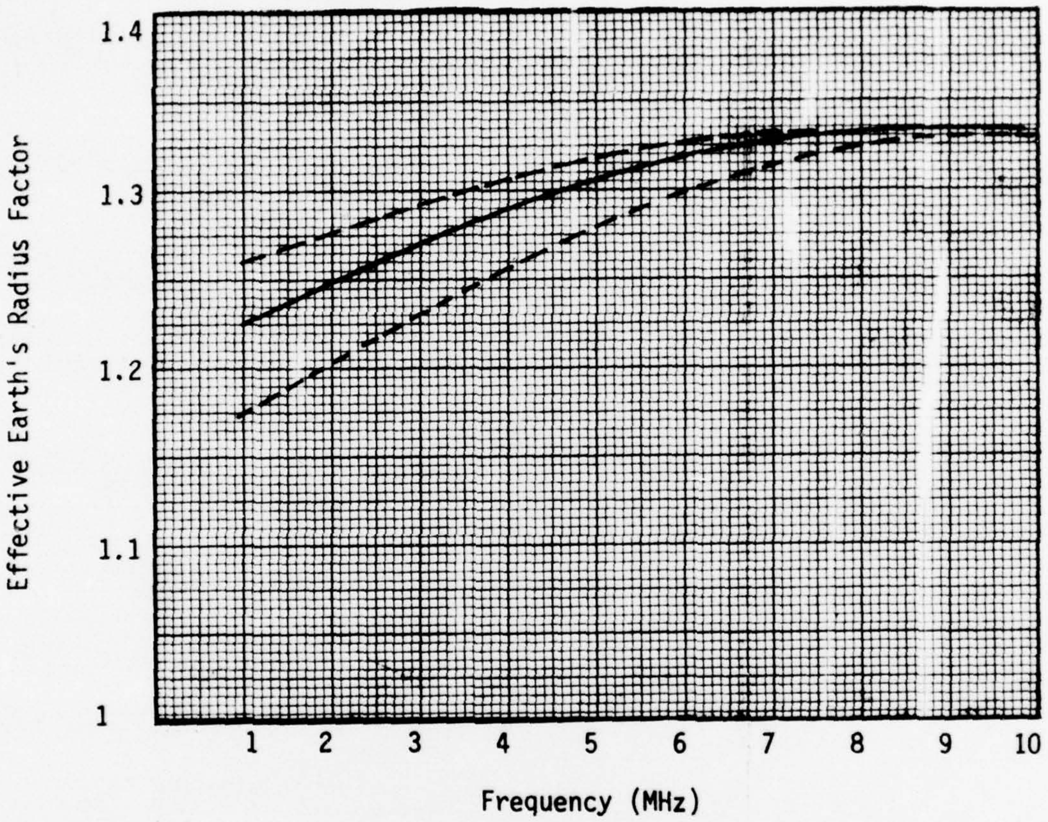

Figure 3. General Reduction of Effective Earth's Radius in the Lower Portion of the High Frequency (HF) Band (After Rotheram[4]).

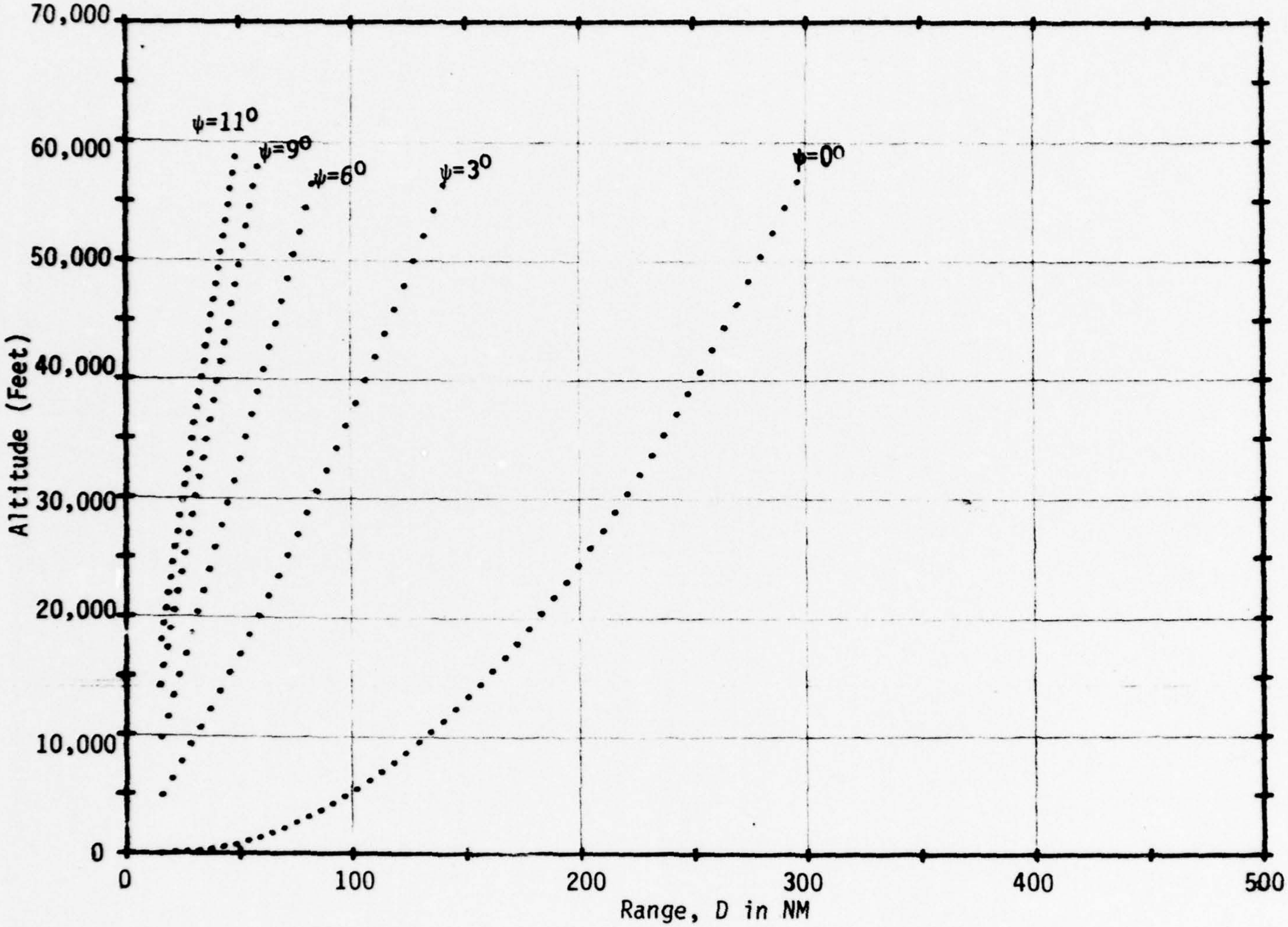

Fig. 4. Aircraft altitude versus radio line-of-sight range for various elevation angles (i.e., with respect to the horizon as seen from the ground-based antenna) using the data given in the sample problem (para 3.3).

4. RECEIVED SIGNAL POWER LEVEL.

4.1 Path Loss Calculation. Within the line-of-sight region, it is convenient to assume free space path loss between the ground-based antenna and the airborne receiver. For simplicity in the derivation of the path loss the ground-based antenna and the airborne antenna are given the radiation properties of an isotropic source and collector in free space. Then by definition the power radiated by an isotropic source is given by:

$$P_R = \frac{P_T}{4\pi S^2} \qquad (10)$$

where:

P_R = power density of the radiated energy (W/m^2)

P_T = power delivered by the transmitter (W)

S = distance (NM)

The power available at the receiver, P_a, can also be defined as:

$$P_a = \left(\frac{\lambda^2}{4\pi}\right) P_R \qquad (11)$$

where:

$\frac{\lambda^2}{4\pi}$ = the aperture of an isotropic collector

Consequently, for this free space example the power available at the receiver can be expressed in terms of the transmitter power and the separation distance, S, between the isotropic antennas, as shown in Eq. (12):

$$P_a = \left(\frac{\lambda}{4\pi}\right)^2 \frac{P_T}{S^2} \qquad (12)$$

From Eqs. (11) and (12), it is easy to compute the free space path loss, L_S, in decibels as a function of frequency in MHz and separation distance in nautical miles, such that:

$$L_S = -10 \log_{10} \frac{P_a}{P_T}$$

$$= -20 \log_{10} \left(\frac{\lambda}{4\pi}\right) + 20 \log_{10} S \qquad (13)$$

Since,

$$\lambda = \frac{0.16177}{F} \qquad (14)$$

where:

λ= wavelength in NM

F= frequency in MHz

then by combining Eqs. (13) and (14) and simplifying,

$$L_S = 37.81 + 20\log_{10}F + 20\log_{10}S \qquad (15)$$

4.2 General Equation for Received Power. Now for the situation of real antennas for which the far-field radiation pattern is known in terms of gain relative to an isotropic antenna in free space, the power available at the receiver and expressed as decibels above 1 watt can be computed from Eq. (16):

$$P_a = P_T - L_s + G_T + G_R \tag{16}$$

where:

P_a = 10 log P_a (dBW)

P_T = 10 log P_t (dBW)

G_T = gain of the transmit antenna (dBi)

G_R = gain of the receive antenna (dBi)

In the case of ground-to-air communications within the line-of-sight or space wave region, Eq. (15) can be rewritten in terms of the aircraft location such that:

$$P_a = P_T - 37.81 - 20\log F - 20\log\left(\frac{(a + H_2)\sin\theta_1 + \theta_2}{1.85325\cos\psi - \theta_1}\right) + G_{T(\psi)} + G_{R(-\psi)} \tag{17}$$

where:

P_T = 10 log P_t , P_t is the transmitter power in watts

F = frequency in MHz

a = effective earth's radius in km from Eq. (8) for F greater than 10 MHz and from Fig. 3 for F less than 10 MHz

H_2 = altitude of the aircraft in km

θ_1 = $\arccos\left(\frac{a}{a + H_1}\right)$; H_1 is the height of the ground-based antenna in km

θ_2 = $\left(\arccos\left(\frac{a + H_1\cos(\theta_1 - \psi)}{a + H_2}\right)\right) - \psi$

ψ = elevation angle of the aircraft with respect to the ground-based antenna

$G_{T(-\psi)}$ = transmit antenna gain for a height of H_1 above the earth and at an elevation angle of ψ

$G_{R(-\psi)}$ = receive antenna gain for the airborne antenna with respect to the elevation angle of ψ

5. COMPUTATIONAL TECHNIQUE.

5.1 General. A convenient method of obtaining the received signal levels at an airborne receiver which is flying at a constant altitude is to follow this computational outline:

a) Compute the subtended angle, θ_1, for a given antenna height, H_1, and the effective earth's radius from Eq. (8) or Fig. 3.

b) Compute the distance to the horizon for the ground-based antenna:

$$D_1 = \frac{\pi a}{180} \text{ arc cos } \left(\frac{a}{a + H_1}\right) \text{ (km)}$$

c) Select a value of ψ, the elevation angle with respect to the ground-based antenna.

d) Compute the subtended angle, θ_2, using Eq. (7) and the values of H_2 and ψ.

e) The distance along the earth from the horizon to the point directly under the aircraft is found from:

$$D_2 = \frac{\pi a}{180} (\theta_2)$$

f) The total earth distance in NM between the ground-based antenna and the aircraft is found from:

$$D = \frac{D_1 + D_2}{1.853} \text{ (NM)}$$

g) The received signal level expressed in terms of signal power (dBW) is found from Eq. (17).

5.2 Example Calculation.

5.2.1 Problem. Determine the received signal power level at the input to an airborne receiver within the line-of-sight region of a ground-based, horizontal, half-wave dipole antenna operating at 9.2 MHz at Ft. Huachuca, Arizona. The following information is given:

a) Aircraft altitude can vary from 10,000 to 50,000 feet. The elevation of the ground terminal is 4810 feet.

b) An azimuth of 52 degree from True North is of interest from the ground terminal.

c) The ground-based antenna is a horizontal, half-wave antenna, 144 feet high, with the antenna elements oriented at 90/270 degrees from True North. The antenna is tuned for resonance at 9.2 MHz. The ground beneath the antenna has a conductivity of 0.001 mho/m and a relative dielectric constant of 4.0.

d) The ground-based transmitter is capable of developing 400 W PEP. The coaxial cable between the transmitter and the antenna is 320 feet in length. The cable has a characteristic impedance of 72 ohms and an attenuation of 0.66 dB per 100 feet at 10 MHz. The balun is 92 percent efficient.

e) The aircraft antenna is assumed to have the characteristics of a lossless isotropic receptor. Losses in the transmission line are in the order of 0.5 dB.

f) No observable horizon obstructions occur on the azimuth of interest.

5.2.2 Atmospheric Conditions. The atmospheric conditions near the ground-based antenna produce the greatest effect on the radio waves so that the surface refractivity value, N_S, is computed from $N_o = 300$ and an elevation of $h_s = 4810$ feet for Ft. Huachuca. Using Eq. (9), N_S is found to be 256.9 which gives an effective earth's radius of $1.24 a_o$ or 7918 km. Since a frequency of less than 10 MHz is being used, the use of $4/3\ a_o$ is not recommended, as is shown by Fig. 2. But, the value obtained from Fig. 3 for the effective earth's radius is greater than the computed value. Therefore, the more conservative value of a = 7918 km is chosen. At this point it is possible to compute the distance from the antenna to radio horizon:

$$H_1 = 144 \text{ ft} \times 0.0003048 \text{ km/ft} = 0.0439 \text{ km}$$

$$\theta_1 = \text{arc cos} \left(\frac{7918}{7918 + 0.0439}\right) = 0.1908 \text{ deg}$$

$$D_1 = \frac{\pi 7918}{180} \times (0.1908) = 26.4 \text{ km}$$

5.2.3 Range. For this calculation it is assumed that the aircraft is flying at 50,000 feet and that the minimum usable elevation angle is 3 degrees *due to ground clutter normally* found even for "smooth" earth.* The ground distance between the aircraft and the antenna is:

$$H_2 = 50{,}000 \text{ ft} \times 0.0003048 \text{ km/ft} = 15.24 \text{ km}$$

$$\theta_2 = \text{arc cos} \frac{(7918 + 0.0439) \cos (3.0 - 0.1908)}{(7918 + 15.24)} - 3$$

$$= 1.5235 \text{ deg}$$

$$D_2 = \frac{=\pi 7918}{180} (1.5235) = 210.5 \text{ km}$$

$$D = \frac{26.4 + 210.5}{1.835} = 127.9$$

$$S = \frac{(7918 + 15.24) \sin (0.1908 + 1.5235)}{1.853 \cos (3 - 0.1908)}$$

$$= 128.2 \text{ NM}$$

5.2.4 Radiated Power. The ground-based transmitter is capable of developing 400 W PEP. However, 0.66 dB per 100 feet of that power is lost due to coaxial cable attenuation. Also the balun is only 92 percent efficient. Collecting the transmission system losses one obtains:

2.11 dB coaxial cable (320 feet)
.36 dB balun
2.47 dB transmission system loss

---

*Private correspondence with Mr. Alan S. Christinsin, Chief, Frequency Management Office, Headquarters AFCS/DOYF, Richards-Gebaur AFB, MO.

The power delivered to the antenna is:

$$P_T = 400 \times \log^{-1} \left(\frac{-2.47}{10} \right) = 226.5 \text{ watts}$$

$$P_T = 10 \log (226.5) = 23.55 \text{ dBW}$$

5.2.5 Antenna Pattern. The radiation pattern for the ground-based antenna can be determined in a number of ways (i.e., reference documents,[5] manufacturer's literature or numerical techniques[6,7]). A rigorous technique for thin wire antenna evaluation is available in the form of the USACEEIA Antenna Modeling Program. This computer program is a modified version of the Antenna Modeling Program developed for the joint services by MB Associates.[7] The numerical solution uses the method of moments for solving the field integral equations and the coefficient of reflection approximation technique for treating a finitely conducting earth plane. To use the USACEEIA Antenna Modeling Program, the specified antenna was quantitatively described, as shown in Table I. This information was encoded in the prescribed manner,[8] as shown by the card listing in Table II, and was processed on the Fort Huachuca CDC 6500 computer system using 39 seconds of central processor time per frequency. The radiation pattern for the desired azimuth of 52 degrees is shown in Fig. 5. At an elevation angle of $\psi = 3$ degrees, the computed antenna gain is minus 4.9 dBi. Furthermore the input impedance is shown to be 76.85 + j 1.48 ohms. In conjunction with the 72 ohms characteristic impedance of the transmission systems this mismatch results in a voltage standing wave ratio (VSWR) of only 1:1.07. With this low value of the VSWR the estimate of the transmission system loss, given in paragraph 5.2.4, should be quite accurate.

TABLE I. Description of the Ground-Based, Horizontal Half-Wave Dipole Antenna

a.	Antenna Height:	144 ft.
b.	Antenna Length:	51.9 ft.
c.	Antenna Wire:	AWG #10 (Copperweld)
d.	Wire Conductivity:	2.274×10^7 mho/m
e.	Separation distance from element ends to support towers:	20 ft.
f.	Support tower height:	150 ft.
g.	Support tower effective radius:	0.5 ft.
h.	Ground Conditions:	0.001 mho/m and $\varepsilon_r = 4.0$

TABLE II. Input Data for USACEEIA Antenna Modeling Program Analysis of the Ground-Based Dipole Antenna

```
CM        ****************************************************************************
CM        ****************************************************************************
CM        **                                                                        **
CM        **                                                                        **
CM        **                       GROUND-BASED ANTENNA                             **
CM        **                                                                        **
CM        **               HORIZONTAL, HALF-WAVE DIPOLE ANTENNA                     **
CM        **                                                                        **
CM        **                                                                        **
CM        **                                  DIMENSIONSN                           **
CM        **                                                                        **
CM        **                       LENGTH  51.9 FT.                                 **
CM        **                       HEIGHT  144 FT.                                  **
CM        **                       WIRE TYPE  AWG NO. 10                            **
CM        **                       WIRE CONDUCTIVITY  2.274 EXP 7 MHO/M             **
CM        **                       SUPPORT TOWERS  150 FT. HIGH                     **
CM        **                                                                        **
CM        **                 GROUND CONDITIONS -  0.001 MHO/M AND DIEL. CONST. 4    **
CM        **                                                                        **
CM        **                                                                        **
CM        ****************************************************************************
CM        ****************************************************************************
CM
CM
CM       1         2         3         4         5         6         7         8
CM345678901234567890123456789012345678901234567890123456789012345678901234567890
CE
GW  1   21       0.0    -25.97     144.0       0.0     25.97     144.0  0.004245
GW  2   10       0.0     -51.9       0.0       0.0     -51.9     150.0       0.5
GW  3   10       0.0      51.9       0.0       0.0      51.9     150.0       0.5
GS          0.3048
GE -1
GN  0    0                 4.0     0.001
LD  5                  2.274E7
FR  0    5                 8.8       0.1
EX  0    1   11    1     100.0                 1.0      72.0
RP  0   20    1            0.0      52.0       1.0
NX
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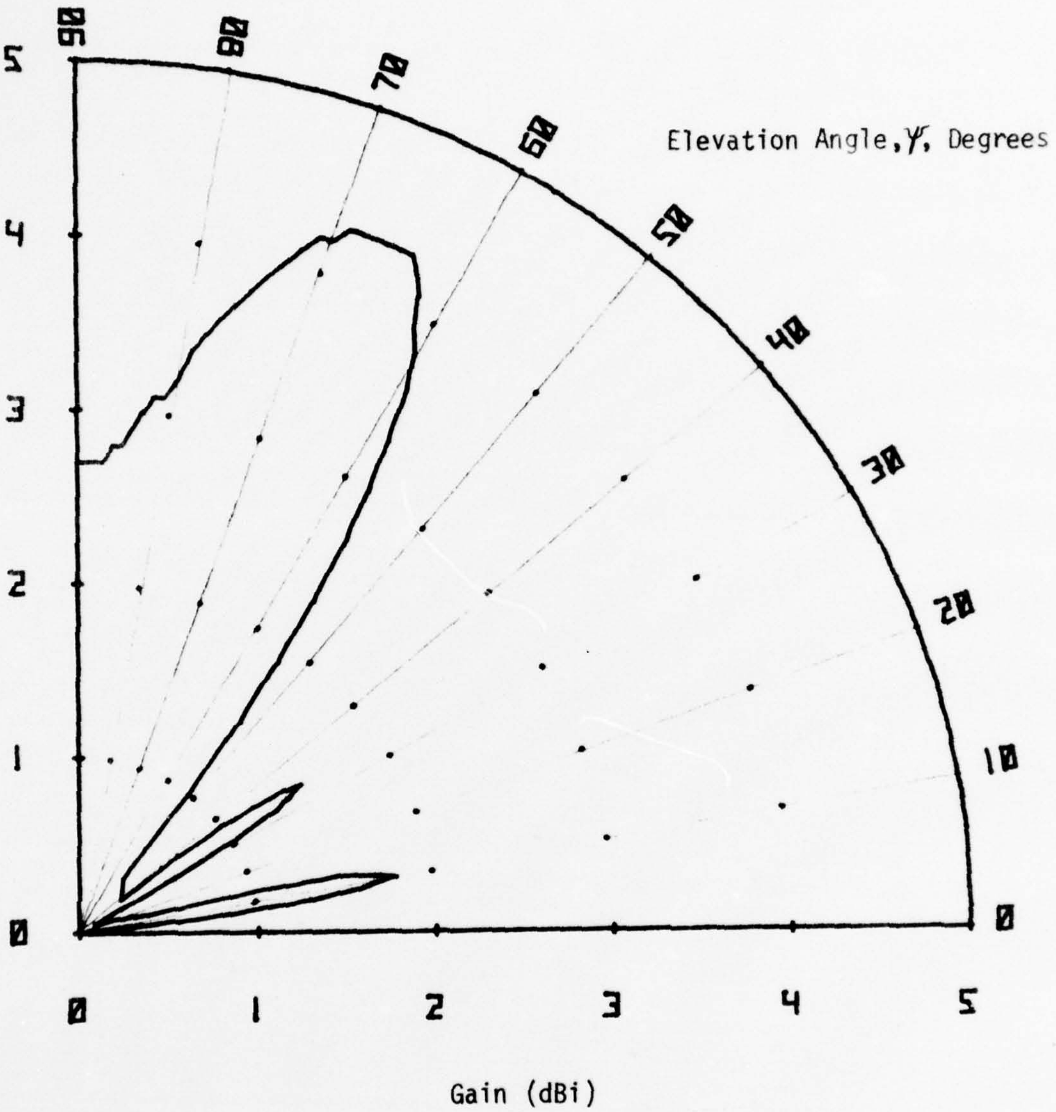

Figure 5. Radiation Pattern in the Vertical Plane for the Ground-Based Antenna at an Azimuth of 52 Degrees from True North (Gain Expressed in dB Relative to an Isotropic Radiator).

5.2.6 Received Signal Power Level. The received signal power level is computed using Eq. (17) and the values obtained for the variables of the example problem, such that:

$$P_a = P_T - 37.81 - 20 \log F - 20 \log S + G_{T(\psi)} + G_{R(-\psi)} \qquad (17)$$

where:

P_T = 23.55 dBW (see para 5.2.4)

F = 9.2 MHz (see para 5.2.1 (c))

S = 128.2 NM (see para 5.2.3)

G_T = -4.9 dBi (see para 5.2.5)

G_R = -0.5 dBi (see para 5.2.1 (e))

P_a = -81.1 dBw

A computer program has been prepared which will evaluate Eq. (17) using radiation pattern cards produced from the USACEEIA Antenna Modeling Program. A listing of "Power for LOS to Aircraft" is given in Appendix II. Using this program a family of curves are obtained, as shown in Fig. 6, for the received signal power level as a function of aircraft range and elevation. The curves are extended to a lower limit of ψ = 1 degree. The remaining variables are the same as those given for the example problem.

5.3 Communications Capability. Knowledge of the received signal power level does not necessarily determine the communications capability for the HF radio system. Generally the communications capability is determined by the signal power relative to noise power at the input of the HF radio receiver. Two primary sources of noise affect HF radio; these are atmospheric and man-made noise. However, for aircraft precipitation static, which is created by charged particles striking the antenna or fuselage, can become the controlling noise source.[9] Recent studies indicate the noise introduced into an aircraft HF receiver exceeds that of "rural level" of man-made noise.[10] This can be accounted for by the large number of electrical devices on a large, modern aircraft. Also, the aircraft antenna can

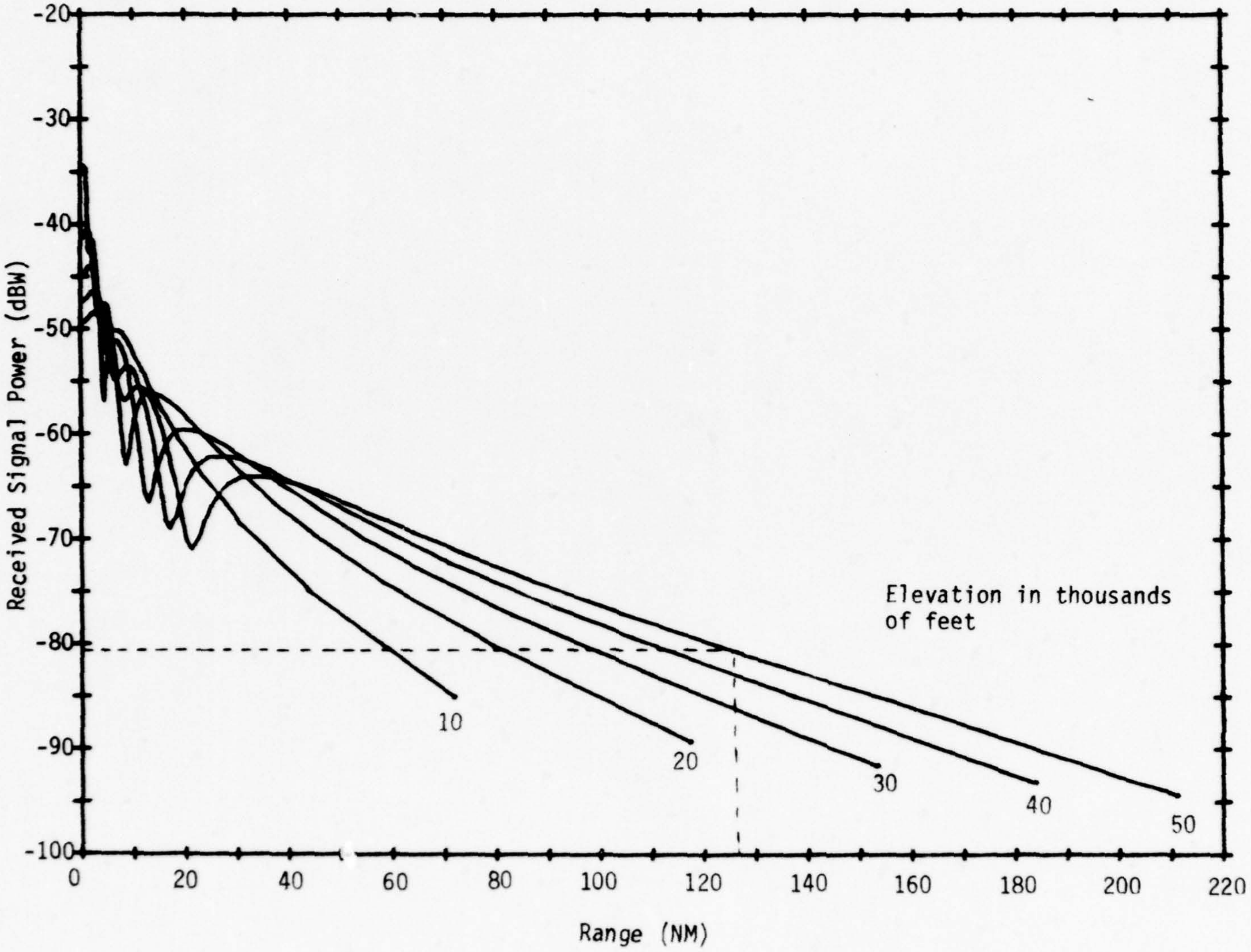

Figure 6. Received Power Level at the Aircraft for Various Altitudes and Ranges

experience a height-gain effect that increases the received noise levels from urban areas as far away as 100 miles.[11] Turning to the example problem, the highest level of atmospheric noise is expected to occur during summer nights. The level of -154 dBW is not expected to be exceeded for more than 10 percent of the time.[14] For a voice circuit using single sideband HF equipment a required signal-to-noise ratio of 48 dB in a 1 Hz noise power bandwidth is accepted as the level that will afford a 90 percent sentence intelligibility.[15] This requires that the received signal power level must exceed -101 dBW. Since atmospheric changes can cause signal level variation, a fade margin should be considered. If a fade margin of 10 dB is assumed, then the maximum range for reliable line-of-sight radio contact using a single channel voice circuit and HF SSB equipment tuned to 9.2 MHz is established when the predicted received signal power level is -91 dBW for the example problem. As may be noted in Fig. 6, voice contact is possible then within the entire line-of-sight range for the antenna specified and for aircraft flying at altitudes of 50,000 feet or less. Actually one might expect that radio contact at greater ranges may also be afforded but since that requires propagation beyond the radio horizon it cannot be addressed with the theory presented here. Let it suffice to say that satisfactory radio contact with an aircraft at an altitude of 50,000 feet and 127.8 NM to the NE of ground-based terminal is predicted with a high degree of confidence.

6. DISCUSSION.

6.1 Validity. The approach given in this report is reasonably valid for estimating the usable line-of-sight region in a ground-to-air communication system.[16] In that the minimum monthly surface refractivity is recommended for use in the computation of the effective earth's radius, the results will be somewhat conservative. Use of the elevation of the ground terminal as the reference point for computing the surface refractivity is not perhaps as accurate as using the elevation of the point where the radio horizon line is tangent to the earth. However, in ground-to-air system calculations it is not customary to allow the usable line-of-sight region to extend down to the radio horizon line ($\psi = 0$ degrees). Therefore, the elevation, h_s, of the ground terminal is recommended for use in computing the surface refractivity. It is also recommended that the ray approach used in this report should not be applied when the elevation angle relative to the horizon is less than:[17]

$$\psi_{MIN} = \arc \tan \left(\frac{0.01777}{F^{1/3}}\right) \qquad (18)$$

At angles less than ψ_{MIN}, divergence of the direct wave and the ground reflected wave from a spherical earth causes the received signal levels to be less than ray theory would predict.[16] Accordingly for the HF band values of ψ should not be less than 0.3 degrees at 30 MHz and 0.7 degrees at 3 MHz. Normally, ground clutter is assumed to be even more of a problem. A standard horizon of 3 degrees is generally assumed for flat land while a minimum horizon angle of 3 degrees plus the angle to the obstruction is used for rough terrain. With this criteria, the resultant received signal power levels in the line-of-sight region should be quite accurate. The antenna radiation patterns generated by the Antenna Modeling Program include accurate estimations of the ground reflected wave and will incorporate surface wave field components, if desired.

6.2 Other Propagation Mechanisms. Beyond the line-of-sight region, the field strength does not immediately drop to zero. Diffraction and scattering modes exist especially at frequencies greater than 5 to 10 MHz. At the lower frequencies the surface wave can be substantial even at great altitudes. Atmospheric changes can cause tropospheric scattering even at frequencies as low as 1.5 MHz at 200 km or more which may occur within the line-of-sight region.[3]

However, the greatest concern is for the presence of ionospheric reflections which can occur either in the line-of-sight region or beyond. Ionospheric reflections or skywave signals can be a serious source of interference. Rapid temporal changes of the ionosphere cause skywave signals to vary in amplitude and phase. These signals in the presence of direct waves having nearly constant amplitude and phase at a given range can cause 30 to 40 dB fades occuring many times over a time span of a minute. Within the line-of-sight region frequency usage above the critical frequency of the ionosphere should be used in an attempt to avoid skywave interference. Also, at these higher frequencies the surface wave should be 40 dB or more below the free space field strength except for very low flying aircraft having antennas receptive to vertically polarized waves.[18]

7. CONCLUSIONS.

A relatively straight forward approach is presented for estimating ground-to-air communications capability using line-of-sight in the HF band. The approach allows for the incorporation of the antenna pattern as determined numerically by the USACEEIA Antenna Modeling Program. Two computer program listings are provided: one for determining the line-of-sight range to an aircraft and the other for predicting the received signal power level at the aircraft. Example solutions are also provided. With the procedures given the line-of-sight coverage region of a ground-based station to aircraft flying at least 3 degrees above the radio horizon line can be rapidly determined with reasonable accuracy. Generally, the method of prediction is conservative and therefore represents a best estimate for long-term planning purposes. The time variability of the received signal is not addressed nor is the seasonal variation of the refractive index taken into account. It is felt that the variation in atmospheric radio noise levels in the HF band and the generally unknown qualities of the aircraft antenna and its orientation over-ride the variability of the signal level. Further refinement of the prediction technique will require extensive knowledge of the system characteristics and the local atmospheric environment.

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APPENDIX I

Listing of Computer Program titled:

LOS Range to Aircraft

Programmer: Charles Masen
Date: 9 March 1977
Computer: HP-9830

```
10 DIM Z$[3],U$[2],P$[4],D$[4],A$[40],XS[250],YS[250],W$[40],T$[40],B$[40]
20 DIM X$[40],Y$[40],E$[40]
30 REM LOS TO AN AIRCRAFT
40 REM THIS PROGRAM WILL DETERMINE AIRCRAFT ALTITUDES ABOVE EARTH SURFACE
50 PRINT
60 PRINT
70 PRINT
80 DISP "ELEVATION ANGLE,W";
90 INPUT W
100 DISP "GEOGRPHCL SURFCE REFRACTIVTY,N0";
110 INPUT N0
120 DISP "ANTENNA HEIGHT,FT";
130 INPUT H
140 PRINT "ANTENA HEIGHT,H=";H,"FT"
150 PRINT
160 PRINT "GEOGRAPHICAL SURFACE REFRACTIVITY,N0=";N0
170 PRINT
180 PRINT "ELEVATION ANGLE,W=";W,"DEGREES"
190 PRINT
200 A0=6370
210 DISP "CALCULATE SURFCE REFRACTIVITY,NS";
220 INPUT Z$
230 IF Z$="Y" THEN 260
240 N1=N0
250 GOTO 290
260 DISP "ANTENNA ALTITUDE AT SEA LEVEL,KM";
270 INPUT H1
280 N1=N0*EXP(-0.1057*H1)
290 DISP "UNITS IN KM OR MI";
300 INPUT U$
310 DISP "STARTING DISTANCES";
320 INPUT S0
330 DISP "DISTANCES INCREMENT";
340 INPUT S1
350 DISP "ENDING DISTANCES";
360 INPUT S2
370 PRINT
380 PRINT "SURFACE REFRACTIVITY,NS=";N1
390 PRINT
400 A=A0/(1-0.04665*EXP(0.005577*N1))
410 PRINT "EFFECTIVE EARTH RADIUS, A=";A,"KM"
420 PRINT
430 PRINT
440 FORMAT 17X,"RANGES",14X,"ALTITUDE"
450 WRITE (15,440)
460 PRINT
470 IF U$="MI" THEN 510
480 FORMAT 11X,"KM",8X,"KM",8X,"KM",11X,"M"
490 WRITE (15,480)
500 GOTO 530
510 FORMAT 7X,"NMILES",4X,"NMILES",4X,"NMILES",10X,"FT"
520 WRITE (15,510)
```

```
530 FORMAT 11X,"D1",8X,"D2",9X,"D"
540 WRITE (15,530)
550 PRINT
560 PRINT
570 DISP "WANT PRINT OUT";
580 INPUT Z$
590 K1=1.85325
600 K2=0.0003048
610 K3=H*K2
620 K4=3.280839895
630 N9=0
640 FOR C=S0 TO S2 STEP S1
650 DEG
660 IF U$="MI" THEN 710
670 A1=A
680 C5=C
690 K5=K3
700 GOTO 740
710 A1=A/K1
720 C5=C/K1
730 K5=K3/K1
740 T0=57.29577951*(C5/A1)
750 C1=A1/(K5+A1)
760 C2=ATN(SQR(1-C1↑2)/C1)
770 C3=COS(C2-W)
780 C4=COS(T0+W)
790 IF C4=0 THEN 1010
800 H2=((((K5+A1)*C3)/C4)-A1)
810 D1=0.0174532925*A1*C2
820 D2=C5
830 D=D1+D2
840 IF U$="MI" THEN 870
850 H3=H2*1000
860 GOTO 900
870 H3=H2*K1*K4*1000
880 IF Z$="N" THEN 910
890 FORMAT 5X,F8.1,2X,F8.1,2X,F8.1,2X,F10.1
900 WRITE (15,890)D1,D2,D,H3
910 N9=N9+1
920 X[N9]=D
930 Y[N9]=H3
940 IF U$="MI" THEN 970
950 IF Y[N9]>18288 THEN 990
960 GOTO 1010
970 IF Y[N9]>60000 THEN 990
980 GOTO 1010
990 Q9=N9-1
1000 GOTO 1020
1010 NEXT C
1020 PRINT
1030 DISP "FIRST PLOT";
1040 INPUT Z$
```

```
1050 IF Z$="N" THEN 1690
1060 DISP "WANT PLOT";
1070 INPUT P$
1080 P9=(POS(P$,"Y")>0)
1090 IF P9>0 THEN 1160
1100 DISP "MORE DATA";
1110 INPUT D$
1120 D9=(POS(D$,"Y")>0)
1130 IF D9>0 THEN 60
1140 STOP
1150 DEG
1160 DISP "MAX X-AXIS";
1170 INPUT X9
1180 X8=X9
1190 DISP "MIN X-AXIS";
1200 INPUT X7
1210 X6=X7
1220 DISP "MAX Y-AXIS";
1230 INPUT Y9
1240 Y8=Y9
1250 DISP "MIN Y-AXIS";
1260 INPUT Y7
1270 Y6=Y7
1280 DISP "WANT SPECIAL CHARACTER PLOTTED";
1290 INPUT A$
1300 A9=(POS(A$,"Y")>0)
1310 IF A9=0 THEN 1350
1320 DISP "WHAT CHARACTER";
1330 INPUT E$
1340 A9=A9-(POS(A$[1,1],".")>0)
1350 SCALE X7-0.2*(X9-X7),X9+0.1*(X9-X7),Y7-0.2*(Y9-Y7),Y9+0.1*(Y9-Y7)
1360 DISP "WANT X-AXIS";
1370 INPUT A$
1380 IF POS(A$,"N") THEN 1510
1390 DISP "WHAT Y-VALUE FOR X-AXIS";
1400 INPUT Y3
1410 DISP "WHAT TIC INCREMENT FOR X-AXIS";
1420 INPUT T9
1430 XAXIS Y3,T9,X6,X8
1440 DISP "WANT TO LABEL X-AXIS";
1450 INPUT W$
1460 IF POS(W$,"N") THEN 1510
1470 FOR K=X6 TO X8 STEP T9
1480 PLOT K-0.4*T9,Y3-0.1*(Y9-Y7),-1
1490 LABEL (*,1.5,2,0,1)K
1500 NEXT K
1510 DISP "WANT Y-AXIS";
1520 INPUT A$
1530 IF POS(A$,"N") THEN 1660
1540 DISP "WHAT X-VALUE FOR Y-AXIS";
1550 INPUT X3
1560 DISP "WHAT TIC INCREMENT FOR Y-AXIS";
1570 INPUT T2
```

```
1580 YAXIS X3,T2,Y6,Y8
1590 DISP "WANT TO LABEL Y-AXIS";
1600 INPUT W$
1610 IF POS(W$,"N") THEN 1660
1620 FOR K=Y6 TO Y8 STEP T2
1630 PLOT X3-0.1*(X9-X7),K,-1
1640 LABEL (*,1.5,2,0,1)K
1650 NEXT K
1660 DISP "WANT MORE AXES";
1670 INPUT A$
1680 IF POS(A$,"Y")>0 THEN 1360
1690 FOR T8=1 TO Q9-1
1700 PLOT X[T8],Y[T8]
1710 PEN
1720 IF A9=0 THEN 1770
1730 CPLOT -0.3,-0.3
1740 LABEL (*)E$[1,1]
1750 IPLOT 0,0
1760 PEN
1770 NEXT T8
1780 DISP "WANT LABELS";
1790 INPUT Z$
1800 IF Z$="N" THEN 1100
1810 IF POS(A$,"Y") THEN 1360
1820 DISP "TITLE";
1830 INPUT T$
1840 DISP "NAME OF X-AXIS";
1850 INPUT X$
1860 DISP "NAME OF Y-AXIS";
1870 INPUT Y$
1880 PLOT X6+0.1*ABS(X8-X6),Y8+0.09*ABS(Y8-Y6),-1
1890 LABEL (*,1.5,2,0,1)T$
1900 PLOT X6+0.1*ABS(X8-X6),Y6-0.15*ABS(Y8-Y6),-1
1910 LABEL (*,1.5,2,0,1)X$
1920 PLOT X6-0.15*ABS(X8-X6),Y6+0.1*ABS(Y8-Y6),-1
1930 LABEL (*,1.5,2,90,1)Y$
1940 GOTO 1100
1950 END
```

APPENDIX II

Listing of Computer Program titled:

Power for LOS to Aircraft

Programmer: Charles Masen
Date: 17 March 1977
Computer: HP-9830

```
10 DIM Z$[3],U$[2],P$[4],D$[4],A$[40],X5[200],Y5[200],W$[40],T$[40],B$[40]
20 DIM X$[40],Y$[40],E$[40],F[50],G5[91],W5[91],V5[15],F$[3]
30 REM PART 2: POWER FOR LOS TO AN AIRCRAFT
40 REM THIS PROGRAM WILL COMPUTE RECEIVE SIGNAL POWER LEVEL
50 PRINT
60 PRINT
70 PRINT
80 DISP "GEOGRPHCL SURFCE REFRACTIVTY,N0";
90 INPUT N0
100 DISP "ANTENNA HEIGHT,FT";
110 INPUT H5
120 DISP "AIRCRAFT ALTITUDE ,FT";
130 INPUT H7
140 A0=6370
150 DISP "CALCULATE SURFCE REFRACTICITY,NS";
160 INPUT Z$
170 IF Z$="Y" THEN 200
180 N1=N0
190 GOTO 230
200 DISP "ANTENNA ELVTION ABVE SEA LVEL,KM";
210 INPUT H1
220 N1=N0*EXP(-0.1057*H1)
230 K1=1.85325
240 K2=0.0003048
250 A=A0/(1-0.04665*EXP(0.005577*N1))
260 DISP "UNITS IN KM OR MI";
270 INPUT U$
280 IF U$="MI" THEN 370
290 F$="M"
300 A1=A
310 H8=H5*K2
320 H9=H7*K2
330 B8=H8*1000
340 B9=H9*1000
350 L5=-32.45
360 GOTO 440
370 F$="FT"
380 A1=A/K1
390 H8=(H5*K2)/K1
400 H9=(H7*K2)/K1
410 B8=H5
420 B9=H7
430 L5=-37.81
440 PRINT "ANTENNA HEIGHT=";B8,F$
450 PRINT "AIRCRAFT ALTITUDE =";B9,F$
460 PRINT "EFFECTIVE EARTH RADIUS =";A1,U$
470 PRINT "GEOGRAPHICAL SURFACE REFRACTIVITY,N0=";N0
480 PRINT "SURFACE REFRACTIVITY,NS=";N1
490 PRINT
500 IF Z$="N" THEN 560
510 IF U$="MI" THEN 540
520 B7=H1*1000
```

```
530 GOTO 550
540 B7=H1/K2
550 PRINT "ANTENNA ELEVATION ABOVE SEA LEVEL =";B7,F$
560 PRINT
570 DISP "HOW MANY FREQUENCY";
580 INPUT N5
590 DISP "CONSTANT RECEIVER GAIN IN DB";
600 INPUT R2
610 DISP "TRANSMITER POWER IN WATTS";
620 INPUT P2
630 PRINT "TRANSMITTER POWER =";P2,"WATTS"
640 FOR M9=1 TO N5
650 FOR M1=1 TO 91
660 G[M1]=0
670 W[M1]=0
680 NEXT M1
690 DISP "WANT TO READ DATA CARDS";
700 INPUT Z$
710 IF Z$="Y" THEN 860
720 DISP "FREQUENCY F("M9") IN MHZ";
730 INPUT F[M9]
740 PRINT
750 PRINT "FREQUENCY=",F[M9]
760 PRINT
770 DISP "HOW MANY ELEVATION ANGLES";
780 INPUT E6
790 FOR A4=1 TO E6
800 DISP "ELEVATION ANGLE W("A4")";
810 INPUT W[A4]
820 DISP "TRANSMITTER GAIN G("A4") IN DB";
830 INPUT G[A4]
840 NEXT A4
850 GOTO 1160
860 I5=0
870 DISP "HOW MANY CARDS PER FREQUENCY";
880 INPUT N8
890 FOR K9=1 TO N8
900 WRITE (1,*)"D"
910 ENTER (1,920)F1,T1,(FORS8=1TO15,V[S8])
920 FORMAT 2F2.0,1X,15F5.0
930 FOR J1=1 TO 15
940 I5=I5+1
950 IF I5>91 THEN 990
960 W[I5]=T1
970 G[I5]=V[J1]
980 T1=T1+1
990 NEXT J1
1000 T1=0
1010 NEXT K9
1020 E6=I5-1
1030 F[M9]=F1
```

```
1040 PRINT
1050 PRINT
1060 DISP "FREQUENCY=",F[M9]
1070 WAIT 1500
1080 DISP "WANT TO CORRECT FREQUENCY";
1090 INPUT Z$
1100 IF Z$="Y" THEN 1120
1110 GOTO 1150
1120 DISP "WHAT  FREQUENCY";
1130 INPUT F1
1140 F[M9]=F1
1150 PRINT "FREQUENCY =";F[M9],"MHZ"
1160 DISP "WANT PRINT OUT";
1170 INPUT Z$
1180 PRINT
1190 FORMAT "ELEVATION",12X,"RANGES",18X,"LOS",18X,"SIGNAL"
1200 WRITE (15,1190)
1210 FORMAT 3X,"ANGLES",43X,"XMT",5X,"RCV",4X,"POWER"
1220 WRITE (15,1210)
1230 FORMAT 67X,"LEVEL"
1240 WRITE (15,1230)
1250 IF U$="MI" THEN 1290
1260 FORMAT 2X,"DEGREES",8X,"KM",7X,"KM",8X,"KM",8X,"KM",5X,"DB",5X,"DB",8X,"D
1270 WRITE (15,1260)
1280 GOTO 1310
1290 FORMAT 2X,"DEGREES",8X,"NM",7X,"NM",8X,"NM",8X,"NM",5X,"DB",5X,"DB",8X,"D
1300 WRITE (15,1290)
1310 N9=0
1320 PRINT
1330 PRINT
1340 FOR W1=1 TO E6
1350 DEG
1360 C1=A1/(H8+A1)
1370 C2=ATN(SQR(1-C1↑2)/C1)
1380 N6=0.0174532925*A1
1390 N7=(A1+H8)/(A1+H9)
1400 D1=N6*C2
1410 C3=COS(C2-W[W1])
1420 C4=N7*C3
1430 C5=ATN(SQR(1-C4↑2)/C4)
1440 T0=C5-W[W1]
1450 D2=N6*T0
1460 D3=D1+D2
1470 S9=((A1+H9)*SIN(C2+T0))/C3
1480 P3=10*LGT(P2)+15-20*LGT(F[N9])-20*LGT(S9)+G[W1]+R2
1490 IF Z$="N" THEN 1520
1500 FORMAT 4X,F5.1,3X,F7.1,2X,F7.1,2X,F8.1,2X,F8.1,2X,F5.1,2X,F5.1,2X,F8.1
1510 WRITE (15,1500)W[W1],D1,D2,D3,S9,G[W1],R2,P3
1520 N9=N9+1
1530 X[N9]=D3
```

```
1540 Y[N9]=P3
1550 IF U$="MI" THEN 1580
1560 IF H9>18288 THEN 1600
1570 GOTO 1590
1580 IF H9>60000 THEN 1600
1590 NEXT W1
1600 Q9=N9-1
1610 PRINT
1620 DISP "FIRST PLOT";
1630 INPUT Z$
1640 IF Z$="N" THEN 2280
1650 DISP "WANT PLOT";
1660 INPUT P$
1670 P9=(POS(P$,"Y")>0)
1680 IF P9>0 THEN 1750
1690 DISP "MORE DATA";
1700 INPUT D$
1710 D9=(POS(D$,"Y")>0)
1720 IF D9>0 THEN 2540
1730 STOP
1740 DEG
1750 DISP "MAX X-AXIS";
1760 INPUT X9
1770 X8=X9
1780 DISP "MIN X-AXIS";
1790 INPUT X7
1800 X6=X7
1810 DISP "MAX Y-AXIS";
1820 INPUT Y9
1830 Y8=Y9
1840 DISP "MIN Y-AXIS";
1850 INPUT Y7
1860 Y6=Y7
1870 DISP "WANT SPECIAL CHARACTER PLOTTED";
1880 INPUT A$
1890 A9=(POS(A$,"Y")>0)
1900 IF A9=0 THEN 1940
1910 DISP "WHAT CHARACTER";
1920 INPUT E$
1930 A9=A9-(POS(A$[1,1],".")>0)
1940 SCALE X7-0.2*(X9-X7),X9+0.1*(X9-X7),Y7-0.2*(Y9-Y7),Y9+0.1*(Y9-Y7)
1950 DISP "WANT X-AXIS";
1960 INPUT A$
1970 IF POS(A$,"N") THEN 2100
1980 DISP "WHAT Y-VALUE FOR X-AXIS";
1990 INPUT Y3
2000 DISP "WHAT TIC INCREMENT FOR X-AXIS";
2010 INPUT T9
2020 XAXIS Y3,T9,X6,X8
2030 DISP "WANT TO LABEL X-AXIS";
2040 INPUT W$
```

```
2050 IF POS(W$,"N") THEN 2100
2060 FOR K=X6 TO X8 STEP T9
2070 PLOT K-0.4*T9,Y3-0.1*(Y9-Y7),-1
2080 LABEL (*,1.5,2,0,1)K
2090 NEXT K
2100 DISP "WANT Y-AXIS";
2110 INPUT A$
2120 IF POS(A$,"N") THEN 2250
2130 DISP "WHAT X-VALUE FOR Y-AXIS";
2140 INPUT X3
2150 DISP "WHAT TIC INCREMENT FOR Y-AXIS";
2160 INPUT T2
2170 YAXIS X3,T2,Y6,Y8
2180 DISP "WANT TO LABEL Y-AXIS";
2190 INPUT W$
2200 IF POS(W$,"N") THEN 2250
2210 FOR K=Y6 TO Y8 STEP T2
2220 PLOT X3-0.1*(X9-X7),K,-1
2230 LABEL (*,1.5,2,0,1)K
2240 NEXT K
2250 DISP "WANT MORE AXES";
2260 INPUT A$
2270 IF POS(A$,"Y")>0 THEN 1950
2280 FOR T8=1 TO Q9-1
2290 PLOT X[T8],Y[T8]
2300 IF A9=0 THEN 2350
2310 CPLOT -0.3,-0.3
2320 LABEL (*)E$[1,1]
2330 IPLOT 0,0
2340 PEN
2350 NEXT T8
2360 PEN
2370 DISP "WANT LABELS";
2380 INPUT Z$
2390 IF Z$="N" THEN 1690
2400 IF POS(A$,"Y") THEN 1950
2410 DISP "TITLE";
2420 INPUT T$
2430 DISP "NAME OF X-AXIS";
2440 INPUT X$
2450 DISP "NAME OF Y-AXIS";
2460 INPUT Y$
2470 PLOT X6+0.1*ABS(X8-X6),Y8+0.09*ABS(Y8-Y6),-1
2480 LABEL (*,1.5,2,0,1)T$
2490 PLOT X6+0.1*ABS(X8-X6),Y6-0.15*ABS(Y8-Y6),-1
2500 LABEL (*,1.5,2,0,1)X$
2510 PLOT X6-0.15*ABS(X8-X6),Y6+0.1*ABS(Y8-Y6),-1
2520 LABEL (*,1.5,2,90,1)Y$
2530 GOTO 1690
2540 NEXT M9
2550 END
```