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An Air-to-Ground HF Propagation Prediction Model for Fast Multicircuit Computation

F. G. Stewart
L. A. Berry
C. M. Rush
V. Agy

U.S. DEPARTMENT OF COMMERCE
Malcolm Baldrige, Secretary
David J. Markey, Assistant Secretary
for Communications and Information

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LIST OF SYMBOLS

A_i = height-related factor, defined by (41)

B = empirical constant, used in (28)

b = bandwidth, Hz

$b_i, i=1,2$ = bearings from transmitter to receiver and vice versa

C = empirical constant, used in (28)

D = ray path length, km

D_ℓ = upper decile of atmospheric noise, dB

D_u = lower decile of atmospheric noise, dB

$D_i, i=1,2$ = distance from antenna i to ground reflection point, km

d = great circle path length, km

$d_i, i=1,2$ = distances used in curve-fitting, (52-56)

e_n = error in iterate for $\sin \beta$, (43)

f = frequency, MHz

f_c = critical frequency, MHz

f_H = gyrofrequency, MHz

f_v = equivalent vertical frequency, MHz

G_R = receiver antenna gain, dB

G_T = transmitter antenna gain, dB

h = true height of reflection, km

h_E = height of maximum electron density of E-layer

h_{max} = height of maximum electron density

$h_i, i=1,2$ = antenna heights, km

h' = virtual height of reflection, km

Δh = retardation.

j = $\sqrt{-1}$

K = correction factor given by (9)

k = Boltzman's constant

L = path loss, dB

L_{bf} = free space loss, dB

L_g = ground reflection loss, dB

L_i = ionospheric absorption loss

m = exponent in (17), given by (18)

N = noise power

N_g = median galactic noise power in 1 Hz bandwidth

N_m = median man-made noise power in 1 Hz bandwidth

N_o = median atmospheric noise power in 1 Hz bandwidth

n = number of skywave hops

P_E = effective radiated power, watts

P_t = transmitter power, dBW

Q = spherical surface impedance, (47)

q_f = chi-square probability distribution, (27)

R = circuit reliability, (57)

R_g = R_V or R_H, ground reflection coefficient

R_H = ground reflection coefficient for horizontal polarization

R_V = ground reflection coefficient for vertical polarization

R_o = "numerical distance," (35)

r_o = radius of earth, km

S = signal strength, dBW

S_n = nth approximation to sin β, (44)

S_{13} = smoothed 13-month sunspot number

s_x = subsolar latitude

s_y = subsolar longitude

T_o = reference temperature, 288°K

t = variable of integration in (46)

t_o = apex of integration contour in (46)

t_g = universal time

u = $foE/(f \cos \alpha)$

V = mismatch polarization loss, V

v = scaling factor, (47)

W = winter anomaly factor, (17)

X = $V\theta$, (47)

$x_i, i=1,2$ = latitude

y = $\gamma h/V$, used in (50)

y_E = semi-thickness of E-layer

y_n = semi-thickness of layer

$y_i, i=1,2$ = longitude

Z = scaled ratio of critical frequencies, (26)

z = scaled numerical distance, (37)

α = angle of incidence of unrefracted ray at E-layer maximum

β = take-off angle

γ = $2\pi/\lambda$, the wave number

Δ = angle ray is bent, (13).

δ = ground surface impedance, (34)

ε = relative dielectric constant of ground

η = refractive index of ground, (23)

θ = great circle path length, radians

λ = radio wave length in free space

ν = collision number in ionosphere

ξ = number of degrees of freedom in χ^2 distribution

σ = ground conductivity, mho/m

ϕ = angle of incidence on ionosphere

χ^2 = "value related to f," (27)

ψ = solar zenith angle

ψ_{12} = solar zenith angle at noon

$\omega=2\pi f$ = angular frequency

AN AIR-TO-GROUND HF PROPAGATION PREDICTION MODEL FOR FAST MULTICIRCUIT COMPUTATION

F. G. Stewart, L. A. Berry, C. M. Rush,* and V. Agy**

A radio propagation prediction computer code has been developed to permit rapid simulation of HF air-to-ground telecommunication circuits. This prediction program provides estimates of both skywave and groundwave HF propagation parameters. The skywave and groundwave propagation parameters can be obtained for radio circuits with transmitters and receivers on the surface of the earth or with one or both ends of the circuit elevated up to 50 km. When a large number of circuits in a given area are simulated for a single time, the program is an order of magnitude faster than its predecessors. This report provides a description of the air-to-ground HF propagation prediction program as well as illustrations of the results obtained from the program.

Key words: air-to-ground propagation; groundwave propagation; HF predictions; ionospheric propagation; propagation predictions; skywave propagation

1. INTRODUCTION

High frequency (3-30 MHz) radio waves that are reflected from the ionosphere are used extensively for communications over distances well beyond the optical horizon. Such communications are used for international broadcasting services, for message traffic between two fixed points on the earth, or between moving terminals. In addition to propagating via the ionosphere, HF radio waves can propagate over the surface of the earth via the conventional groundwave. Groundwaves that travel along the surface of the earth may be of operational use out to distances of the order of 100-300 km from the transmitter.

High frequency skywave signal strengths vary relative to the ionosphere: hour-to-hour, diurnal, seasonal, solar cycle, and spatial. The performance of telecommunication systems that rely upon HF skywave signals is dependent on transmitter power, transmitted frequency, transmitter and receiver antenna characteristics, and the noise and interference environment in which the system must operate. The performance of telecommunication systems relying on HF groundwave is dependent upon the same parameters as well as the type of ground over which the signal is propagated.

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[*] F. G. Stewart, L. A. Berry, and C. M. Rush are with the Institute for Telecommunication Sciences, National Telecommunications and Information Administration, U.S. Department of Commerce, 325 Broadway, Boulder, Colorado 80303.

[**] V. Agy is with OAO Corporation, Lakewood, Colorado 80227.

Many numerical methods have been devised to permit calculation and prediction of the performance of HF telecommunication systems that rely upon skywave or groundwave propagation. The most useful of these methods invariably form the bases of complex computer programs that are recognized and used by system designers and propagation scientists worldwide. The skywave prediction methods of general use include those reported by Barghausen et al. (1969), the CCIR (1982 a and b), Bradley (1975), and John Lloyd (private communication, 1983). The groundwave prediction methods for HF systems that are of general use include those reported by Berry and Herman (1971), Ott (1971), and Hill (1982).

For the most part, the numerical methods to predict HF field strength treat either skywave or groundwave, but not both. In most instances of HF field propagation applications the user desires information regarding either skywave characteristics or groundwave characteristics. Generally, the distance between the terminals of a given HF circuit is such that only skywave (greater than 100 km) or groundwave (less than 100-300 km) signals provide sufficient amplitude for the required time periods to be operationally useful. A notable exception, however, occurs when consideration is given to the situation in which one terminal (or more) of an HF system is mobile or has the capability of becoming mobile. In this case, the transmitter and receiver locations can vary from essentially being colocated to being separated by distances far beyond the horizon. Depending upon the particular geometry, both skywave and groundwave signals need to be considered in predicting or assessing the performance of the HF system.

In this report, an HF propagation prediction program is described that permits calculation of both skywave and groundwave signal characteristics for path geometries that are specified by the user. The program has been optimized to rapidly calculate a large number of HF air-to-ground circuits in an area at a given universal time. The calculations can be performed for any number of propagation paths, and the transmitters and/or receivers can be located anywhere in altitude from the surface of the earth to 50 km. The primary use of the program is expected to be for circuits spanning distances from 0 to 2000 km, but it is not limited to these distances.

The HF propagation program that is reported herein relies on two distinct programs developed at the Institute for Telecommunication Sciences. The skywave prediction method used essentially follows from the HF prediction program developed by Barghausen et al. (1969). The groundwave prediction method used is based on work described by L. A. Berry (OT Technical Memorandum 78-247, January 1978). The air-to-ground prediction program derived from these two programs is optimized for calculations for a large number of air-to-ground HF circuits operating simultaneously. In the next section, the skywave propagation prediction methodology is described. The description is brief for those parts of the skywave method that are exactly the same as given by Barghausen et al. (1969). More detailed discussion is given to areas of the prediction method where changes were made to speed up the calculations, particularly for the estimation of ionospheric parameters and atmospheric noise. In Section 3, the groundwave prediction methodology is presented. The output from Berry's groundwave prediction program was fitted with parametric curves that produce rapid estimates of the groundwave propagation loss.

In Section 4, the results of a number of calculations of circuit performance are given to illustrate the wide range of application of the prediction program. In addition, estimates are given of the decrease in program running time because of the optimization. In Section 5, overall conclusions drawn from this effort are provided and recommendations for further work are put forth.

2. HF SKYWAVE PREDICTION METHOD

The skywave prediction technique employed in the current air-to-ground circuit simulation follows rather closely that of Barghausen et al. (1969). This program is referred to by many HF skywave prediction users as HFMUFES. In this discussion the program will be referred to as either HFMUFES or Barghausen et al. (1969).

The propagation program predicts monthly median operational parameters that characterize an HF skywave circuit such as maximum usable frequency (MUF), optimum traffic frequency (FOT), and lowest useful frequency (LUF) in terms of the probability of successful transmission for a particular circuit. The probability of successful transmission depends on the probability that the transmission frequency is below the critical frequency (i.e., the maximum frequency for reflection) of the F2 layer and the probability that the available signal-to-noise ratio is above a specified level.

The performance of an HF skywave circuit depends upon the path geometry, the strength of the signal at the receiver, the structure of the ionosphere, and the noise and interference environment in which the circuit must operate. In the air-to-ground program the same path geometry as in the HFMUFES program is used. The signal strength is determined, also, using the same loss terms as in the HFMUFES program. The ionospheric structure and the noise environment have as their basis the same models as in the HFMUFES program; however, the application of the numerical coefficients to determine the ionospheric structure and the atmospheric noise characteristics differs substantially from the HFMUFES program.

2.1 Path Geometry

To determine the operational parameters for an HF ionospheric radio communication circuit, it is necessary to calculate several parameters that are based on the geometry of the path. These include the path length, path bearings, and zenith angle of the sun.

The path length, which is taken to be the shorter of the great-circle distances between the two points, is computed as follows (Barghausen et al. (1969), equation 5.1):

$$\cos \theta = \sin x_1 \sin x_2 + \cos x_1 \cos x_2 \cos(y_1 - y_2) \qquad (1)$$

where

x_1 = geographic latitude of transmitter,
y_1 = geographic longitude of transmitter,
x_2 = geographic latitude of receiver,
y_2 = geographic longitude of receiver, and
θ = path length in radians.

Having obtained the path length, the bearing of transmitter to receiver and receiver to transmitter along the great-circle path is calculated as follows (Barghausen et al. (1969), equations 5.2 and 5.3):

$$\cos b_1 = (\sin x_2 - \sin x_1 \cos \theta)/\cos x_1 \sin \theta \quad , \qquad (2)$$

and

$$\cos b_2 = (\sin x_1 - \sin x_2 \cos \theta)/\cos x_2 \sin \theta \quad , \qquad (3)$$

where

b_1 = bearing transmitter to receiver in radians, and
b_2 = bearing receiver to transmitter in radians.

The zenith angle of the sun is needed to determine the appropriate ionospheric structure and noise environment for each hour of the day. It is used in calculating the ionospheric loss or absorption factor and is computed from the following equation (Barghausen et al. (1969), equation 5.7):

$$\cos \psi = \sin x_n \sin s_x + \cos x_n \cos s_x \cos(s_y - y_n) \quad , \qquad (4)$$

where

x_n = latitude of the point in question,
y_n = longitude of the point in question,
s_y = $15\ t_g\quad 180$ = subsolar longitude,
t_g = universal time,
s_x = subsolar latitude for the middle of the month, and
ψ = sun's zenith angle.

In this program only five ray paths can be evaluated for each circuit and frequency. The ray path must be geometrically possible for a takeoff angle equal to or greater than the value given as input data. The skywave paths evaluated are two ray paths via reflections from the regular E layer or E_s layer and three ray paths via reflections from the F layer.

The E-layer modes considered are, first, the mode with the least number of hops possible for the given takeoff angle and, second, the mode with the next greater number of hops. If the calculations indicate that the ray at any particular frequency penetrates the E layer, then the sporadic-E mode may be investigated if desired. This is included as a program option.

The first F-layer mode considered is the mode with the least number of hops geometrically possible, taking into account not only the lower limit of the given takeoff angle, but also the cutoff effect of the E layer. The sporadic-E layer is always considered transparent for F-layer propagation. The next two F modes have successively higher hop numbers.

For any given circuit, parabolic layer theory is used to calculate the maximum usable frequency (MUF) and the takeoff angle β and virtual height h' of reflection of all frequencies.

The problem resolves into the solution of the equation

$$f = f_v K \sec \phi \ , \tag{5}$$

where

f = the probing frequency at oblique incidence,
f_v = the equivalent vertical-incidence frequency,
K = a correction factor resulting from curved geometry, and
ϕ = the semi-vertex angle of the equivalent triangular path.

These quantities are not immediately available; therefore, several intermediate equations must be evaluated, and f_v is found iteratively. The virtual height h' is obtained from the equation (Barghausen et al. (1969), equation 5.12)

$$h' = h_o + y_m f_V/f_c \operatorname{arctanh}(f_V/f_c) \quad , \tag{6}$$

where

h_o = the height of the bottom of the reflecting layer,

y_m = semithickness of the reflecting layer, and

f_c = the critical frequency of the reflecting layer.

The value of ϕ is obtained (Barghausen et al. (1969), equation 5.13) from

$$\tan \phi = \sin(\theta/2) \Big/ \left(1 - \cos\left(\frac{\theta}{2}\right) + \frac{h'}{r_o}\right) \quad , \tag{7}$$

where r_o = radius of the earth (6371.2 km). Then from

$$h = h_o + y_m \left(1 - \sqrt{1 - (f_V/f_c)^2}\right) \quad , \tag{8}$$

the true height of reflection h is obtained. Finally, the correction factor is determined as follows (Barghausen et al. (1969), equation 5.15):

$$K = 1 \Big/ \sqrt{1 - \left(\frac{2(h' - h)}{r_o + h_o}\right) \tan^2 \phi}. \tag{9}$$

If the takeoff angle and virtual height are desired for a specific frequency f_o, a suitable initial estimate of f_v, say f_{v1} is made, and f is calculated from (5). Using Newton's iteration method, successive approximations of f_v are obtained from

$$f_{v_{(n+1)}} = f_{v_n} + (f_o - f) \frac{\partial f}{\partial f_v} \quad , \tag{10}$$

until the value of $(f_o - f)$ is sufficiently accurate. The value of h' is obtained in the process from (6), and the takeoff angle is then computed by

$$\tan \beta = \left(\cos\left(\frac{\theta}{2}\right) - \frac{r_o}{r_o + h'}\right) \Big/ \sin \frac{\theta}{2} \quad . \tag{11}$$

When the MUF is to be calculated from (5), neither f_v nor f is known. However, at the MUF the value of the first derivative of the probing frequency is known to be zero; therefore, the iteration is again started with an estimated value of f_v

and a better estimate is obtained using Newton's iteration method (Barghausen et al. (1969), equation 5.18):

$$f_{v_{(n+1)}} = f_{v_n} - \frac{\partial f/\partial f_v}{\partial^2 f/\partial f_v^2} , \tag{12}$$

until the desired accuracy is attained.

The bending of the ray from a parabolic E layer is incorporated into the calculations of F-layer reflection by an additional iteration procedure. The bending is assumed to take place at both ends of the path. A calculation is made as described for an F-layer reflection without regard to an underlying E layer. Then the bending produced by an E layer is calculated from Barghausen et al. (1969), equation 5.19,

$$\Delta = 2\left(\frac{y_E}{r_o + h_E}\right)\left(\frac{\operatorname{arctanh} u}{u} - 1\right) \tan\alpha , \tag{13}$$

where

Δ = angle in radians by which ray is bent,

y_E = semithickness of the E layer = 20 km,

h_E = height of maximum electron density of the E layer = 110 km,

α = angle of incidence of the unrefracted ray at the E-layer maximum,

$\sin\alpha$ = $r_o \cos\beta/(r_o + h_E)$,

u = $\mathrm{foE}/(f\cos\alpha)$, and

foE = critical frequency of E layer. (14)

The bending, in effect, increases the path length and is used to reduce the path length for new calculation of unrefracted rays. The bending calculations are iterated until the desired precision is reached. During this iteration procedure, steps are taken to determine if the E layer does indeed cut off the F-layer propagation.

The ionospheric parameters needed to determine the propagation path geometry (and hence the propagation characteristics) are discussed in Section 2.3.

2.2 Signal Strength

The signal power that is available at a receiving antenna terminal can be expressed in logarithmic units as

$$S = P_t + G_t - L - V + G_r \quad , \tag{15}$$

where

S = signal power in dBW,

P_t = transmitted power in dBW,

L = path loss,

V = polarization mismatch loss, and

G_t, G_r = absolute gains of the transmitting and receiving antennas, respectively.

The gain of the transmitting and receiving antennas depends upon the efficiency of the antenna and its directivity with respect to the source. The HFMUFES program contains a subroutine devoted to the determination of the gain of the appropriate transmitting and receiving antennas used in HF skywave circuit simulations. The current air-to-ground program does not compute antenna gains. Antenna gains can be specified by the user if so desired. No polarization mismatch loss is included in the air-to-ground program.

The path loss is determined in exactly the same manner as given in the HFMUFES programs. Three main mechanisms account for almost all the energy losses. Normally the major energy loss is geometrical and is caused by the spreading of the energy over progressively larger areas as the signal propagates from the transmitter. The free-space loss, L_{bf}, results from the geometrical spreading of energy as the radio wave progresses away from the transmitter and can be expressed as (Barghausen et al. (1969), equation 7.2):

$$L_{bf} = 32.44 + 20 \log_{10} f + 20 \log_{10} D \quad , \tag{16}$$

where f is wave frequency in MHz and D is the path length in kilometers.

The second major loss mechanism in radio-wave propagation via the ionosphere is absorption by the ionosphere. Radio waves that are reflected by the E or F2 region lose energy each time they pass through the highly absorbing D region. Nondeviative absorption in the D region is the predominant absorption mechanism at HF, except for radio frequencies in the immediate vicinity of the layer critical frequency. As is the case for HFMUFES, only nondeviative absorption is explicitly calculated by the prediction computer program, as follows (Barghausen et al. (1969), equations 7.4, 7.5):

$$L_i = \frac{286(1 + 0.0087x_n)\ (1 + 0.005S_{13})W \cos^m(\psi_{12})}{\nu^2/4\pi^2 + (f + f_H)^2} \cdot \left[\frac{\cos(0.893\psi)}{\cos(0.893\psi_{12})}\right]^n \sec\ \phi\ , \text{(dB)}\ , \tag{17}$$

where

$$m = 2.25 - 0.32x_n\ , \tag{18}$$

where x_n is the geographic latitude in degrees measured positive from the equator, S_{13} is the smoothed 13-month sunspot number, ψ is the solar zenith angle in degrees, ψ_{12} is the solar zenith angle at local noon, ϕ is the angle of incidence of radio ray at 100 km, ν is the collision number ($\nu = 20$ at 63 km, and $\nu^2/4\pi^2 = 10$), f_H is the gyrofrequency at absorbing height in megahertz, W is the winter anomaly factor (discussed later), and n is the number of hops.

At night, the factor

$$(1 + 0.005S_{13})\ \cos^m(\psi_{12})\ \frac{\cos\ (0.893\psi)}{\cos\ (0.893\psi_{12})} \cdot W \tag{19}$$

of equation (17) is set equal to 0.01 to give results that agree with observations. The exponent m in equation (18) gives results that agree with vertical-incidence absorption measurements at high latitudes, but it yields absorption values that are too large for oblique arctic propagation. Therefore, it is necessary to limit m in the computer program to m=1.3. The coefficient W in equation (17) is an empirical correction for the winter anomaly of ionospheric absorption (Appleton and Piggott, 1954); i.e., in the local winter at medium to high latitudes more absorption is observed than is expected on the basis of simple photoionization theory. In the calculation of ionospheric loss, losses associated with signals reflected from the sporadic-E layer are the same as those estimated for the regular E layer.

The third major loss of radio energy for multiple-hop propagation occurs when the radio wave is reflected from the earth's surface. It is assumed that the incident skywaves are randomly polarized and that the radio energy is distributed equally in the horizontally and vertically polarized fields. The loss caused by reflection is given by Barghausen et al. (1969), equation 7.7:

$$L_g = 10 \log_{10} \left[\frac{|R_v|^2 + |R_h|^2}{2} \right] \quad (\mathrm{dB}) \quad , \qquad (20)$$

where R_v is the reflection coefficient for the vertically polarized wave (electric vector parallel to the plane of incidence), and R_h is the reflection coefficient for the horizontally polarized wave (electric vector perpendicular to the plane of incidence). The reflection coefficients are defined as the ratios of the electric vector in the reflected wave to the electric vector in the incident wave. Generally, the reflection coefficients are complex numbers, since the refractive index of the earth is a complex quantity. If the earth's magnetic field is neglected, the quantities R_v and R_h are given by the Fresnel formulas

$$R_v = \frac{\eta^2 \sin\beta - (\eta^2 - \cos^2\beta)^{\frac{1}{2}}}{\eta^2 \sin\beta + (\eta^2 - \cos^2\beta)^{\frac{1}{2}}} \quad , \qquad (21)$$

$$R_h = \frac{\sin\beta - (\eta^2 - \cos^2\beta)^{\frac{1}{2}}}{\sin\beta + (\eta^2 - \cos^2\beta)^{\frac{1}{2}}} \quad , \qquad (22)$$

where β is the takeoff angle of the ray above the earth. The quantity η is the complex refractive index. For a time variation of the electric field proportional to $\exp(j\omega t)$,

$$\eta^2 = \varepsilon - j\, 18000\sigma/f \quad , \qquad (23)$$

where ε is the relative dielectric constant of the earth, and σ is the real conductivity of the earth (mhos/meter). The values of ε and σ used in the HFMUFES prediction program also are used in the air-to-ground program.

As is the case with the HFMUFES program, there is an additional loss term in the air-to-ground program: the excess system loss. This term was employed by Barghausen et al. (1969) in order to account for the day-to-day variations of signals from the monthly median and other losses not explicitly attributed to the mechanisms described above. The excess system loss term in the air-to-ground program is exactly that used in the HFMUFES program.

2.3 Ionospheric Structure

The ionospheric structure of the air-to-ground skywave prediction program is the same as that contained within the HFMUFES program. The vertical electron density profile is represented by two parabolas, one each for the E and F2 region of the ionosphere. There is no account taken of the F1 region.

For each parabola, the electron density distribution is specified by the critical frequency, height of maximum ionization, and the semithickness of the region. Sporadic-E ionization is taken into account in the calculation of circuit performance and will be described later in this section.

The E-region critical frequency is determined by use of numerical coefficients of the monthly median foE values valid for the entire globe (Leftin, 1976). The numerical coefficients representing foE were derived from measurements taken during 1958 and 1964. These years were selected for analysis because the data are representative of the high (1958) and low (1964) phases of the sunspot cycle. A linear interpolation procedure is used between the representative data for the high (SSN = 150) and low (SSN = 10) solar activity periods to obtain foE estimates at all other phases of the solar cycle. The height of the maximum electron density of the E region is taken to be constant at 110 km and the semithickness is 20 km (Barghausen et al., 1969).

The F2 region critical frequency is also determined from numerical coefficients valid for the entire globe (Jones et al., 1966). The long-term U_{SK} coefficients are used primarily for long-range frequency planning and equipment specification and design. The solar activity dependence factor is accounted for by a linear interpolation procedure for any index of sunspot activity from SSN = 0 to SSN = 100. <u>The long-term U_{SK} coefficients should not be used with sunspot numbers above 150</u>.

The height of the maximum electron density of the F layer is developed in two steps. First, the M(3000)F2 factor is obtained from global numerical maps, and then the true height of the maximum ionization h_{max} in the layer (Wright and McDuffie, 1960) is calculated on the basis of the following relationship (Shimazaki, 1955):

$$h_{max} = \frac{1490}{M(3000)F2} - 176 \quad . \qquad (24)$$

The virtual height of the bottom of the F region is also obtained from numerical maps and is reduced by the retardation (Δh) in kilometers caused by the underlying E layer (Barghausen et al., 1969, equation 5.9),

$$\Delta h = y_E \left[Z \log_e \left(\frac{Z+1}{Z-1} \right) - 2 \right] \quad , \qquad (25)$$

where

$$Z = 0.834(f_oF2)/f_oE \quad . \qquad (26)$$

The results of the calculations are then deemed to be the true heights.

The MUF calculated from parabolic layer theory is based upon median values of the ionospheric characteristics; the probability of a skywave path for this frequency is therefore assumed to be 50 percent. The frequency that would have a 90 percent probability of propagating (FOT) and the frequency that has 10 percent probability (HPF) are obtained by multiplying the MUF by the factors given in the HFMUFES program. For the F2 region, the probability of ionospheric support at a given frequency propagated at a given elevation angle is determined by evaluating the chi-square probability distribution function:

$$q_f = \int_o^{\chi^2} \frac{1}{2^{\xi/2} \quad (\xi/2)} \exp(-z/2)\, z^{\xi/2 - 1}\, dz \quad , \qquad (27)$$

where

χ^2 = a value related to the operating frequency, and
ξ = number of degrees of freedom; describes skewness in the χ^2 distribution.

It is assumed that any MUF is related to a χ^2 value by the linear relation,

$$\mathrm{MUF} = C + B\,\chi^2 \quad , \qquad (28)$$

where C and B are constants. The value of the constants C and B and the term ξ is determined in exactly the same manner as given in the HFMUFES program.

When the regular E region supports propagation, it is assumed to have a probability of 0.99 since the E region is stable and very predictable. When propagation by the regular E region is not possible, the probability that propagation by the sporadic E layer is considered. The median and upper and lower decile values of foEs are obtained from numerical coefficients and converted into values for the oblique path by the secant law relationship. The multiplicative factor, sec ϕ, is computed as follows:

$$\sec \phi = \frac{1}{\cos(\frac{\pi}{2} - \frac{d}{2} - \beta)} \qquad (29)$$

The probability of sporadic-E propagation is then calculated for the operating frequency from these median and decile values using the chi-squared probability function as given by equation (27). There is no additional loss determined for the partial transparency of the E_s layer of radio waves.

Most of the ionospheric parameters that are needed to evaluate the equations for the path geometry, the ionospheric loss, and the ionospheric structure and propagation characteristics must be obtained from numerical coefficients. The evaluation of these coefficients is quite lengthy when a large number of skywave circuits are to be simulated. Rather than evaluating the required parameters circuit by circuit, as in the HFMUFES program, the air-to-ground program uses the following procedure.

The area of interest is chosen by assuming that no path is greater than 2000 km and all ionospheric control points fall inside the area. A grid of the ionospheric parameters is generated for a specific sunspot number, month, day, and time of day. The density of the grid is determined by the geographic area selected and accuracy required for the prediction. In the most accurate mode, the results should be exactly those values predicted by program HFMUFES. The control points for a given path are found, and if the control point falls between grid points, each parameter is computed with a two-dimensional interpolation in the grid. The values are used to evaluate the losses and expected performance for that circuit. This method of ionospheric parameter evaluation is significantly faster when the number of circuits exceeds the number of grid points (or when speed in evaluation of a given circuit is required). The speed advantage and the degradation in accuracy will be estimated and discussed in Section 4.

2.4 Noise Parameters

The probability of successful HF transmission depends on the probability that the signal available at the receiving location is above the noise level by a specified amount. The three major types of external noise are galactic, man-made, and atmospheric. In general, these noise types have spectral energy distributions that vary more or less uniformly over the entire high frequency range; however, one type will usually predominate at a given time and place. If each of the two lower noise sources is more than 6 dB below the highest noise power source, they increase the total noise power less than 1 dB and are ignored. However, if one or both of them is within 6 dB of the highest noise source, they make a significant contribution to the total noise power. The amount that must be added to the highest noise power is the same as in the HFMUFES program. If the difference in decibels between the highest noise source and the noise power from a lower noise source is defined as ΔN, then the contribution (in dB) to the total noise power from the other sources is as given in Table 1.

Table 1. Contribution in dB to Highest Noise Power from Other Sources

		Second Highest Noise Source			
		$\Delta N \leq 0.1$	$0.1 < \Delta N \leq 3.0$	$3.0 < \Delta N \leq 6.0$	$N > 6.0$
Third Highest Noise Source	$\Delta N > 6.0$	3.0	1.8	1.0	0.0
	$3.0 < \Delta N \leq 6.0$	3.5	2.4	1.8	
	$0.1 < \Delta N \leq 3.0$	4.0	3.0		
	$\Delta N \leq 0.1$	4.8			

The median galactic noise is represented by (Lucas and Haydon, 1966)

$$N_g = 165 + 9.555 \log_e \left(\frac{f}{3}\right) \quad \text{dBW} \quad , \tag{30}$$

where N_g is the expected median value of the galactic noise power in decibels relative to 1 W in a 1 Hz bandwidth. The temporal variation is estimated at ±2 dB (CCIR, 1982c).

The man-made radio noise may arise from any number of sources such as power lines, industrial activity, ignition systems, etc. Man-made noise displays wide geographical and short-term variations (CCIR, 1982d). The median level of man-made noise is based on the same formulation as used by Barghausen et al. (1969), equation 4.2:

$$N_m = N_o + b_N \log_{10} \left(\frac{f}{3}\right) \text{dBW} \quad , \tag{31}$$

where N_m is the man-made noise power in decibels below 1 W in a 1 Hz bandwidth, and

b_N is the constant derived from measurements and is given in Table 2.

Values of N_o, b_N, and D_u or D_ℓ for three frequency intervals, for four different noise environments, are given in Table 2, where D_u and D_ℓ represent the numerical departure of the upper and lower deciles, respectively, of the distribution from the median. An "urban" location is the industrial-business area of large cities; a "suburban" location is one near a large city or within a small town; and a "rural" location is one well removed from all populated areas and chosen to be as free as possible of man-made noise. The upper and lower decile values, D_u and D_ℓ, are equidistant from the tabulated values of N_o, which are the medians (JTAC,

Table 2. Values of Parameters for the Man-Made Noise Models

Man-made Noise Model	Frequency Interval (MHz)	N_o (dBW)	b_N	$D_\mu = D_\ell$ (dB)
Urban	$f \leq 10$	-136.5	-27.1	4.2
	$10 < f < 20$	-150.2	- 1.0	5.8
	$f \geq 20$	-132.5	-22.5	7.4
Suburban	$f \leq 10$	-148.6	-29.4	5.8
	$10 < f < 20$	-167.5	+ 6.6	8.8
	$f \geq 20$	-142.2	-24.0	11.8
Rural	$f \leq 10$	-165.6	-34.3	10.0
	$10 < f < 20$	-196.5	+24.9	7.1
	$4 \geq 10$	-155.4	-25.0	4.2
User Designated	$f \leq 20$	N_{user}	-29.3	5.8
	$10 < f < 20$	N_{user} -18.9	+ 6.6	8.8
	$f \geq 20$	N_{user} +6.4	-24.0	11.8

1968). The estimated uncertainties in predicting the median and deciles are 3 dB and 1.5 dB, respectively.

The man-made noise used in this prediction program does not include man-made noise generated by aircraft. Further, there is no altitude variation in either man-made noise or atmospheric noise in the program. These limitations could be significant in assessing reception of signals in elevated platforms.

Atmospheric noise is the most erratic of the three major types of noise. It is generally characterized by short pulses with random recurrence superimposed upon a background of random noise (Crichlow et al., 1955). Averaging these short pulses of noise power over several minutes yields average values that are nearly constant during a given hour. The variations seldom exceed ±2 dB, except during sunrise or sunset periods and when local thunderstorms are present. Worldwide maps published in CCIR Report 322, representing the median of hourly medians of atmospheric noise at 1 MHz within 4-hour time blocks for the four (3-month) seasons of the year, are used as the basis for estimating this noise at any given receiving location. Levels of atmospheric noise for other frequencies and their associated distributions about the medians are available for each time block and season.

The maps in CCIR Report 322 were used to generate, by means of a least-squares fit based on Fourier analysis, numerical coefficients representing the worldwide distribution of atmospheric noise (Lucas and Harper, 1965) as a function of geographic location. The curves of frequency dependence and variability of the radio noise were generated from a power series or least-squares fit. The numerical maps and complete listings of the numerical coefficients used in the prediction program are given in NBS Technical Note 318 (Lucas and Harper, 1965). The numerical coefficients in latitude, longitude, and local mean time at the receiving location give the median atmospheric noise power in decibels above $k\ T_0 b$, at 1 MHz for each time block and season. The value of k (Boltzmann's constant) is 1.38×10^{-23} joules per degree Kelvin, the reference temperature is 288°K, and b is the bandwidth in Hz. Noise values for other frequencies and their distributions are evaluated from numerical arrays derived from the frequency curves for each time block and season. Because evaluating the coefficients for the atmospheric noise each time that the performance characteristics of a given HF skywave circuit is required would take too long, the atmospheric noise parameters are precalculated for a given universal time at the same grid points used for the ionospheric parameters. Then, during circuit evaluation, atmospheric noise is interpolated from the precalculated values. The noise parameters that are frequency dependent, such as the man-made noise, are not precalculated.

3. GROUNDWAVE FIELD STRENGTH CALCULATIONS

When the transmitter and receiver are not widely separated (less than 300 km during the day and less than 100 km during the night), the groundwave may provide a better communications mode than the skywave. This is especially true when at least one terminal is elevated. The term groundwave is used to include the surface wave that diffracts around the curved earth, the direct line-of-sight space wave, and the ground-reflected wave. The direct wave is assumed to suffer attenuation due only to spreading of the wave as it propagates.

The basis of the calculations of the signal strength of the groundwave in the air-to-ground program is the work of Berry (L. A. Berry, User's Guide to Low-Frequency Radio Coverage Programs, OT Technical Memorandum 78-247, January 1978). The model used is applicable to predicting groundwave signal strength for smooth, homogeneous paths (GWSNR in the Berry reference). The field strength is calculated with one of three different formulas, depending on the geometry of the transmitter and receiver locations, the ground constants, and the radio frequency.

If both transmitter and receiver are near the earth (in wavelengths), then the radio wave propagates as a surface wave. For short path lengths, it is valid to assume that the earth is flat. For these conditions, use is made of the flat earth attenuation function (Wait, 1964),

$$E(d) = \frac{9.487\sqrt{P_E}}{d} A(z) \quad , \qquad V/m \quad , \tag{32}$$

where P_E is the effective radiated power in watts, d is the distance in kilometers, and $A(z)$ is the flat earth attenuation function.

$$A(z) \quad = \quad (1 - R_o\delta \, e^{z^2} \, \text{erfc}(z)) \quad , \tag{33}$$

where δ is the surface impedance of the ground,

$$\delta = \begin{cases} \sqrt{\eta^2 - 1}\;/\eta^2 & \text{for vertical polarization,} \\ \sqrt{\eta^2 - 1} & \text{for horizontal polarization,} \end{cases} \tag{34}$$

and η^2 is given in (23).

$$R_o \quad = \quad e^{j\pi/4} \sqrt{\pi\gamma D/2} \quad , \tag{35}$$

$$D = \sqrt{d^2 + (h_1 - h_2)^2} \quad , \tag{36}$$

where h_1 and h_2 are the heights of the transmitter and receiver, $\gamma = 2\pi/\lambda$ where λ is the free space wavelength,

$$z = e^{j\pi/4} \sqrt{\frac{\gamma D}{2}} \, \delta (1 + \frac{h_1 + h_2}{\delta D}) \quad , \tag{37}$$

and erfc (z) is the complementary error function (Abramowitz and Stegun, 1964).

If the transmitter and receiver are high enough that one is well above the radio horizon when viewed from the other, the field is calculated using geometrical optics. The geometrical quantities are defined in Figure 1.

$$E = 9.487 \sqrt{P_E} \, \frac{e^{-j\gamma(D - d)}}{2D} (1 + R_g e^{-i\gamma(D_1 + D_2 - D)}) \quad , \tag{38}$$

where R_g is the appropriate ground reflection coefficient, R_V or R_h (21, 22), and

$$D = \sqrt{(2\theta_o{}^2 + 2\theta_o(h_1 + h_2))(1 - \cos\theta) + h_1^2 + h_2^2 - 2h_1h_2\cos\theta} \; . \tag{39}$$

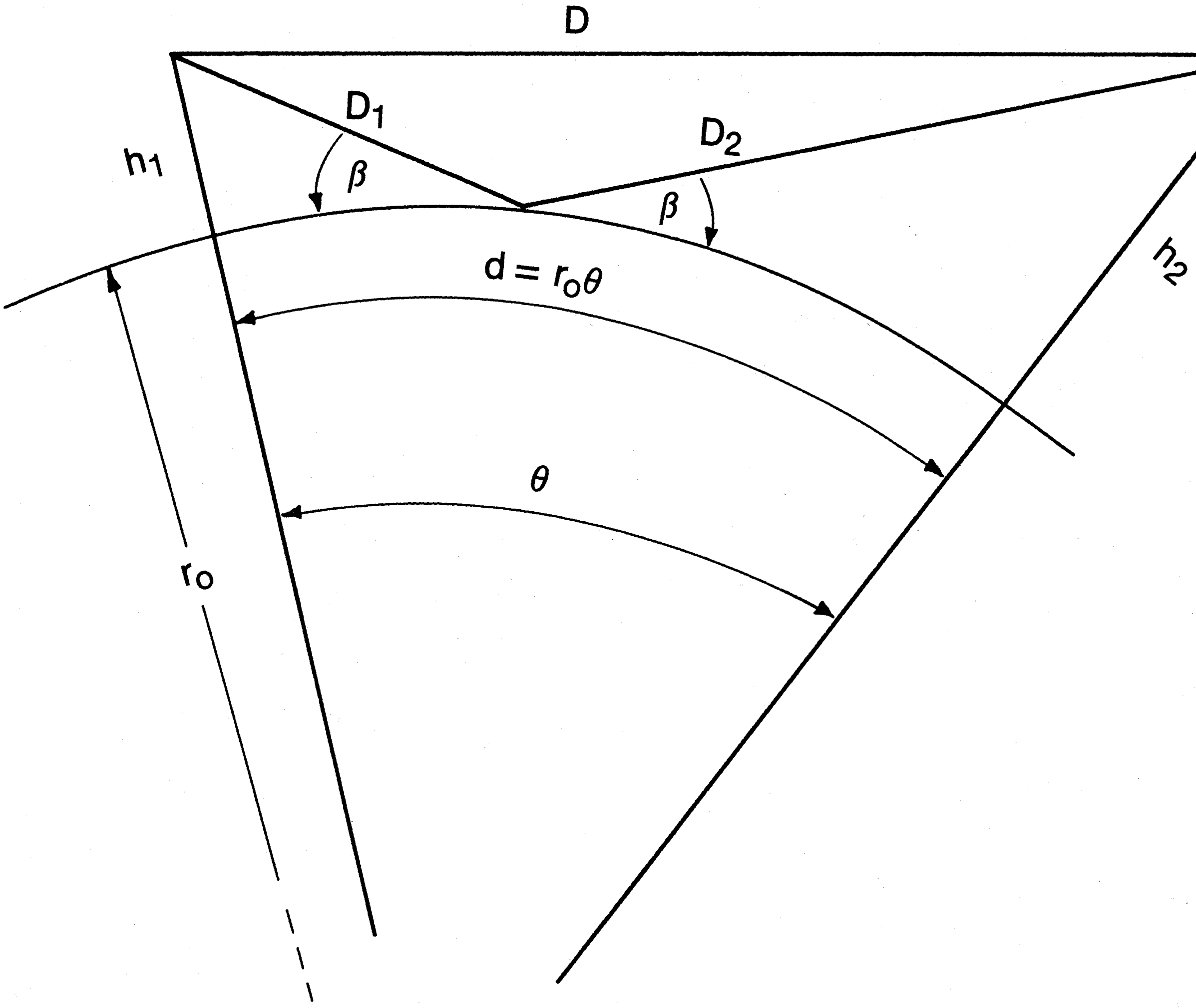

Figure 1. Geometrical representation for groundwave calculations.

Closed form solutions for D_1, D_2, and β are not possible, but an iteration using the following relations will converge. Let

$$D_i = \sqrt{r_0^2 \sin^2 \beta + A_i} - a \sin \beta \quad , \qquad i = 1, 2 \quad , \tag{40}$$

where

$$A_i = 2r_0 \, h_i + h_i^2 \quad . \tag{41}$$

Using the law of cosines, it can be shown that

$$(D_1 + D_2)^2 - 4D_1D_2 \sin^2 \beta - D^2 = 0 \quad . \tag{42}$$

Perform the following iteration:

(i) For an n-th approximation to sin β, S_n, compute D_1 and D_2 using (40).

(ii) Compute $e_n = (D_1 + D_2)^2 - 4D_1D_2 \sin^2 \beta - D^2$. (43)

If e_n is sufficiently small, (42) is satisfied and iteration has converged. Otherwise,

(iii) $$S_{n+1} = S_n + e_n \left(\frac{S_n - S_{n-1}}{e_n - e_{n-1}} \right) \quad . \tag{44}$$

(This assumes that e_n is an approximately linear function of S_n.) Return to (i) and do another iteration.

For small β, $D_1 + D_2 \sim D$, so that computing $D_1 + D_2$ directly results in unacceptable round-off error. To avoid this loss of precision, use

$$D_1 + D_2 - D = \frac{4 \, D_1D_2 \sin^2 \beta}{D_1 + D_2 + D} \quad . \tag{45}$$

When the receiving antenna is near the radio horizon of the transmitting antenna, the field is difficult to compute because diffraction effects are important, but the direct ray is also present. In this region, it is necessary to numerically integrate the full-wave theory integral shown below:

$$E = 9.487 \;\; P_E \sqrt{\frac{v}{12 \sin \theta}} \; \frac{e^{j3\pi/4}}{r_0} \int_{\Gamma}^{e} e^{-j\gamma t} \, F_I(Q,t) \, dt \quad , \tag{46}$$

where

$$v = (\gamma r_0/2)^{1/3}\ , \ x = v\Theta, \text{ and } Q = -jv\delta \quad . \tag{47}$$

The contour Γ comes from $\infty\ e^{-j\pi/4}$ on a straight line with a slope of -1 to $(\mathrm{Re}(t_0) - j/2\ \mathrm{Im}(t_0))$ and then proceeds on a straight line with slope +1 to $\infty\ e^{-j3\pi/4}$. t_0 is the first pole of $F_I(Q,t)$. Re designates the "real part of" and Im designates the "imaginary part of."

$$F_I(Q,t) = \frac{H_1(h_1)\ H_2(h_2)}{\dfrac{W_1'(t)}{W_1(t)} - Q} \quad . \tag{48}$$

The height gain functions are

$$H_1(h) = \frac{W_1(t - y)}{W_1(t)} \tag{49}$$

and

$$H_2(h) = -.5j\ W_2(t - y)[W_1'(t) - QW_1(t)] \\ -W_1(t - y)[W'_2(t) - QW_2(t)] \quad , \tag{50}$$

where $y = \gamma h/v$. Note that $H_1(0) = H_2(0) = 1$. The functions $W_n(t)$ are Airy functions (Wait, 1964) which satisfy

$$W_n''(t) = tW_n(t) \quad . \tag{51}$$

The computations of the groundwave signal strength that follow from the preceding equations are time-consuming. Therefore, it was decided to seek a faster procedure for determination of the groundwave signal strength. The method adopted relies upon results of calculations of groundwave signal loss that are plotted as families of curves that are then represented by a set of numerical coefficients. The coefficients for a given circuit are determined by interpolating between the input coefficients, and then evaluating the simple formulas given below.

Specifically, the determination of the coefficients is as follows: Using program GWSNR, a family of curves of loss as a function of frequency and distance was generated and plotted for each of the following antenna height combinations:

(1 m, 1 m), (1 m, 5 m), (1 m, 10 m), (1 m, 50 m), ... (1 m, 50 km)
(5 m, 5 m), (5 m, 10 m), (5 m, 50 m), (5 m, 100 m), ... (5 m, 50 km)
.
.
.
(10 km, 10 km), (10 km, 50 km)
(50 km, 50 km) .

Examples for heights (1 m, 1 m) and (1 m, 10 km) are given in Figure 2. The permittivity and ground conductivity were fixed at 10.0 and 0.005 mho/m. The antenna polarity was assumed vertical. For each antenna combination, two equations were fitted to the 2 MHz through 30 MHz curve. The equations were of the type

$$y = a_0 + a_1 \log (d - d_1) \tag{52}$$

$$y = a_{00} + a_{11} (d - d_2) \quad , \tag{53}$$

where d is the great circle distance, d_1 is the distance at which the groundwave loss is greater than the free space loss, and $d_2 = d_1 + 110$ km.

When d is less than d_1, the loss is calculated as

$$\text{Loss} = 32.45 + 20.0 \log_{10} (d \cdot f) \quad . \tag{54}$$

When d is greater than d_1, the loss is calculated as

$$\text{Loss} = [32.45 + 20.0 \log (d \cdot f)] + [a_0 + a_1 \log(d - d_1)] \quad . \tag{55}$$

When d is greater than d_1 + 110 km, the loss is calculated as

$$\text{Loss} = [32.45 + 20.0 \log (d \cdot f)] + [a_{00} + a_{11}(d - d_2)] \quad . \tag{56}$$

The a_{11} coefficient does not vary with height until one of the antenna heights exceeds 5 km. When the 5-km height is exceeded, a constant factor is subtracted from coefficient a_{11} before calculation of the equation. The a_0, a_1, and a_{00} coefficients vary both with frequency and antenna height, and therefore must be interpolated in two dimensions. After analyses of all the height combinations and frequency levels, the sets of coefficients to be used for interpolation are the following:

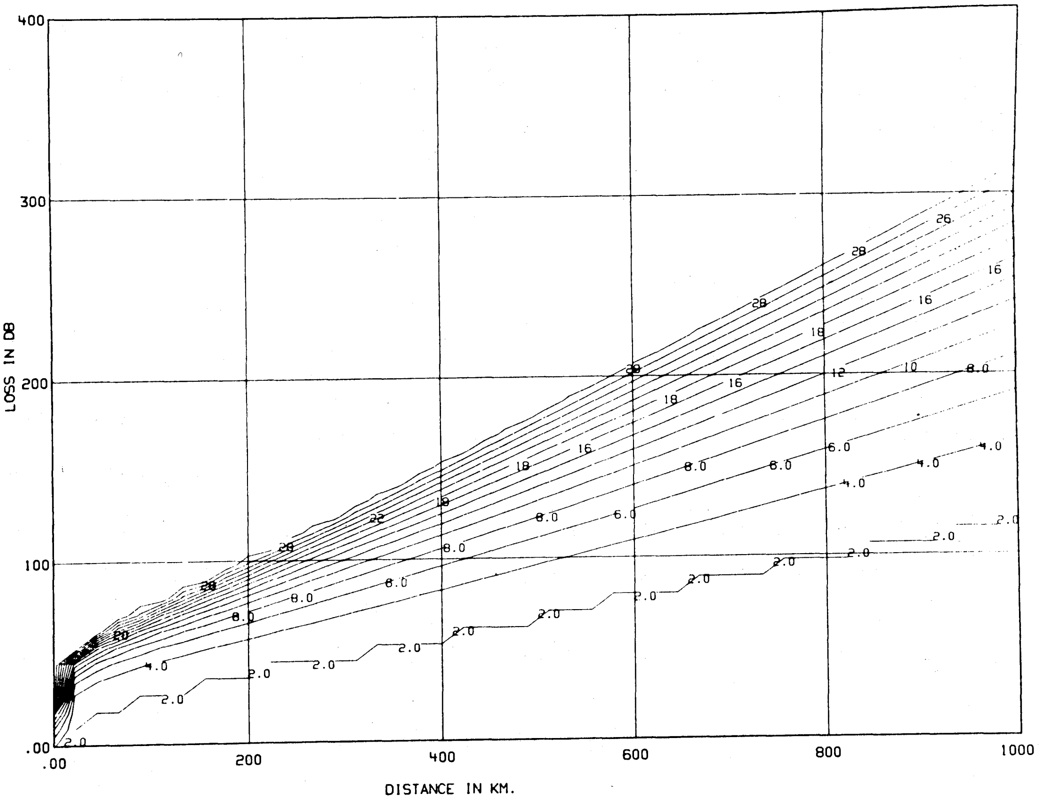

Figure 2a. Groundwave loss (in dB) for antenna heights of 1 m, parametric in frequency (2 to 30 MHz), for transmitter and receiver.

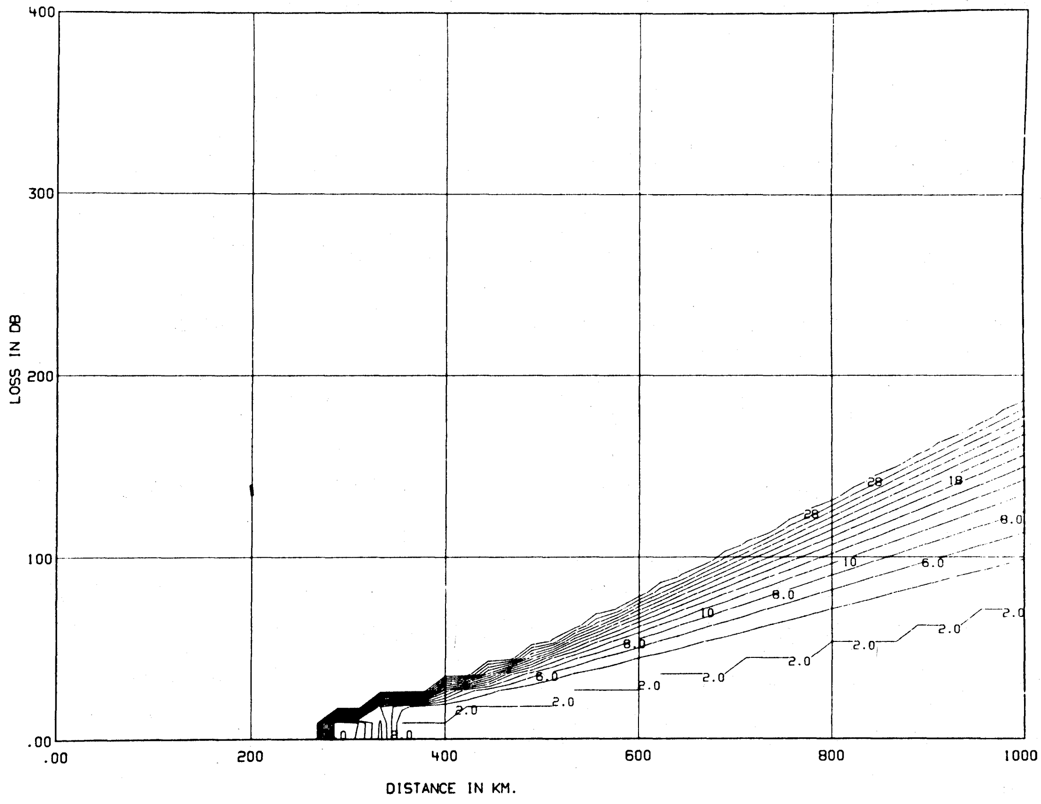

Figure 2b. Groundwave loss (in dB), parametric in frequency (2 to 30 MHz), for antenna heights of 1 m for the transmitter and 10 km for the receiver.

d_1 for all height combinations and frequencies 2 MHz to 30 MHz,
a_{11} for each frequency 2 MHz to 30 MHz,
a_{00} for all height combinations at frequencies 2 MHz and 30 MHz, and
a_0 for all height combinations at frequencies 2 MHz and 30 MHz.

The final sets of distances and coefficients are used as constant tables in subroutine GWAVE. When subroutine GWAVE is executed, the inputs are antenna heights, frequency, and path length. The coefficients are interpolated in these three dimensions, and the output is ground loss in dB. The angle of arrival of the groundwave is calculated as the direct wave when the antennas are within line-of-sight and as the horizonal angle when the antennas are not within line-of-sight. An error analyses of this model will be presented in Section 4.

4. CIRCUIT CALCULATIONS USING THE AIR-TO-GROUND HF PROPAGATION MODEL

In this section the air-to-ground HF propagation model is used to calculate circuit parameters for a number of different paths contained within Europe. This section provides a description of the input required for the prediction program and the output generated. Also a discussion of the accuracy and speed of the program is presented.

In Figure 3, two ground-to-air circuits are shown in a schematic fashion. The letter "T" represents the location of the transmitter, and there are two receiving aircraft pictured. The great circle paths for a short propagation circuit and a long circuit are shown as the dashed lines. The letter "A" is used to indicate the path mid-point for both circuits. This is the location at which the E and F layer parameters are evaluated. The solid line adjacent to the great circle path for the short circuit represents the groundwave. For the long path, the points B and C represent the penetration of the radiowave through the lower ionosphere. This is the location where the ionospheric loss is evaluated for the up-going (B) and down-coming (C) positions of the path. The points "D" and "E" indicate the points of reflection if two ionospheric reflections were to occur along the longer propagation path.

In the discussions that follow, reference will be made to a number of HF circuits that were simulated for this study. The particulars of the circuits are given in Table 3.

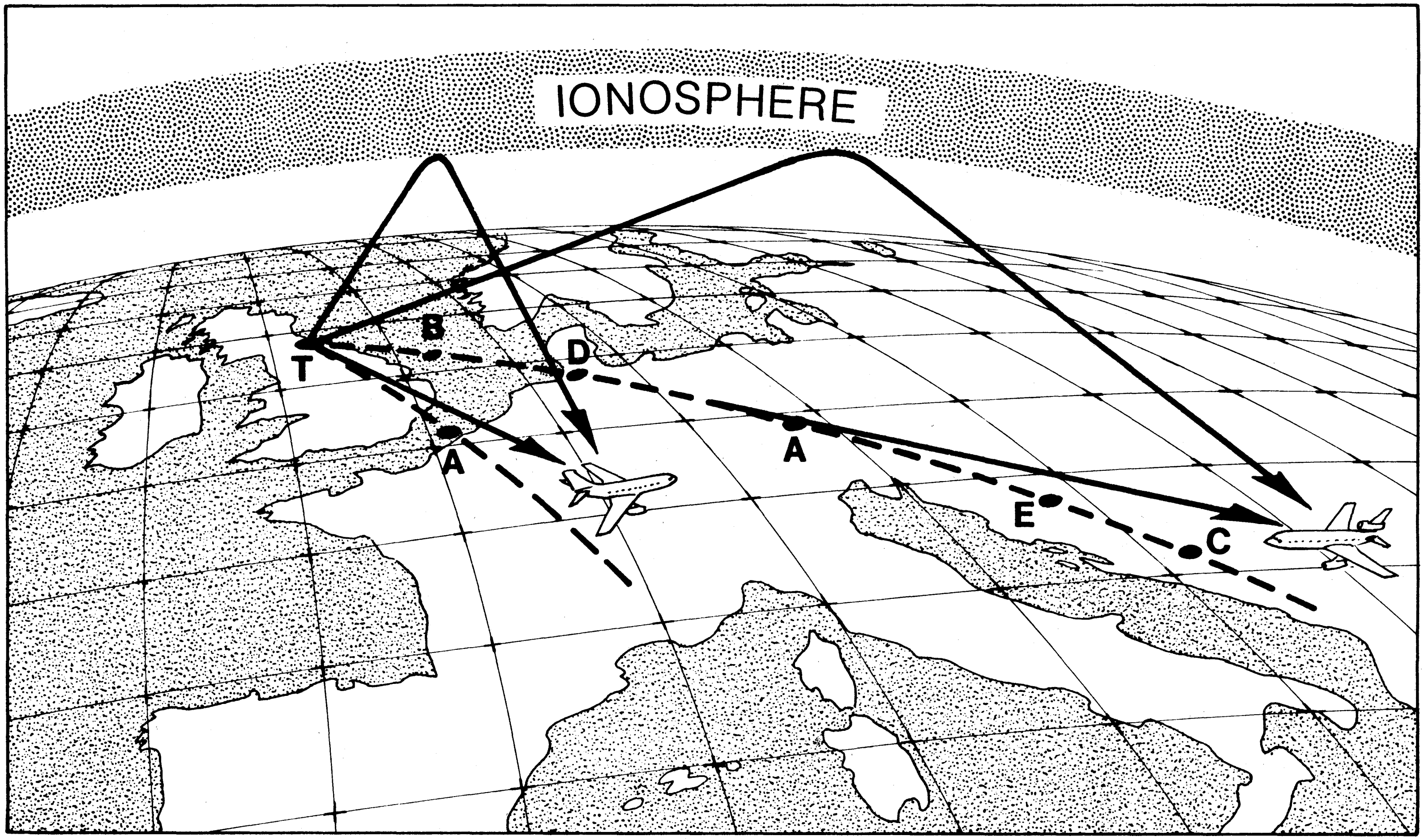

Figure 3. Conceptual air-to-ground HF skywave and groundwave circuits.

Table 3. Characteristics of Simulated Circuits for Frequencies 3, 5, 8, 11, 15, 18, 21, and 26 MHz

Circuit Number	Transmitter Location*	Receiver Location	Transmitter Power (watts)	Receiver Height (km)
1	45°N,5°E	45°N,10°E	100	0
2	45°N,5°E	45°N,15°E	100	0
3	45°N,5°E	45°N,20°E	500	0
4	45°N,5°E	45°N,25°E	500	0
5	45°N,5°E	45°N,30°E	500	0
6	55°N,15°E	50°N,15°E	100	0
7	55°N,15°E	45°N,15°E	100	0
8	55°N,15°E	40°N,15°E	100	0
9	55°N,15°E**	35°N,15°E	500	0
10	55°N,15°E**	30°N,15°E	500	0
11	45°N,10°E	45°N,11°E	100	10
12	45°N,10°E	45°N,12°E	100	10
13	45°N,10°E	45°N,13°E	100	10
14	45°N,10°E	45°N,14°E	100	10
15	45°N,10°E	45°N,15°E	100	10
16	45°N,10°E	45°N,16°E	200	10
17	45°N,10°E	45°N,18°E	200	10
18	45°N,10°E	45°N,20°E	200	10
19	45°N,10°E	45°N,22°E	200	10

*All transmitters are on the surface of the earth.

**Path length greater than 2000 km; results not included in summary in Table 6.

4.1 Program Input and Output

The following parameters must be specified by the user in order to compute HF propagation parameters with the air-to-ground model:

(1) Location of transmitters and receivers.
(2) Time for which calculations are to be performed--month and hour.
(3) Solar activity conditions.
(4) Frequency for which calculations are to be performed.
(5) Transmitter power (or powers).
(6) Minimum useful elevation angle at the transmitters and/or receivers.
(7) Man-made noise level as indicated in Table 2.
(8) Required signal level above the noise in order to assure proper operation of the circuit.
(9) Required reliability (discussed below).
(10) Maximum tolerable time-delay difference between two modes. This time-delay difference is used to determine the likelihood of multipath interference. The quantities used depend on the quality of reception (reliability) expected for the circuit.
(11) Ground conductivity and ground constant if the default values (σ = 0.005 mho/m and ε = 15) are not desired.

The circuit reliability is based upon the monthly median estimates of propagation parameters and their distributions and represents the fraction of days in the month at the given hour that successful communication is expected at a specific operating frequency. The primary factor in determining the circuit reliability is the median S/N_0 ratio. A minimum required S/N_0 ratio is associated with the desired grade of service. This ratio depends upon many factors, such as modulation index, signalling rates and codes, and includes effects of fading, error-correcting schemes, optimum modulation and detection techniques, and diversity schemes.

Mathematically, the circuit reliability can be expressed as a dimensionless quantity R given by

$$R = qp/100 \quad , \qquad (57)$$

where R, q, p are expressed as percentages; q is the skywave availability defined as the percentage probability that radio signals can propagate at a given hour over a given skywave path; and p is the percentage probability that the mean received signal-to-noise ratio is above the required signal-to-noise ratio.

In the prediction program, the two factors q, p do not need to be associated with the same propagation mode. The program selects the lowest loss of all the likely modes and combines this with the highest likelihood of ionospheric support to calculate the circuit reliability. A detailed discussion of the effect of signal-to-noise on reliability has been most recently described by Maslin (1978).

As was indicated in Section 2, for each hour of time that is specified, a latitude-longitude grid is generated in a subroutine named MAPPR. A number of parameters are evaluated at the grid points. These parameters are listed in Table 4. Table 5 provides a listing of the subroutine HFŠKGD, which controls the input and output for the calculations of path parameters and statistics.

The output of the air-to-ground computer program can be varied to satisfy the requirements of the user. The complete output is shown in Figure 4 for the case of a circuit with a 100 W transmitter at 45°N, 5°E on a frequency of 11 MHz and receiver on the ground at 45°N, 10°E. Shown are the various parameters involved in the system performance predictions by tabulating the geometry used for the ray paths, the ionosphere characteristics involved, and the expected performance of each mode for selected times and frequencies.

The first line contains the universal time, month, day, year, and the solar activity level as indicated by the 12-month running average Zurich sunspot number. The second and third lines contain the coordinates and heights of the transmitter and receiver, the azimuthal bearings (in degrees east of north) of the receiver from the transmitter and vice versa, and the length of the circuit in kilometers. The fourth line contains the frequency, the transmitter power, the hourly median signal-to-noise ratio required to provide the type of service needed, the type of man-made noise at the receiver location, the required percent reliability, the multipath power tolerance in decibel, and the multipath delay tolerance in milliseconds.

The next section of the figure provides the information concerning the data representative of the skywave reflection area. The following are tabulated:

DIST FM TX -	the distance in kilometers along the great-circle path from the transmitter toward the receiver to each reflection area where the ionosphere is sampled,
LATITUDE -	the latitude in degrees of the sample location--southern latitudes are indicated by a (-) preceding the degrees,
LONGITUDE -	the longitude of the sample location--east longitudes are indicated by a (-) preceding the degrees,
GEOM LAT -	the geomagnetic latitude,
TIME HOURS -	the local time at the sample location,

Table 4. Input-Output Parameter Description for Subroutine MAPPR

SUBROUTINE MAPPR (SSN, GMT, MONDAY, GLAT, GLONG, GRD)

Input:

SSN = 12 month smoothed Zurich sunspot number

GMT = universal time

MONDAY = month and day

GLAT(1) = southern-most geographic latitude,
+ = north, - = south

GLAT(2) = northern-most geographic latitude,
+ = north, - = south

GLONG(1) = western-most longitude,
+ = west, - = east

GLONG(2) = eastern-most longitude,
+ = west, - = east

Output:

GRD (1) = latitude of the southern-most point in the grid (radians)
(2) = latitude of the northern-most point in the grid (radians)
(3) = step size between latitude points (radians)
(4) = longitude of the eastern-most point of the grid (radians)
(5) = longitude of the western-most point of the grid (radians)
(6) = step size between longitude points (radians)
(7) = universal time for this grid
(8) = 12-month smoothed mean sunspot number for this grid
(9) = month and day for this grid (MMDD)
(10) = 100 km gyrofrequency for the first grid point
(11) = FoE for first grid point
(12) = FoEs upper decile for first grid point
(13) = FoEs median for first grid point
(14) = FoEs lower decile for first grid point
(15) = HoF2 for first grid point
(16) = FoF2 for first grid point
(17) = M3000 for first grid point
(18) = 300 km gyrofrequency for first grid point
(19) = absorption for the first grid point
(20) = intercept of regression on K factor (from PMUFK)
(21) = slope of regression on K factor (from PMUFK)
(22) = noise for the first grid point (from WOMAP)
(23) = ground constant for the first grid point (from WOMAP)
(24) = FOT factor for first grid point (from F2DIS)
(25) = HPF factor for first grid point (from F2DIS)
(26) = excess system loss for first grid point (from SYSSY)
(27) = upper standard deviation of excess system loss (from SYSSY)

Table 4. Input-Output Parameters Description for Subroutine MAPPR (continued)

GRD (28) = lower standard deviation of excess system loss (from SYSSY)
(29) = error in excess system loss for the first grid point (from SYSSY)
(30) = upper standard deviation of error in excess system loss (from SYSSY)
(31) = lower standard deviation of error in excess system loss (from SYSSY)
(32) = 100 km gyrofrequency for second point in the grid

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GRD (54) = 100 km gyrofrequency for third point in grid

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GRD (9 + 22 x No. of grid points) = lower standard deviation of the error in excess system loss for the last grid point (from SYSSY)
GRD (10 + 22 x No. of grid points) = first atmospheric noise coefficient

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GRD (468 + 22 x No. of grid points) = last atmospheric noise coefficient

MAPPR uses the standard HFMUFES data tape, or data file, to make parameter predictions.

Table 5. Input-Output Parameter Description for Subroutine HFSKGD

SUBROUTINE HFSKGD (PPRAM, NPRAM, FPIN, FPOT)

A routine to calculate path parameters and statistics for transmitter to receiver circuit.

Input:

Path Parameters

PPRAM (1) = power to transmitter in kW
(2) = frequency in MHz
(3) = transmitter latitude in degrees
(4) = transmitter longitude in degrees
(5) = height of transmitter in km
(6) = receiver latitude in degrees
(7) = receiver longitude in degrees
(8) = height of receiver in km

System Parameters

NPRAM (1) = required signal-to-noise ratio in dB
(2) = man-made noise:
 1 = urban
 2 = suburban
 3 = rural
 >3 = user designated
(3) = required circuit reliability
(4) = minimum difference in signal power in dB for multipath
(5) = maximum difference in time delay in ms for multipath

FPIN = input grid of ionospheric characteristics and the statistics associated with them

Output:

FPOT (1) = mean path loss (dB) for skywave
(2) = upper decile of path loss
(3) = lower decile of path loss
(4) = mode indicator
(5) = angle of arrival skywave
(6) = angle of arrival direct
(7) = noise level
(8) = circuit reliability
(9) = time delay in ms
(10) = multipath probability
(11) = groundwave loss in dB

All control points must remain within the grid of latitude and longitude that was used to generate FPIN.

ABSORP FAC - an index of ionospheric absorption depending primarily upon the solar zenith angle,

E LAYER CR - the maximum frequency in megahertz returned from the E region at vertical incidence,

F LAYER BT - the height of the lower part of the F region in kilometers,

HT OF F MAX- the height of the maximum ionization of the F region in kilometers,

GYRO FREQ - the gyrofrequency in megahertz at 100 km,

F LAYER CT - the critical frequency of the F region in megahertz,

ES UP DEC - the upper decile of the frequency supported by sporadic E at vertical incidence,

ES MED VAL - the vertical incident monthly median frequency supported by sporadic E,

ES LOW DEC - the lower decile of sporadic E,

EX SYS STS - an estimate of propagation losses in decibels not specifically included in the computations, and

ANO STATIS - an estimate of the noise statistics in decibels.

The next part of the figure tabulates parameters associated with the expected modes of propagation: (E MODES), (F MODES), and (E F MODES). For each mode the tabulation includes:

NO OF HOPS - the number of ionospheric reflections considered for each mode,

TK OFF ANG - the vertical angle of departure and arrival corresponding to the number of hops,

VIRTUAL HT - the apparent height of ionospheric reflection for the mode,

TM DLY MS - the propagation time for the mode in milliseconds

SKY WV LOS - a loss in decibels due to the free-space spreading of the transmitted energy as it travels via the skywave,

ABSRP LOSS - loss in decibels due to absorption in the lower ionosphere,

GRD REF LS - a loss in decibels due to ground reflection when multiple ionosphere reflections are involved,

TRNSMSN LS - a summation of the above losses (including the "excess system loss"),

FIELD STRN - the monthly median strength of the signal at the receiver in decibels relative to 1 μV/m,

SIG POWER - an estimate of the power available at the receiver in decibels referred to 1 W,

S/N IN DB - total signal power relative to noise power in a 1 Hz bandwidth at the receiver input, FRACT DAYS - the percentage of days within the month that this mode of propagation is expected,

FRACT S/N - the fraction of days that the required S/N ratio is expected to be equalled or exceeded,

RELIABILITY- the percentage of days within the month that the required S/N ratio is expected to be equalled or exceeded and the mode is expected to be supported by the ionosphere [the product of (FRACT DAYS) and (FRACT S/N), and

SERV PROB - the likelihood that the circuit reliability requirement will be met.

The bottom of the figure provides a listing of the most important characteristics for the frequency being calculated. The third from the last line shows the skywave mode with the least loss, reliability, the multipath probability for that mode, the path loss in decibels, the upper and lower decile of the path loss, and the time delay in milliseconds for the mode. The next to the last line shows the angle of arrival of the mode with the least loss, the noise level at the receiver location, and the circuit reliability. The last line shows the angle of arrival of the direct wave and the loss in decibels of the groundwave mode.

If the reader requires further explanation of the output parameters, reference should be made to the work of Haydon et al. (1976).

4.2 Air-to-ground Program Speed and Accuracy

Figures 4 through 22 show the results of calculations for all the circuits listed in Table 3. The calculations are for a universal time of 1100 hours for solar activity conditions appropriate for December 1982. For each of the circuits, calculations were performed for the frequencies listed in Table 3, but only 11-MHz results are shown. The path lengths range from 79 km to 2780 km.

The air-to-ground computer program was designed to calculate circuit parameters for a large number of frequencies and path lengths in a given area for a given time. It takes a little over 4 s on the Boulder Laboratory CYBER 750 to generate the values of all the parameters on the grid using subroutine MAPPR. Once the grid is specified, it takes about 60 ms to compute the skywave propagation characteristics for each frequency specified. In order to calculate the same parameters using the HFMUFES program, the ionospheric and noise parameters would have to be evaluated each time a different frequency and circuit length are specified. Thus the more circuits and frequencies to be calculated, the faster the air-to-ground program is relative to HFMUFES. Subroutine HFSKGD calculates skywave parameters about six times faster than HFMUFES. The calculations of the groundwave loss in the air-to-

```
 TIME= 11.00UT  DATE=12/15/82     SSN=  88.

                    LAT.     LONG. DEG. E     HEIGHT    AZMOUTH     DIST. KM
      TRANSMITTR    45.0         5.0            1.0       88.2        393.1
        RECEIVER    45.0        10.0            1.0      271.8        393.1

 FREQ-MHZ  PWR-KW  REQ S/N-DB  MM-NOISE  REQ-REL  MP-SIGPOW  MP-TMDLY
 11.0       .100      55        SUBURBAN     90     4.0       2.000


                      1            2            3            4            5
DIST FM TX      196.542       98.271      294.813      196.542      196.542
  LATITUDE       45.027       45.020       45.020       45.027       45.027
 LONGITUDE       -7.500       -6.250       -8.750       -7.500       -7.500
GEOM. LAT.       46.563       46.806       46.308       46.563       46.563
TIME HOURS       11.500        0.000        0.000        0.000        0.000
ABSORP FAC         .799        0.000        0.000        0.000        0.000
E LAYER CR        2.990        0.000        0.000        0.000        0.000
F LAYER BT      221.349        0.000        0.000        0.000        0.000
HT OF FMAX      272.919        0.000        0.000        0.000        0.000
GYRO FREQ.        1.284        0.000        0.000        0.000        0.000
F LAYER CT       10.089        0.000        0.000        0.000        0.000
 ES UP DEC        3.738        0.000        0.000        0.000        0.000
ES MED VAL        3.219        0.000        0.000        0.000        0.000
ES LOW DEC        2.647        0.000        0.000        0.000        0.000
EX SYS STS        9.000        6.835        4.311        3.062        2.062        1.062
AND STATIS     -174.848        8.034        6.518        3.392        2.301        5.564


                           E MODES                          F MODES                          EF MODES
NO OF HOPS        1.000        2.000        1.000        2.000        3.000        0.000        0.000
TK OFF ANG        0.000        0.000       54.452       74.938       80.293        0.000        0.000
VIRTUAL HT        0.000        0.000      289.052      386.830      406.485        0.000        0.000
TM DLY MS.        0.000        0.000        2.357        5.352        8.272        0.000        0.000
SKY WV LOS     1000.000     1000.000      110.262      117.384      121.167     1000.000     1000.000
ABSRP LOSS     1000.000     1000.000        2.433        4.127        6.069     1000.000     1000.000
GND REF LS     1000.000     1000.000        0.000         .462         .927     1000.000     1000.000
TRNSMSN LS     1000.000     1000.000      121.695      130.973      137.162     1000.000     1000.000
FIELD STRN    -1000.000    -1000.000       26.333       17.055       10.866    -1000.000    -1000.000
 SIG POWER    -1000.000    -1000.000     -101.695     -110.973     -117.162    -1000.000    -1000.000
S/N IN DB.    -1000.000    -1000.000       61.583       52.305       46.116    -1000.000    -1000.000
FRACT DAYS        0.000        0.000         .580         .496         .495        0.000        0.000
FRACT  S/N        0.000        0.000         .762         .376         .135        0.000        0.000
RELIABILTY        0.000        0.000         .443         .187         .067        0.000        0.000
SERV. PROB        0.000        0.000         .086         .001         .000        0.000        0.000


 MODE= 1 F   MULTI PTH PROB= .01   PATH LOSS=112.9  UD=108.9  LD=117.0  TIM DLY MS=  2.357
 ANGLE OF ARRIVAL SKYWAVE=   54.5   NOISE LEVEL= -163.3   CIRCUIT RELIABILITY=  .76
 ANGLE OF ARRIVAL DIRECT=    -.0   GROUNDWAVE LOSS=   218.3
```

Figure 4. Output of air/ground model for circuit (1) in Table 3, 11 MHz.

```
  TIME= 11.00UT  DATE=12/15/82     SSN=  88.

                   LAT.    LONG. DEG. E    HEIGHT    AZMOUTH     DIST. KM
     TRANSMITTR    45.0         5.0          1.0       86.5         785.8
       RECEIVER    45.0        15.0          1.0      273.5         785.8

  FREQ-MHZ  PWR-KW  REQ S/N-DB  MM-NOISE  REQ-REL  MP-SIGPOW  MP-TMDLY
  11.0      .100      55        SUBURBAN     90     4.0     2.000


                    1          2          3          4          5
DIST FM TX    392.896    196.448    589.344    392.896    392.896
  LATITUDE     45.109     45.082     45.082     45.109     45.109
 LONGITUDE    -10.000     -7.498    -12.502    -10.000    -10.000
GEOM. LAT.     46.144     46.616     45.619     46.144     46.144
TIME HOURS     11.667      0.000      0.000      0.000      0.000
ABSORP FAC       .803      0.000      0.000      0.000      0.000
E LAYER CR      2.995      0.000      0.000      0.000      0.000
F LAYER BT    221.545      0.000      0.000      0.000      0.000
HT OF FMAX    274.917      0.000      0.000      0.000      0.000
GYRO FREQ.      1.288      0.000      0.000      0.000      0.000
F LAYER CT     10.150      0.000      0.000      0.000      0.000
 ES UP DEC      3.750      0.000      0.000      0.000      0.000
ES MED VAL      3.243      0.000      0.000      0.000      0.000
ES LOW DEC      2.655      0.000      0.000      0.000      0.000
EX SYS STS      9.000      6.556      4.111      3.022      2.022      1.022
AND STATIS   -174.715      8.045      6.526      3.427      2.278      5.581


                       E MODES                          F MODES                         EF MODES
NO OF HOPS      1.000      2.000      1.000      2.000      3.000      0.000      0.000
TK OFF ANG      0.000      0.000     29.792     54.577     69.311      0.000      0.000
VIRTUAL HT      0.000      0.000    241.286    290.291    366.860      0.000      0.000
TM DLY MS.      0.000      0.000      3.133      4.727      7.846      0.000      0.000
SKY WV LOS   1000.000   1000.000    112.733    116.307    120.707   1000.000   1000.000
ABSRP LOSS   1000.000   1000.000      3.859      4.883      6.416   1000.000   1000.000
GND REF LS   1000.000   1000.000      0.000       .647      1.345   1000.000   1000.000
TRNSMSN LS   1000.000   1000.000    125.592    130.837    137.468   1000.000   1000.000
FIELD STRN  -1000.000  -1000.000     22.436     17.191     10.560  -1000.000  -1000.000
 SIG POWER  -1000.000  -1000.000   -105.592   -110.837   -117.468  -1000.000  -1000.000
S/N IN DB.  -1000.000  -1000.000     57.677     52.432     45.801  -1000.000  -1000.000
FRACT DAYS      0.000      0.000       .994       .586       .499      0.000      0.000
FRACT  S/N      0.000      0.000       .620       .380       .122      0.000      0.000
RELIABILTY      0.000      0.000       .616       .223       .061      0.000      0.000
SERV. PROB      0.000      0.000       .036       .001       .000      0.000      0.000


 MODE= 1 F   MULTI PTH PROB= .01   PATH LOSS=117.2  UD=113.2  LD=121.2  TIM DLY MS=  3.133
 ANGLE OF ARRIVAL SKYWAVE=   29.8   NOISE LEVEL= -163.3   CIRCUIT RELIABILITY=  .62
 ANGLE OF ARRIVAL DIRECT=    -.0   GROUNDWAVE LOSS=   298.3
```

Figure 5. Output of air/ground model for circuit (2) in Table 3, 11 MHz.

```
  TIME= 11.00UT   DATE=12/15/82     SSN=   88.

                     LAT.    LONG. DEG. E     HEIGHT    AZMOUTH    DIST. KM
      TRANSMITTR     45.0         5.0            1.0      84.7       1177.7
        RECEIVER     45.0        20.0            1.0     275.3       1177.7

  FREQ-MHZ  PWR-KW   REQ S/N-DB  MM-NOISE   REQ-REL  MP-SIGPOW  MP-TMDLY
  11.0      .500       55       SUBURBAN       90     4.0      2.000

                   1           2           3           4           5
DIST FM TX      588.874     294.437     883.311     588.874     588.874
  LATITUDE       45.246      45.184      45.184      45.246      45.246
 LONGITUDE      -12.500      -8.742     -16.258     -12.500     -12.500
GEOM. LAT.       45.777      46.467      44.971      45.777      45.777
TIME HOURS       11.833       0.000       0.000       0.000       0.000
ABSORP FAC         .804       0.000       0.000       0.000       0.000
E LAYER CR        2.989       0.000       0.000       0.000       0.000
F LAYER BT      221.780       0.000       0.000       0.000       0.000
HT OF FMAX      276.680       0.000       0.000       0.000       0.000
GYRO FREQ.        1.294       0.000       0.000       0.000       0.000
F LAYER CT       10.196       0.000       0.000       0.000       0.000
 ES UP DEC        3.753       0.000       0.000       0.000       0.000
ES MED VAL        3.252       0.000       0.000       0.000       0.000
ES LOW DEC        2.653       0.000       0.000       0.000       0.000
EX SYS STS        9.009       7.160       4.104       3.019       2.019       1.019
AND STATIS     -174.583       8.056       6.534       3.462       2.254       5.598

                         E MODES                      F MODES                          EF MODES
NO OF HOPS        1.000       2.000       1.000       2.000       3.000       0.000       0.000
TK OFF ANG        7.600       0.000      19.457      39.398      54.728       0.000       0.000
VIRTUAL HT      107.434       0.000     231.899     255.839     291.751       0.000       0.000
TM DLY MS.        4.024       0.000       4.312       5.286       7.114       0.000       0.000
SKY WV LOS      114.908    1000.000     115.508     117.277     119.856    1000.000    1000.000
ABSRP LOSS        9.189    1000.000       5.394       6.180       7.312    1000.000    1000.000
GND REF LS        0.000    1000.000       0.000       8.164       9.438    1000.000    1000.000
TRNSMSN LS      133.107    1000.000     129.911     140.630     145.615    1000.000    1000.000
FIELD STRN       21.911   -1000.000      25.107      14.388       9.402   -1000.000   -1000.000
 SIG POWER     -106.117   -1000.000    -102.921    -113.640    -118.626   -1000.000   -1000.000
S/N IN DB.       57.142   -1000.000      60.338      49.619      44.634   -1000.000   -1000.000
FRACT DAYS         .994       0.000        .994        .885        .592       0.000       0.000
FRACT  S/N         .594       0.000        .718        .258        .091       0.000       0.000
RELIABILTY         .591       0.000        .714        .228        .054       0.000       0.000
SERV. PROB         .021       0.000        .086        .000       0.000       0.000       0.000


 MODE= 1 E    MULTI PTH PROB= .01     PATH LOSS=123.9  UD=120.0  LD=127.9  TIM DLY MS=  4.024
 ANGLE OF ARRIVAL SKYWAVE=     7.6     NOISE LEVEL= -163.3   CIRCUIT RELIABILITY=  .59
 ANGLE OF ARRIVAL DIRECT=     -.0     GROUNDWAVE LOSS=   375.6
```

Figure 6. Output of air/ground model for circuit (3) in Table 3, 11 MHz.

```
  TIME= 11.00UT  DATE=12/15/82     SSN=  88.

                    LAT.    LONG. DEG. E    HEIGHT     AZMOUTH     DIST. KM
      TRANSMITTR  45.0            5.0          1.0       82.9        1568.6
        RECEIVER  45.0           25.0          1.0      277.1        1568.6

  FREQ-MHZ  PWR-KW  REQ S/N-DB  MM-NOISE  REQ-REL  MP-SIGPOW  MP-TMDLY
  11.0      .500      55       SUBURBAN      90     4.0     2.000


                  1           2           3           4           5
DIST FM TX     784.285     392.142    1176.427     784.285     784.285
  LATITUDE      45.439      45.328      45.328      45.439      45.439
 LONGITUDE     -15.000      -9.981     -20.019     -15.000     -15.000
GEOM. LAT.      45.465      46.358      44.369      45.465      45.465
TIME HOURS      12.000       0.000       0.000       0.000       0.000
ABSORP FAC        .803       0.000       0.000       0.000       0.000
E LAYER CR       2.981       0.000       0.000       0.000       0.000
F LAYER BT     221.990       0.000       0.000       0.000       0.000
HT OF FMAX     278.360       0.000       0.000       0.000       0.000
GYRO FREQ.       1.301       0.000       0.000       0.000       0.000
F LAYER CT      10.244       0.000       0.000       0.000       0.000
 ES UP DEC       3.751       0.000       0.000       0.000       0.000
ES MED VAL       3.259       0.000       0.000       0.000       0.000
ES LOW DEC       2.650       0.000       0.000       0.000       0.000
EX SYS STS       9.014       7.740       4.084       3.014       2.014       1.014
AND STATIS    -174.450       8.067       6.542       3.497       2.231       5.616


                      E MODES                     F MODES                          EF MODES
NO OF HOPS       1.000       2.000       1.000       2.000       3.000       0.000       0.000
TK OFF ANG       3.747       0.000      13.864      29.984      43.853       0.000       0.000
VIRTUAL HT     101.019       0.000     230.382     242.761     264.897       0.000       0.000
TM DLY MS.       5.313       0.000       5.570       6.267       7.555       0.000       0.000
SKY WV LOS     117.321    1000.000     117.731     118.755     120.379    1000.000    1000.000
ABSRP LOSS      10.743    1000.000       6.822       7.675       8.538    1000.000    1000.000
GND REF LS       0.000    1000.000       0.000       7.401      16.760    1000.000    1000.000
TRNSMSN LS     137.078    1000.000     133.567     142.845     154.692    1000.000    1000.000
FIELD STRN      17.940   -1000.000      21.451      12.172        .326   -1000.000   -1000.000
 SIG POWER    -110.088   -1000.000    -106.577    -115.855    -127.702   -1000.000   -1000.000
S/N IN DB.      53.161   -1000.000      56.672      47.394      35.547   -1000.000   -1000.000
FRACT DAYS        .994       0.000        .994        .994        .798       0.000       0.000
FRACT  S/N        .417       0.000        .572        .174        .001       0.000       0.000
RELIABILTY        .415       0.000        .569        .173        .001       0.000       0.000
SERV. PROB        .001       0.000        .012        .000       0.000       0.000       0.000


 MODE= 1 E   MULTI PTH PROB= .01   PATH LOSS=127.2  UD=123.2  LD=131.1  TIM DLY MS=  5.313
 ANGLE OF ARRIVAL SKYWAVE=    3.7   NOISE LEVEL= -163.2   CIRCUIT RELIABILITY=  .42
 ANGLE OF ARRIVAL DIRECT=    -.0   GROUNDWAVE LOSS=   451.8
```

Figure 7. Output of air/ground model for circuit (4) in Table 3, 11 MHz.

```
  TIME= 11.00UT  DATE=12/15/82     SSN=  88.

                    LAT.    LONG. DEG. E    HEIGHT    AZMOUTH    DIST. KM
      TRANSMITTR    45.0         5.0           1.0     81.1        1957.9
        RECEIVER    45.0        30.0           1.0     278.9       1957.9

  FREQ-MHZ  PWR-KW  REQ S/N-DB  MM-NOISE  REQ-REL  MP-SIGPOW  MP-TMDLY
  11.0      .500      55       SUBURBAN      90     4.0     2.000

                   1           2           3           4           5
DIST FM TX     978.933     489.467    1468.400     978.933     978.933
  LATITUDE      45.687      45.514      45.514      45.687      45.687
 LONGITUDE     -17.500     -11.212     -23.788     -17.500     -17.500
GEOM. LAT.      45.208      46.291      43.813      45.208      45.208
TIME HOURS      12.167       0.000       0.000       0.000       0.000
ABSORP FAC        .798       0.000       0.000       0.000       0.000
E LAYER CR       2.963       0.000       0.000       0.000       0.000
F LAYER BT     222.165       0.000       0.000       0.000       0.000
HT OF FMAX     279.641       0.000       0.000       0.000       0.000
GYRO FREQ.       1.310       0.000       0.000       0.000       0.000
F LAYER CT      10.280       0.000       0.000       0.000       0.000
 ES UP DEC       3.738       0.000       0.000       0.000       0.000
ES MED VAL       3.253       0.000       0.000       0.000       0.000
ES LOW DEC       2.639       0.000       0.000       0.000       0.000
EX SYS STS       9.008       7.678       4.047       3.008       2.008       1.008
ANO STATIS    -174.322       8.078       6.550       3.532       2.208       5.633

                        E MODES                      F MODES                         EF MODES
NO OF HOPS       1.000       2.000       1.000       2.000       3.000       0.000       0.000
TK OFF ANG       1.355       0.000      11.742      23.839      35.962       0.000       0.000
VIRTUAL HT      99.654       0.000       0.000     236.458     251.552       0.000       0.000
TM DLY MS.       6.609       0.000       0.000       7.398       8.383       0.000       0.000
SKY WV LOS     119.217    1000.000    1000.000     120.196     121.283    1000.000    1000.000
ABSRP LOSS      11.282    1000.000    1000.000       9.169       9.898    1000.000    1000.000
GND REF LS       0.000    1000.000    1000.000       6.598      15.880    1000.000    1000.000
TRNSMSN LS     139.506    1000.000    1000.000     144.971     156.068    1000.000    1000.000
FIELD STRN      15.511   -1000.000   -1000.000      10.047      -1.050   -1000.000   -1000.000
 SIG POWER    -112.517   -1000.000   -1000.000    -117.981    -129.078   -1000.000   -1000.000
S/N IN DB.      50.723   -1000.000   -1000.000      45.258      34.161   -1000.000   -1000.000
FRACT DAYS        .994       0.000       0.000        .994        .980       0.000       0.000
FRACT  S/N        .307       0.000       0.000        .106        .000       0.000       0.000
RELIABILTY        .305       0.000       0.000        .106        .000       0.000       0.000
SERV. PROB        .000       0.000       0.000       0.000       0.000       0.000       0.000


 MODE= 1 E    MULTI PTH PROB= .01    PATH LOSS=129.7  UD=125.7  LD=133.6  TIM DLY MS=  6.609
 ANGLE OF ARRIVAL SKYWAVE=    1.4    NOISE LEVEL= -163.2   CIRCUIT RELIABILITY=  .31
 ANGLE OF ARRIVAL DIRECT=    -.0    GROUNDWAVE LOSS=   527.0
```

Figure 8. Output of air/ground model for circuit (5) in Table 3, 11 MHz.

```
  TIME= 11.00UT  DATE=12/15/82   SSN=  88.

                  LAT.    LONG. DEG. E  HEIGHT   AZMOUTH    DIST. KM
     TRANSMITTR   55.0       15.0          1.0    180.0        556.0
       RECEIVER   50.0       15.0          1.0       .0        556.0

  FREQ-MHZ PWR-KW REQ S/N-DB MM-NOISE REQ-REL MP-SIGPOW MP-TMDLY
  11.0       .100      55     SUBURBAN   90     4.0     2.000

                 1          2          3          4          5
DIST FM TX    277.996    138.998    416.994    277.996    277.996
  LATITUDE     52.500     53.750     51.250     52.500     52.500
 LONGITUDE    -15.002    -15.002    -15.003    -15.002    -15.002
GEOM. LAT.     52.196     53.377     51.011     52.196     52.196
TIME HOURS     12.000      0.000      0.000      0.000      0.000
ABSORP FAC       .678      0.000      0.000      0.000      0.000
E LAYER CR      2.616      0.000      0.000      0.000      0.000
F LAYER BT    222.412      0.000      0.000      0.000      0.000
HT OF FMAX    274.255      0.000      0.000      0.000      0.000
GYRO FREQ.      1.352      0.000      0.000      0.000      0.000
F LAYER CT     10.189      0.000      0.000      0.000      0.000
 ES UP DEC      3.644      0.000      0.000      0.000      0.000
ES MED VAL      2.959      0.000      0.000      0.000      0.000
ES LOW DEC      2.367      0.000      0.000      0.000      0.000
EX SYS STS      9.000      7.600      4.000      3.000      2.000      1.000
AND STATIS   -174.719      8.045      6.526      3.427      2.278      5.581

                      E MODES                    F MODES                     EF MODES
NO OF HOPS      1.000      2.000      1.000      2.000      3.000      0.000      0.000
TK OFF ANG      0.000      0.000     41.253     67.853     75.893      0.000      0.000
VIRTUAL HT      0.000      0.000    258.068    361.486    391.111      0.000      0.000
TM DLY MS.      0.000      0.000      2.566      5.198      8.076      0.000      0.000
SKY WV LOS   1000.000   1000.000    110.999    117.131    120.958   1000.000   1000.000
ABSRP LOSS   1000.000   1000.000      2.607      3.775      5.417   1000.000   1000.000
GND REF LS   1000.000   1000.000      0.000      8.774     17.577   1000.000   1000.000
TRNSMSN LS   1000.000   1000.000    122.606    138.681    152.952   1000.000   1000.000
FIELD STRN  -1000.000  -1000.000     25.422      9.347     -4.924  -1000.000  -1000.000
 SIG POWER  -1000.000  -1000.000   -102.606   -118.681   -132.952  -1000.000  -1000.000
S/N IN DB.  -1000.000  -1000.000     60.663     44.589     30.318  -1000.000  -1000.000
FRACT DAYS      0.000      0.000       .854       .499       .497      0.000      0.000
FRACT  S/N      0.000      0.000       .725       .088       .000      0.000      0.000
RELIABILTY      0.000      0.000       .619       .044       .000      0.000      0.000
SERV. PROB      0.000      0.000       .070      0.000      0.000      0.000      0.000


 MODE= 1 F   MULTI PTH PROB= .01   PATH LOSS=112.9  UD=108.9  LD=116.8  TIM DLY MS=  2.566
 ANGLE OF ARRIVAL SKYWAVE=   41.3   NOISE LEVEL= -163.3   CIRCUIT RELIABILITY=  .72
 ANGLE OF ARRIVAL DIRECT=    -.0   GROUNDWAVE LOSS=   252.0
```

Figure 9. Output of air/ground model for circuit (6) in Table 3, 11 MHz.

```
  TIME= 11.00UT  DATE=12/15/82     SSN=  88.

                    LAT.    LONG. DEG. E    HEIGHT    AZMOUTH    DIST. KM
      TRANSMITTR    55.0        15.0           1.0     180.0       1112.0
        RECEIVER    45.0        15.0           1.0        .0       1112.0

  FREQ-MHZ  PWR-KW  REQ S/N-DB  MM-NOISE  REQ-REL  MP-SIGPOW  MP-TMDLY
  11.0      .100      55       SUBURBAN      90     4.0     2.000

                  1           2           3           4           5
DIST FM TX      555.992     277.996     833.988     555.992     555.992
  LATITUDE       50.000      52.500      47.500      50.000      50.000
 LONGITUDE      -15.003     -15.002     -15.004     -15.003     -15.003
GEOM. LAT.       49.823      52.196      47.438      49.823      49.823
TIME HOURS       12.000       0.000       0.000       0.000       0.000
ABSORP FAC         .730       0.000       0.000       0.000       0.000
E LAYER CR        2.750       0.000       0.000       0.000       0.000
F LAYER BT      221.954       0.000       0.000       0.000       0.000
HT OF FMAX      274.857       0.000       0.000       0.000       0.000
GYRO FREQ.        1.336       0.000       0.000       0.000       0.000
F LAYER CT       10.286       0.000       0.000       0.000       0.000
 ES UP DEC        3.627       0.000       0.000       0.000       0.000
ES MED VAL        3.076       0.000       0.000       0.000       0.000
ES LOW DEC        2.480       0.000       0.000       0.000       0.000
EX SYS STS        9.000       7.600       4.000       3.000       2.000       1.000
AND STATIS     -174.715       8.045       6.526       3.427       2.278       5.581


                        E MODES                      F MODES                         EF MODES
NO OF HOPS        1.000       2.000       1.000       2.000       3.000       0.000       0.000
TK OFF ANG        0.000       0.000      20.516      41.178      56.286       0.000       0.000
VIRTUAL HT        0.000       0.000     232.449     257.145     291.973       0.000       0.000
TM DLY MS.        0.000       0.000       4.100       5.125       6.988       0.000       0.000
SKY WV LOS     1000.000    1000.000     115.069     117.009     119.701    1000.000    1000.000
ABSRP LOSS     1000.000    1000.000       4.816       5.551       6.676    1000.000    1000.000
GND REF LS     1000.000    1000.000       0.000       8.259      17.379    1000.000    1000.000
TRNSMSN LS     1000.000    1000.000     128.885     139.819     152.756    1000.000    1000.000
FIELD STRN    -1000.000   -1000.000      19.142       8.209      -4.728   -1000.000   -1000.000
 SIG POWER    -1000.000   -1000.000    -108.885    -119.819    -132.756   -1000.000   -1000.000
S/N IN DB.    -1000.000   -1000.000      54.383      43.450      30.513   -1000.000   -1000.000
FRACT DAYS        0.000       0.000        .994        .870        .590       0.000       0.000
FRACT  S/N        0.000       0.000        .472        .063        .000       0.000       0.000
RELIABILTY        0.000       0.000        .469        .055        .000       0.000       0.000
SERV. PROB        0.000       0.000        .003       0.000       0.000       0.000       0.000


 MODE= 1 F   MULTI PTH PROB= .01   PATH LOSS=119.1  UD=115.2  LD=123.1  TIM DLY MS=  4.100
 ANGLE OF ARRIVAL SKYWAVE=   20.5   NOISE LEVEL= -163.3   CIRCUIT RELIABILITY=  .47
 ANGLE OF ARRIVAL DIRECT=    -.0   GROUNDWAVE LOSS=   362.8
```

Figure 10. Output of air/ground model for circuit (7) in Table 3, 11 MHz.

```
  TIME= 11.00UT  DATE=12/15/82      SSN=  88.

                    LAT.     LONG. DEG. E    HEIGHT     AZMOUTH     DIST. KM
      TRANSMITTR    55.0         15.0           1.0      180.0        1668.0
        RECEIVER    40.0         15.0           1.0         .0        1668.0

  FREQ-MH7   PWP-KW   REQ S/N-DB   MM-NOISE  REQ-REL  MP-SIGPOW  MP-TMDLY
  11.0       .100       55         SUBURBAN     90      4.0       2.000


                    1           2           3           4           5
DIST FM TX     833.938     416.994    1250.982     833.988     833.988
  LATITUDE      47.500      51.250      43.750      47.500      47.500
 LONGITUDE     -15.004     -15.003     -15.004     -15.004     -15.004
GEOM. LAT.      47.438      51.011      43.842      47.438      47.438
TIME HOURS      12.000       0.000       0.000       0.000       0.000
ABSORP FAC        .771       0.000       0.000       0.000       0.000
E LAYER CR       2.878       0.000       0.000       0.000       0.000
F LAYER RT     221.927       0.000       0.000       0.000       0.000
HT OF FMAX     276.616       0.000       0.000       0.000       0.000
GYRO FREQ.       1.317       0.000       0.000       0.000       0.000
F LAYER CT      10.269       0.000       0.000       0.000       0.000
 ES UP DEC       3.684       0.000       0.000       0.000       0.000
ES MED VAL       3.178       0.000       0.000       0.000       0.000
ES LOW DEC       2.575       0.000       0.000       0.000       0.000
EX SYS STS       9.000       7.600       4.000       3.000       2.000       1.000
AND STATIS    -174.688       8.045       6.526       3.427       2.278       5.581


                        E MODES                        F MODES                          EF MODES
NO OF HOPS       1.000       2.000       1.000       2.000       3.000       0.000       0.000
TK OFF ANG       3.125       0.000      12.683      28.049      41.370       0.000       0.000
VIRTUAL HT     101.505       0.000     229.461     239.813     258.724       0.000       0.000
TM DLY MS.       5.645       0.000       5.891       6.537       7.712       0.000       0.000
SKY WV LOS     117.847    1000.000     118.219     119.122     120.558    1000.000    1000.000
ABSRP LOSS      10.620    1000.000       6.992       7.860       8.660    1000.000    1000.000
GND REF LS       0.000    1000.000       0.000       7.178      12.589    1000.000    1000.000
TRNSMSN LS     137.467    1000.000     134.211     143.160     150.807    1000.000    1000.000
FIELD STRN      10.561   -1000.000      13.817       4.868      -2.779   -1000.000   -1000.000
 SIG POWER    -117.467   -1000.000    -114.211    -123.160    -130.807   -1000.000   -1000.000
S/N IN DB.      45.800   -1000.000      49.056      40.107      32.460   -1000.000   -1000.000
FRACT DAYS        .994       0.000        .994        .994        .858       0.000       0.000
FRACT  S/N        .121       0.000        .236        .018        .000       0.000       0.000
RELIABILTY        .120       0.000        .234        .018        .000       0.000       0.000
SERV. PROB       0.000       0.000        .000       0.000       0.000       0.000       0.000


 MODE= 1 E   MULTI PTH PROB= .01   PATH LOSS=127.7  UD=123.8  LD=131.7  TIM DLY MS=  5.645
 ANGLE OF ARRIVAL SKYWAVE=    3.1   NOISE LEVEL= -163.3   CIRCUIT RELIABILITY=  .12
 ANGLE OF ARRIVAL DIRECT=    -.0   GROUNDWAVE LOSS=   471.0
```

Figure 11. Output of air/ground model for circuit (8) in Table 3, 11 MHz.

```
 TIME= 11.00UT   DATE=12/15/82      SSN=  88.

                     LAT.     LONG. DEG. E     HEIGHT     AZMOUTH     DIST. KM
      TRANSMITTR     55.0          15.0           1.0      180.0        2224.0
        RECEIVER     35.0          15.0           1.0         .0        2224.0

 FREQ-MHZ  PWR-KW  REQ S/N-DB  MM-NOISE  REQ-REL  MP-SIGPOW  MP-TMDLY
 11.0      .500       55        SUBURBAN     90      4.0      2.000


                      1              2              3              4              5
DIST FM TX       1111.984        555.992       1667.976       1111.984       1111.984
  LATITUDE         45.000         50.000         40.000         45.000         45.000
 LONGITUDE        -15.004        -15.003        -15.005        -15.004        -15.004
GEOM. LAT.         45.043         49.823         40.228         45.043         45.043
TIME HOURS         12.000         12.000         12.000          0.000          0.000
ABSORP FAC           .808           .730           .858          0.000          0.000
E LAYER CR          3.002          2.750          3.228          0.000          0.000
F LAYER BT        222.052        221.954        222.980          0.000          0.000
HT OF FMAX        278.899        274.857        286.265          0.000          0.000
GYRO FREQ.          1.297          1.336          1.249          0.000          0.000
F LAYER CT         10.233         10.286         10.168          0.000          0.000
 ES UP DEC          3.777          3.627          4.156          0.000          0.000
ES MED VAL          3.275          3.076          3.470          0.000          0.000
ES LOW DEC          2.664          2.480          2.824          0.000          0.000
EX SYS STS          9.350          9.100          4.900          3.550          2.200          1.200
ANO STATIS       -174.672          8.045          6.526          3.427          2.278          5.581


                          E MODES                             F MODES                                   EF MODES
NO OF HOPS          1.000          2.000          2.000          3.000          4.000          0.000          0.000
TK OFF ANG           .160          0.000         20.611         31.710         41.628          0.000          0.000
VIRTUAL HT        101.474          0.000        233.658        245.570        261.390          0.000          0.000
TM DLY MS.          7.498          0.000          8.206          9.051         10.328          0.000          0.000
SKY WV LOS        120.314       1000.000        121.097        121.948        123.095       1000.000       1000.000
ABSRP LOSS         11.298       1000.000         10.191         10.866         11.690       1000.000       1000.000
GND REF LS          0.000       1000.000          4.025          7.817         12.783       1000.000       1000.000
TRNSMSN LS        140.961       1000.000        144.664        149.981        156.918       1000.000       1000.000
FIELD STRN         14.056      -1000.000         10.354          5.037         -1.900      -1000.000      -1000.000
 SIG POWER       -113.972      -1000.000       -117.674       -122.991       -129.928      -1000.000      -1000.000
S/N IN DB.         49.294      -1000.000         45.592         40.275         33.338      -1000.000      -1000.000
FRACT DAYS           .994          0.000           .994           .994           .850          0.000          0.000
FRACT  S/N           .263          0.000           .133           .026           .000          0.000          0.000
RELIABILTY           .261          0.000           .132           .026           .000          0.000          0.000
SERV. PROB           .000          0.000          0.000          0.000          0.000          0.000          0.000


 MODE= 1 E    MULTI PTH PROB= .01    PATH LOSS=129.3  UD=124.8  LD=133.8  TIM DLY MS=  7.498
 ANGLE OF ARRIVAL SKYWAVE=      .2    NOISE LEVEL= -163.3   CIRCUIT RELIABILITY=  .25
 ANGLE OF ARRIVAL DIRECT=    -.0    GROUNDWAVE LOSS=    578.2
```

Figure 12. Output of air/ground model for circuit (9) in Table 3, 11 MHz.

```
  TIME= 11.00UT  DATE=12/15/82     SSN=  88.

                    LAT.    LONG. DEG. E    HEIGHT    AZMOUTH     DIST. KM
      TRANSMITTR    55.0        15.0           1.0     180.0        2780.0
        RECEIVER    30.0        15.0           1.0        .0        2780.0

  FREQ-MHZ  PWR-KW  REQ S/N-DB  MM-NOISE  REQ-REL  MP-SIGPOW  MP-TMDLY
  11.0      .500      55       SUBURBAN      90     4.0     2.000

                  1           2           3           4           5
DIST FM TX    1389.980     694.990    2084.970    1389.980    1389.980
  LATITUDE      42.500      48.750      36.250      42.500      42.500
 LONGITUDE     -15.005     -15.003     -15.005     -15.005     -15.005
GEOM. LAT.      42.639      48.632      36.600      42.639      42.639
TIME HOURS      12.000      12.000      12.000       0.000       0.000
ABSORP FAC        .838        .751        .876       0.000       0.000
E LAYER CR       3.120       2.814       3.376       0.000       0.000
F LAYER BT     222.405     221.940     223.966       0.000       0.000
HT OF FMAX     281.979     275.735     294.477       0.000       0.000
GYRO FREQ.       1.275       1.327       1.207       0.000       0.000
F LAYER CT      10.170      10.278      10.359       0.000       0.000
 ES UP DEC       3.925       3.655       4.606       0.000       0.000
ES MED VAL       3.366       3.127       3.676       0.000       0.000
ES LOW DEC       2.744       2.527       2.961       0.000       0.000
EX SYS STS       9.600       9.600       5.200       4.000       2.300       1.300
ANO STATIS    -174.561       8.045       6.526       3.427       2.278       5.581


                        E MODES                      F MODES                          EF MODES
NO OF HOPS       2.000       3.000       2.000       3.000       4.000       0.000       0.000
TK OFF ANG       5.432       0.000      16.075      25.339      34.073       0.000       0.000
VIRTUAL HT     105.551       0.000     231.352     239.422     250.947       0.000       0.000
TM DLY MS.       9.450       0.000       9.981      10.636      11.630       0.000       0.000
SKY WV LOS     122.323    1000.000     122.798     123.350     124.126    1000.000    1000.000
ABSRP LOSS      20.275    1000.000      12.413      13.222      13.900    1000.000    1000.000
GND REF LS       1.037    1000.000        .424       7.021       8.225    1000.000    1000.000
TRNSMSN LS     153.235    1000.000     145.235     153.193     155.851    1000.000    1000.000
FIELD STRN       1.782   -1000.000       9.783       1.824       -.833   -1000.000   -1000.000
 SIG POWER    -126.246   -1000.000    -118.245    -126.204    -128.861   -1000.000   -1000.000
S/N IN DB.      37.182   -1000.000      45.182      37.224      34.566   -1000.000   -1000.000
FRACT DAYS        .994       0.000        .994        .994        .994       0.000       0.000
FRACT  S/N        .007       0.000        .130        .007        .001       0.000       0.000
RELIABILTY        .007       0.000        .129        .007        .001       0.000       0.000
SERV. PROB       0.000       0.000       0.000       0.000       0.000       0.000       0.000


 MODE= 2 E   MULTI PTH PROB= .01   PATH LOSS=140.9  UD=136.0  LD=145.9  TIM DLY MS=   9.450
 ANGLE OF ARRIVAL SKYWAVE=    5.4   NOISE LEVEL= -163.4   CIRCUIT RELIABILITY=   .01
 ANGLE OF ARRIVAL DIRECT=    -.0   GROUNDWAVE LOSS=   684.9
```

Figure 13. Output of air/ground model for circuit (10) in Table 3, 11 MHz.

```
TIME= 11.00UT  DATE=12/15/82      SSN=  88.

                    LAT.     LONG. DEG. E     HEIGHT     AZMOUTH     DIST. KM
      TRANSMITTR    45.0         10.0            1.0       89.6          78.6
        RECEIVER    45.0         11.0            1.0      270.4          78.6

 FREQ-MHZ  PWR-KW  REQ S/N-DB  MM-NOISE  REQ-REL  MP-SIGPOW  MP-TMDLY
 11.0      .100      55        SUBURBAN     90      4.0      2.000

                     1           2           3           4           5
DIST FM TX        39.314      19.657      58.971      39.314      39.314
  LATITUDE        45.001      45.001      45.001      45.001      45.001
 LONGITUDE       -10.500     -10.250     -10.750     -10.500     -10.500
GEOM. LAT.        45.940      45.990      45.890      45.940      45.940
TIME HOURS        11.700       0.000       0.000       0.000       0.000
ABSORP FAC          .805       0.000       0.000       0.000       0.000
E LAYER CR         3.000       0.000       0.000       0.000       0.000
F LAYER BT       221.597       0.000       0.000       0.000       0.000
HT OF FMAX       275.409       0.000       0.000       0.000       0.000
GYRO FREQ.         1.288       0.000       0.000       0.000       0.000
F LAYER CT        10.158       0.000       0.000       0.000       0.000
 ES UP DEC         3.758       0.000       0.000       0.000       0.000
ES MED VAL         3.250       0.000       0.000       0.000       0.000
ES LOW DEC         2.659       0.000       0.000       0.000       0.000
EX SYS STS         9.002       6.702       4.127       3.025       2.025       1.025
AND STATIS      -174.821       8.036       6.520       3.399       2.296       5.567

                         E MODES                       F MODES                         EF MODES
NO OF HOPS         1.000       2.000       1.000       2.000       3.000       0.000       0.000
TK OFF ANG         0.000       0.000      84.875      87.704      88.478       0.000       0.000
VIRTUAL HT         0.000       0.000     469.508     529.783     533.118       0.000       0.000
TM DLY MS.         0.000       0.000       3.152       7.091      10.699       0.000       0.000
SKY WV LOS      1000.000    1000.000     112.787     119.829     123.401    1000.000    1000.000
ABSRP LOSS      1000.000    1000.000       2.016       4.019       6.025    1000.000    1000.000
GND REF LS      1000.000    1000.000       0.000        .588       1.177    1000.000    1000.000
TRNSMSN LS      1000.000    1000.000     123.805     133.438     139.606    1000.000    1000.000
FIELD STRN     -1000.000   -1000.000      24.222      14.590       8.421   -1000.000   -1000.000
 SIG POWER     -1000.000   -1000.000    -103.805    -113.438    -119.606   -1000.000   -1000.000
S/N IN DB.     -1000.000   -1000.000      59.471      49.838      43.670   -1000.000   -1000.000
FRACT DAYS         0.000       0.000        .495        .494        .494       0.000       0.000
FRACT  S/N         0.000       0.000        .691        .266        .071       0.000       0.000
RELIABILTY         0.000       0.000        .342        .131        .035       0.000       0.000
SERV. PROB         0.000       0.000        .036        .000       0.000       0.000       0.000


 MODE= 1 F    MULTI PTH PROB= .01    PATH LOSS=115.2  UD=111.2  LD=119.2  TIM DLY MS=  3.152
 ANGLE OF ARRIVAL SKYWAVE=   84.9    NOISE LEVEL= -163.3   CIRCUIT RELIABILITY=  .69
 ANGLE OF ARRIVAL DIRECT=    -.0     GROUNDWAVE LOSS=   147.9
```

Figure 14. Output of air/ground model for circuit (11) in Table 3, 11 MHz.

```
  TIME= 11.00UT  DATE=12/15/82     SSN=  88.

                    LAT.     LONG. DEG. E    HEIGHT     AZMOUTH     DIST. KM
     TRANSMITTR -   45.0         10.0           1.0       89.3         157.3
       RECEIVER     45.0         12.0           1.0      270.7         157.3

  FREQ-MHZ  PWR-KW  REQ S/N-DB  MM-NOISE  REQ-REL  MP-SIGPOW  MP-TMDLY
  11.0       .100      55       SUBURBAN     90      4.0      2.000


                     1              2              3              4              5
DIST FM TX        78.627         39.314        117.941         78.627         78.627
  LATITUDE        45.004         45.003         45.003         45.004         45.004
 LONGITUDE       -11.000        -10.500        -11.500        -11.000        -11.000
GEOM. LAT.        45.844         45.942         45.743         45.844         45.844
TIME HOURS        11.733          0.000          0.000          0.000          0.000
ABSORP FAC          .805          0.000          0.000          0.000          0.000
E LAYER CR         3.000          0.000          0.000          0.000          0.000
F LAYER BT       221.648          0.000          0.000          0.000          0.000
HT OF FMAX       275.790          0.000          0.000          0.000          0.000
GYRO FREQ.         1.289          0.000          0.000          0.000          0.000
F LAYER CT        10.166          0.000          0.000          0.000          0.000
 ES UP DEC         3.760          0.000          0.000          0.000          0.000
ES MED VAL         3.252          0.000          0.000          0.000          0.000
ES LOW DEC         2.659          0.000          0.000          0.000          0.000
EX SYS STS         9.005          6.829          4.129          3.025          2.025          1.025
AND STATIS      -174.795          8.038          6.521          3.406          2.292          5.571


                         E MODES                                F MODES                                 `EF MODES
NO OF HOPS         1.000          2.000          1.000          2.000          3.000          0.000          0.000
TK OFF ANG         0.000          0.000         78.532         84.891         86.635          0.000          0.000
VIRTUAL HT         0.000          0.000        411.866        471.112        478.009          0.000          0.000
TM DLY MS.         0.000          0.000          2.809          6.326          9.608          0.000          0.000
SKY WV LOS      1000.000       1000.000        111.785        118.837        122.467       1000.000       1000.000
ABSRP LOSS      1000.000       1000.000          2.048          4.032          6.035       1000.000       1000.000
GND REF LS      1000.000       1000.000          0.000           .626          1.255       1000.000       1000.000
TRNSMSN LS      1000.000       1000.000        122.838        132.501        138.762       1000.000       1000.000
FIELD STRN     -1000.000      -1000.000         25.190         15.527          9.266      -1000.000      -1000.000
 SIG POWER     -1000.000      -1000.000       -102.838       -112.501       -118.762      -1000.000      -1000.000
S/N IN DB.     -1000.000      -1000.000         60.437         50.774         44.513      -1000.000      -1000.000
FRACT DAYS         0.000          0.000           .496           .495           .495          0.000          0.000
FRACT  S/N         0.000          0.000           .725           .307           .090          0.000          0.000
RELIABILTY         0.000          0.000           .359           .152           .044          0.000          0.000
SERV. PROB         0.000          0.000           .050           .000          0.000          0.000          0.000


 MODE= 1 F   MULTI PTH PROB= .01   PATH LOSS=114.1  UD=110.1  LD=118.1  TIM DLY MS=  2.809
 ANGLE OF ARRIVAL SKYWAVE=   78.5   NOISE LEVEL= -163.3   CIRCUIT RELIABILITY=  .72
 ANGLE OF ARRIVAL DIRECT=    -.0   GROUNDWAVE LOSS=   165.9
```

Figure 15. Output of air/ground model for circuit (12) in Table 3, 11 MHz.

```
  TIME= 11.00UT  DATE=12/15/82     SSN=  88.

                   LAT.    LONG. DEG. E    HEIGHT    AZMOUTH     DIST. KM
       TRANSMITTR  45.0       10.0            1.0      88.9        235.9
         RECEIVER  45.0       13.0            1.0     271.1        235.9

  FREQ-MHZ  PWR-KW  REQ S/N-DB  MM-NOISE  REQ-REL  MP-SIGPOW  MP-TMDLY
  11.0      .100      55        SUBURBAN     90     4.0      2.000

                   1          2          3          4          5
DIST FM TX    117.937     58.968    176.905    117.937    117.937
  LATITUDE     45.010     45.007     45.007     45.010     45.010
 LONGITUDE    -11.500    -10.750    -12.250    -11.500    -11.500
GEOM. LAT.     45.749     45.896     45.598     45.749     45.749
TIME HOURS     11.767      0.000      0.000      0.000      0.000
ABSORP FAC       .806      0.000      0.000      0.000      0.000
E LAYER CR      3.000      0.000      0.000      0.000      0.000
F LAYER BT    221.698      0.000      0.000      0.000      0.000
HT OF FMAX    276.170      0.000      0.000      0.000      0.000
GYRO FREQ.      1.290      0.000      0.000      0.000      0.000
F LAYER CT     10.175      0.000      0.000      0.000      0.000
 ES UP DEC      3.762      0.000      0.000      0.000      0.000
ES MED VAL      3.255      0.000      0.000      0.000      0.000
ES LOW DEC      2.660      0.000      0.000      0.000      0.000
EX SYS STS      9.007      6.956      4.131      3.025      2.025      1.025
AND STATIS   -174.768      8.041      6.523      3.413      2.287      5.574

                      E MODES                    F MODES                      EF MODES
NO OF HOPS      1.000      2.000      1.000      2.000      3.000      0.000      0.000
TK OFF ANG      0.000      0.000     71.853     81.543     84.907      0.000      0.000
VIRTUAL HT      0.000      0.000    381.203    421.879    472.708      0.000      0.000
TM DLY MS.      0.000      0.000      2.677      5.704      9.521      0.000      0.000
SKY WV LOS   1000.000   1000.000    111.368    117.938    122.388   1000.000   1000.000
ABSRP LOSS   1000.000   1000.000      2.110      4.060      6.050   1000.000   1000.000
GND REF LS   1000.000   1000.000      0.000       .675      1.359   1000.000   1000.000
TRNSMSN LS   1000.000   1000.000    122.486    131.681    138.804   1000.000   1000.000
FIELD STRN  -1000.000  -1000.000     25.542     16.347      9.224  -1000.000  -1000.000
 SIG POWER  -1000.000  -1000.000   -102.486   -111.681   -118.804  -1000.000  -1000.000
S/N IN DB.  -1000.000  -1000.000     60.787     51.592     44.469  -1000.000  -1000.000
FRACT DAYS      0.000      0.000       .497       .495       .495      0.000      0.000
FRACT  S/N      0.000      0.000       .735       .344       .089      0.000      0.000
RELIABILTY      0.000      0.000       .366       .170       .044      0.000      0.000
SERV. PROB      0.000      0.000       .054       .000      0.000      0.000      0.000


 MODE= 1 F   MULTI PTH PROB= .01   PATH LOSS=113.6  UD=109.6  LD=117.6  TIM DLY MS=  2.677
 ANGLE OF ARRIVAL SKYWAVE=   71.9   NOISE LEVEL= -163.3   CIRCUIT RELIABILITY=  .74
 ANGLE OF ARRIVAL DIRECT=    -.0   GROUNDWAVE LOSS=   184.3
```

Figure 16. Output of air/ground model for circuit (13) in Table 3, 11 MHz.

```
   TIME= 11.00UT   DATE=12/15/82      SSN=  88.

                     LAT.     LONG. DEG. E     HEIGHT     AZMOUTH     DIST. KM
      TRANSMITTR     45.0         10.0            1.0        88.6         314.5
        RECEIVER     45.0         14.0            1.0       271.4         314.5

   FREQ-MHZ  PWR-KW  REQ S/N-DB  MM-NOISE  REQ-REL  MP-SIGPOW  MP-TMDLY
   11.0      .100       55       SUBURBAN     90      4.0       2.000


                       1            2            3            4            5
 DIST FM TX     157.242       78.621      235.864      157.242      157.242
   LATITUDE      45.017       45.013       45.013       45.017       45.017
  LONGITUDE     -12.000      -11.000      -13.000      -12.000      -12.000
 GEOM. LAT.      45.657       45.852       45.454       45.657       45.657
 TIME HOURS      11.800        0.000        0.000        0.000        0.000
 ABSORP FAC        .806        0.000        0.000        0.000        0.000
 E LAYER CR       3.000        0.000        0.000        0.000        0.000
 F LAYER BT     221.748        0.000        0.000        0.000        0.000
 HT OF FMAX     276.547        0.000        0.000        0.000        0.000
 GYRO FREQ.       1.291        0.000        0.000        0.000        0.000
 F LAYER CT      10.183        0.000        0.000        0.000        0.000
  ES UP DEC       3.763        0.000        0.000        0.000        0.000
 ES MED VAL       3.257        0.000        0.000        0.000        0.000
 ES LOW DEC       2.660        0.000        0.000        0.000        0.000
 EX SYS STS       9.010        7.081        4.133        3.025        2.025        1.025
 AND STATIS    -174.742        8.043        6.524        3.420        2.282        5.578


                         E MODES                         F MODES                               EF MODES
 NO OF HOPS       1.000        2.000        1.000        2.000        3.000        0.000        0.000
 TK OFF ANG       0.000        0.000       64.354       78.596       83.216        0.000        0.000
 VIRTUAL HT       0.000        0.000      345.986      414.346      472.203        0.000        0.000
 TM DLY MS.       0.000        0.000        2.555        5.650        9.538        0.000        0.000
 SKY WV LOS    1000.000     1000.000      110.962      117.855      122.404     1000.000     1000.000
 ABSRP LOSS    1000.000     1000.000        2.221        4.097        6.069     1000.000     1000.000
 GND REF LS    1000.000     1000.000        0.000         .741        1.507     1000.000     1000.000
 TRNSMSN LS    1000.000     1000.000      122.193      131.703      138.989     1000.000     1000.000
 FIELD STRN   -1000.000    -1000.000       25.835       16.325        9.039    -1000.000    -1000.000
  SIG POWER   -1000.000    -1000.000     -102.193     -111.703     -118.989    -1000.000    -1000.000
 S/N IN DB.   -1000.000    -1000.000       61.078       51.568       44.282    -1000.000    -1000.000
 FRACT DAYS       0.000        0.000         .500         .496         .495        0.000        0.000
 FRACT  S/N       0.000        0.000         .744         .343         .084        0.000        0.000
 RELIABILTY       0.000        0.000         .372         .170         .042        0.000        0.000
 SERV. PROB       0.000        0.000         .058         .000        0.000        0.000        0.000


  MODE= 1 F    MULTI PTH PROB= .01    PATH LOSS=113.1  UD=109.1  LD=117.1  TIM DLY MS=  2.555
  ANGLE OF ARRIVAL SKYWAVE=    64.4    NOISE LEVEL= -163.3   CIRCUIT RELIABILITY=  .74
  ANGLE OF ARRIVAL DIRECT=     -.0    GROUNDWAVE LOSS=   201.6
```

Figure 17. Output of air/ground model for circuit (14) in Table 3, 11 MHz.

```
 TIME= 11.00UT  DATE=12/15/82      SSN=  88.


                      LAT.     LONG. DEG. E     HEIGHT     AZMOUTH     DIST. KM
     TRANSMITTR       45.0         10.0            1.0       88.2         393.1
       RECEIVER       45.0         15.0            1.0      271.8         393.1

 FREQ-MHZ  PWR-KW  REQ S/N-DB  MM-NOISE  REQ-REL  MP-SIGPOW  MP-TMDLY
 11.0      .100      55        SUBURBAN     90     4.0      2.000


                    1           2           3           4           5
DIST FM TX    196.542      98.271     294.813     196.542     196.542
  LATITUDE     45.027      45.020      45.020      45.027      45.027
 LONGITUDE    -12.500     -11.250     -13.750     -12.500     -12.500
GEOM. LAT.     45.567      45.809      45.312      45.567      45.567
TIME HOURS     11.833       0.000       0.000       0.000       0.000
ABSORP FAC       .806       0.000       0.000       0.000       0.000
E LAYER CR      3.000       0.000       0.000       0.000       0.000
F LAYER BT    221.797       0.000       0.000       0.000       0.000
HT OF FMAX    276.922       0.000       0.000       0.000       0.000
GYRO FREQ.      1.292       0.000       0.000       0.000       0.000
F LAYER CT     10.192       0.000       0.000       0.000       0.000
 ES UP DEC      3.765       0.000       0.000       0.000       0.000
ES MED VAL      3.260       0.000       0.000       0.000       0.000
ES LOW DEC      2.660       0.000       0.000       0.000       0.000
EX SYS STS      9.012       7.207       4.134       3.024       2.024       1.024
AND STATIS   -174.715       8.045       6.526       3.427       2.278       5.581


                        E MODES                     F MODES                          EF MODES
NO OF HOPS      1.000       2.000       1.000       2.000       3.000       0.000       0.000
TK OFF ANG      0.000       0.000      54.732      75.353      80.586       0.000       0.000
VIRTUAL HT      0.000       0.000     292.180     399.060     420.293       0.000       0.000
TM DLY MS.      0.000       0.000       2.375       5.510       8.545       0.000       0.000
SKY WV LOS   1000.000    1000.000     110.326     117.637     121.448    1000.000    1000.000
ABSRP LOSS   1000.000    1000.000       2.443       4.150       6.109    1000.000    1000.000
GND REF LS   1000.000    1000.000       0.000        .836       1.751    1000.000    1000.000
TRNSMSN LS   1000.000    1000.000     121.781     131.635     138.320    1000.000    1000.000
FIELD STRN  -1000.000   -1000.000      26.247      16.393       9.708   -1000.000   -1000.000
 SIG POWER  -1000.000   -1000.000    -101.781    -111.635    -118.320   -1000.000   -1000.000
S/N IN DB.  -1000.000   -1000.000      61.488      51.634      44.949   -1000.000   -1000.000
FRACT DAYS      0.000       0.000        .592        .497        .496       0.000       0.000
FRACT  S/N      0.000       0.000        .756        .346        .100       0.000       0.000
RELIABILTY      0.000       0.000        .448        .172        .049       0.000       0.000
SERV. PROB      0.000       0.000        .075        .000       0.000       0.000       0.000


 MODE= 1 F   MULTI PTH PROB= .01   PATH LOSS=112.5  UD=108.6  LD=116.5  TIM DLY MS=  2.375
 ANGLE OF ARRIVAL SKYWAVE=   54.7   NOISE LEVEL= -163.3   CIRCUIT RELIABILITY=  .76
 ANGLE OF ARRIVAL DIRECT=    -.0   GROUNDWAVE LOSS=   218.3
```

Figure 18. Output of air/ground model for circuit (15) in Table 3, 11 MHz.

```
  TIME= 11.00UT   DATE=12/15/82      SSN=  88.

                   LAT.     LONG. DEG. E     HEIGHT     AZMOUTH      DIST. KM
      TRANSMITTR   45.0         10.0            1.0       87.9          471.7
        RECEIVER   45.0         16.0            1.0      272.1          471.7

  FREQ-MHZ  PWR-KW  REQ S/N-DB  MM-NOISE  REQ-REL  MP-SIGPOW  MP-TMDLY
  11.0      .200        55      SUBURBAN     90      4.0      2.000


                      1          2          3          4          5
DIST FM TX      235.834    117.917    353.750    235.834    235.834
  LATITUDE       45.039     45.029     45.029     45.039     45.039
 LONGITUDE      -13.000    -11.499    -14.501    -13.000    -13.000
GEOM. LAT.       45.479     45.768     45.171     45.479     45.479
TIMF HOURS       11.867      0.000      0.000      0.000      0.000
ABSORP FAC         .806      0.000      0.000      0.000      0.000
E LAYER CR        2.999      0.000      0.000      0.000      0.000
F LAYER BT      221.846      0.000      0.000      0.000      0.000
HT OF FMAX      277.296      0.000      0.000      0.000      0.000
GYRO FREQ.        1.294      0.000      0.000      0.000      0.000
F LAYER CT       10.200      0.000      0.000      0.000      0.000
 ES UP DEC        3.766      0.000      0.000      0.000      0.000
ES MED VAL        3.262      0.000      0.000      0.000      0.000
ES LOW DEC        2.661      0.000      0.000      0.000      0.000
EX SYS STS        9.014      7.331      4.134      3.024      2.024      1.024
AND STATIS     -174.689      8.047      6.527      3.434      2.273      5.585


                         E MODES                       F MODES                        EF MODES
NO OF HOPS        1.000      2.000      1.000      2.000      3.000      0.000      0.000
TK OFF ANG        0.000      0.000     47.713     71.986     78.658      0.000      0.000
VIRTUAL HT        0.000      0.000    272.927    384.333    416.803      0.000      0.000
TM DLY MS.        0.000      0.000      2.438      5.394      8.523      0.000      0.000
SKY WV LOS     1000.000   1000.000    110.555    117.452    121.426   1000.000   1000.000
ABSRP LOSS     1000.000   1000.000      2.683      4.220      6.146   1000.000   1000.000
GND REF LS     1000.000   1000.000      0.000       .989      2.315   1000.000   1000.000
TRNSMSN LS     1000.000   1000.000    122.252    131.676    138.902   1000.000   1000.000
FIELD STRN    -1000.000  -1000.000     28.786     19.362     12.136  -1000.000  -1000.000
 SIG POWER    -1000.000  -1000.000    -99.242   -108.666   -115.892  -1000.000  -1000.000
S/N IN DB.    -1000.000  -1000.000     64.025     54.601     47.375  -1000.000  -1000.000
FRACT DAYS        0.000      0.000       .707       .498       .496      0.000      0.000
FRACT  S/N        0.000      0.000       .825       .482       .173      0.000      0.000
RELIABILTY        0.000      0.000       .583       .240       .086      0.000      0.000
SERV. PROB        0.000      0.000       .176       .002       .000      0.000      0.000


 MODE= 1 F    MULTI PTH PROB= .01    PATH LOSS=112.9  UD=108.9  LD=116.8  TIM DLY MS=  2.438
 ANGLE OF ARRIVAL SKYWAVE=   47.7   NOISE LEVEL= -163.3   CIRCUIT RELIABILITY=  .83
 ANGLE OF ARRIVAL DIRECT=    -.0    GROUNDWAVE LOSS=   234.7
```

Figure 19. Output of air/ground model for circuit (16) in Table 3, 11 MHz.

```
  TIME= 11.00UT  DATE=12/15/82      SSN=  88.

                    LAT.    LONG. DEG. E     HEIGHT    AZMOUTH    DIST. KM
      TRANSMITTR    45.0        10.0           1.0       87.2        628.8
        RECEIVER    45.0        18.0           1.0      272.8        628.8

  FREQ-MHZ  PWR-KW  REQ S/N-DB  MM-NOISE  REQ-REL  MP-SIGPOW  MP-TMDLY
  11.0      .200      55       SUBURBAN      90     4.0      2.000


                  1           2           3           4           5
DIST FM TX     314.389     157.194     471.583     314.389     314.389
  LATITUDE      45.070      45.052      45.052      45.070      45.070
 LONGITUDE     -14.000     -11.999     -16.001     -14.000     -14.000
GEOM. LAT.      45.309      45.691      44.896      45.309      45.309
TIME HOURS      11.933       0.000       0.000       0.000       0.000
ABSORP FAC        .807       0.000       0.000       0.000       0.000
E LAYER CR       2.998       0.000       0.000       0.000       0.000
F LAYER BT     221.942       0.000       0.000       0.000       0.000
HT OF FMAX     278.034       0.000       0.000       0.000       0.000
GYRO FREQ.       1.296       0.000       0.000       0.000       0.000
F LAYER CT      10.218       0.000       0.000       0.000       0.000
 ES UP DEC       3.769       0.000       0.000       0.000       0.000
ES MED VAL       3.267       0.000       0.000       0.000       0.000
ES LOW DEC       2.661       0.000       0.000       0.000       0.000
EX SYS STS       9.019       7.579       4.135       3.023       2.023       1.023
AND STATIS    -174.636       8.052       6.531       3.448       2.264       5.591


                        E MODES                      F MODES                       EF MODES
NO OF HOPS       1.000       2.000       1.000       2.000       3.000       0.000       0.000
TK OFF ANG       0.000       0.000      37.181      64.077      74.476       0.000       0.000
VIRTUAL HT       0.000       0.000     252.879     341.414     400.636       0.000       0.000
TM DLY MS.       0.000       0.000       2.736       5.054       8.329       0.000       0.000
SKY WV LOS    1000.000    1000.000     111.556     116.888     121.226    1000.000    1000.000
ABSRP LOSS    1000.000    1000.000       3.242       4.455       6.252    1000.000    1000.000
GND REF LS    1000.000    1000.000       0.000       2.538       9.753    1000.000    1000.000
TRNSMSN LS    1000.000    1000.000     123.816     132.899     146.250    1000.000    1000.000
FIELD STRN   -1000.000   -1000.000      27.222      18.139       4.788   -1000.000   -1000.000
 SIG POWER   -1000.000   -1000.000    -100.806    -109.888    -123.240   -1000.000   -1000.000
S/N IN DB.   -1000.000   -1000.000      62.457      53.375      40.023   -1000.000   -1000.000
FRACT DAYS       0.000       0.000        .951        .504        .498       0.000       0.000
FRACT  S/N       0.000       0.000        .780        .427        .019       0.000       0.000
RELIABILTY       0.000       0.000        .742        .215        .009       0.000       0.000
SERV. PROB       0.000       0.000        .146        .001       0.000       0.000       0.000


 MODE= 1 F   MULTI PTH PROB= .01    PATH LOSS=114.1  UD=110.1  LD=118.1  TIM DLY MS=  2.736
 ANGLE OF ARRIVAL SKYWAVE=   37.2   NOISE LEVEL= -163.3   CIRCUIT RELIABILITY=  .78
 ANGLE OF ARRIVAL DIRECT=    -.0   GROUNDWAVE LOSS=   266.8
```

Figure 20. Output of air/ground model for circuit (17) in Table 3, 11 MHz.

```
  TIME= 11.00UT  DATF=12/15/82     SSN=  88.

                    LAT.    LONG. DEG. E    HEIGHT    AZMOUTH    DIST. KM
      TRANSMITTR    45.0        10.0           1.0      86.5       785.8
        RECEIVER    45.0        20.0           1.0     273.5       785.8

  FREQ-MHZ  PWR-KW  REQ S/N-DB  MM-NOISE  REQ-REL  MP-SIGPOW  MP-TMDLY
  11.0      .200      55       SUBURBAN      90    4.0    2.000


                  1           2           3           4           5
DIST FM TX     392.896     196.448     589.344     392.896     392.896
  LATITUDE      45.109      45.082      45.082      45.109      45.109
 LONGITUDE     -15.000     -12.498     -17.502     -15.000     -15.000
GEOM. LAT.      45.149      45.620      44.627      45.149      45.149
TIME HOURS      12.000       0.000       0.000       0.000       0.000
ABSORP FAC        .807       0.000       0.000       0.000       0.000
E LAYER CR       2.997       0.000       0.000       0.000       0.000
F LAYER RT     222.036       0.000       0.000       0.000       0.000
HT OF FMAX     278.762       0.000       0.000       0.000       0.000
GYRO FREQ.       1.298       0.000       0.000       0.000       0.000
F LAYER CT      10.236       0.000       0.000       0.000       0.000
 ES UP DEC       3.771       0.000       0.000       0.000       0.000
ES MED VAL       3.271       0.000       0.000       0.000       0.000
ES LOW DEC       2.661       0.000       0.000       0.000       0.000
EX SYS STS       9.022       7.823       4.134       3.022       2.022       1.022
ANO STATIS    -174.583       8.056       6.534       3.462       2.254       5.598


                        E MODES                      F MODES                          EF MODES
NO OF HOPS       1.000       2.000       1.000       2.000       3.000       0.000       0.000
TK OFF ANG       0.000       0.000      29.956      54.882      69.788       0.000       0.000
VIRTUAL HT       0.000       0.000     242.938     293.733     376.903       0.000       0.000
TM DLY MS.       0.000       0.000       3.139       4.766       8.035       0.000       0.000
SKY WV LOS    1000.000    1000.000     112.749     116.377     120.914    1000.000    1000.000
ABSRP LOSS    1000.000    1000.000       3.853       4.880       6.415    1000.000    1000.000
GND REF LS    1000.000    1000.000       0.000       8.670      10.394    1000.000    1000.000
TRNSMSN LS    1000.000    1000.000     125.624     138.949     146.745    1000.000    1000.000
FIELD STRN   -1000.000   -1000.000      25.414      12.090       4.293   -1000.000   -1000.000
 SIG POWER   -1000.000   -1000.000    -102.614    -115.938    -123.735   -1000.000   -1000.000
S/N IN DB.   -1000.000   -1000.000      60.645      47.321      39.524   -1000.000   -1000.000
FRACT DAYS       0.000       0.000        .994        .599        .499       0.000       0.000
FRACT  S/N       0.000       0.000        .722        .173        .014       0.000       0.000
RELIABILTY       0.000       0.000        .717        .104        .007       0.000       0.000
SERV. PROB       0.000       0.000        .076        .000       0.000       0.000       0.000


 MODE= 1 F   MULTI PTH PROB= .01   PATH LOSS=115.6  UD=111.6  LD=119.6  TIM DLY MS=  3.139
 ANGLE OF ARRIVAL SKYWAVE=   30.0   NOISE LEVEL= -163.3   CIRCUIT RELIABILITY=  .72
 ANGLE OF ARRIVAL DIRECT=    -.0   GROUNDWAVE LOSS=   298.3
```

Figure 21. Output of air/ground model for circuit (18) in Table 3, 11 MHz.

```
  TIME= 11.00UT  DATE=12/15/82      SSN=  88.

                    LAT.    LONG. DEG. E    HEIGHT    AZMOUTH    DIST. KM
      TRANSMITTR    45.0        10.0          1.0      85.7         942.7
        RECEIVER    45.0        22.0          1.0     274.3         942.7

  FREQ-MHZ  PWR-KW  REQ S/N-DB  MM-NOISE  REQ-REL  MP-SIGPOW  MP-TMDLY
  11.0      .200      55        SUBURBAN      90     4.0     2.000


                  1           2           3           4           5
DIST FM TX     471.343     235.671     707.014     471.343     471.343
  LATITUDE      45.157      45.118      45.118      45.157      45.157
 LONGITUDE     -16.000     -12.996     -19.004     -16.000     -16.000
GEOM. LAT.      44.997      45.555      44.366      44.997      44.997
TIME HOURS      12.067       0.000       0.000       0.000       0.000
ABSORP FAC        .806       0.000       0.000       0.000       0.000
E LAYER CR       2.992       0.000       0.000       0.000       0.000
F LAYER BT     222.126       0.000       0.000       0.000       0.000
HT OF FMAX     279.352       0.000       0.000       0.000       0.000
GYRO FREQ.       1.301       0.000       0.000       0.000       0.000
F LAYER CT      10.247       0.000       0.000       0.000       0.000
 ES UP DEC       3.769       0.000       0.000       0.000       0.000
ES MED VAL       3.270       0.000       0.000       0.000       0.000
ES LOW DEC       2.658       0.000       0.000       0.000       0.000
EX SYS STS       9.021       7.811       4.126       3.021       2.021       1.021
AND STATIS    -174.530       8.061       6.537       3.476       2.245       5.605


                        E MODES                      F MODES                         EF MODES
NO OF HOPS       1.000       2.000       1.000       2.000       3.000       0.000       0.000
TK OFF ANG       0.000       0.000      24.830      47.899      64.091       0.000       0.000
VIRTUAL HT       0.000       0.000     237.394     274.595     341.457       0.000       0.000
TM DLY MS.       0.000       0.000       3.591       4.891       7.581       0.000       0.000
SKY WV LOS    1000.000    1000.000     113.918     116.603     120.409    1000.000    1000.000
ABSRP LOSS    1000.000    1000.000       4.471       5.345       6.671    1000.000    1000.000
GND REF LS    1000.000    1000.000       0.000       8.520      17.516    1000.000    1000.000
TRNSMSN LS    1000.000    1000.000     127.410     139.488     153.618    1000.000    1000.000
FIELD STRN   -1000.000   -1000.000      23.629      11.550      -2.580   -1000.000   -1000.000
 SIG POWER   -1000.000   -1000.000    -104.399    -116.478    -130.607   -1000.000   -1000.000
S/N IN DB.   -1000.000   -1000.000      58.856      46.777      32.648   -1000.000   -1000.000
FRACT DAYS       0.000       0.000        .994        .714        .507       0.000       0.000
FRACT  S/N       0.000       0.000        .659        .154        .000       0.000       0.000
RELIABILTY       0.000       0.000        .655        .110        .000       0.000       0.000
SERV. PROB       0.000       0.000        .036       0.000       0.000       0.000       0.000


 MODE= 1 F   MULTI PTH PROB= .01   PATH LOSS=117.4  UD=113.4  LD=121.4  TIM DLY MS=  3.591
 ANGLE OF ARRIVAL SKYWAVE=   24.8   NOISE LEVEL= -163.3   CIRCUIT RELIABILITY=  .66
 ANGLE OF ARRIVAL DIRECT=    -.0   GROUNDWAVE LOSS=   329.4
```

Figure 22. Output of air/ground model for circuit (19) in Table 3, 11 MHz.

ground program take about 1 ms for each frequency and path. This is about one hundred times faster than the calculations given by GWSNR in OT Technical Memorandum 78-247.

It is reasonable to expect that the computer time required to undertake specific calculations will vary with different main-frame machines. Thus the results quoted above should be treated as illustrative rather than absolute.

The accuracy of the HF air-to-ground calculations are as important as the speed. To determine this accuracy, the calculated results of the air-to-ground program were compared with the HFMUFES and GRWSN results for a large number of cases.

The most meaningful comparisons between results of the air-to-ground program and the more general skywave and groundwave programs are the various loss parameters. Differences in the values of the loss parameters are caused principally by the grid system invoked in the air-to-ground program. An example of the relative accuracy of the air-to-ground program is given in Table 6, which shows the root-mean-square errors in decibels for the 17 circuits listed in Table 3 with path lengths less than 2000 km. In all cases the errors in skywave losses and absorption losses were less than 0.5 dB for each circuit. The errors in ground reflection losses for skywave circuits are generally less than one-half of 1 dB, except when the reflection area crosses a boundary between land or sea or good earth to poor earth. The interpolation listed in subroutine HFSKGD makes the transition across one grid interval, whereas in the HFMUFS program the transition is made in a very short interval. If the grid interval was decreased, this error could be decreased. In general, the skywave portion of HFSKGD is quite accurate, and if more accuracy is needed, a more dense grid can be implemented.

The groundwave errors are displayed at the bottom of Table 6. They are the errors over the 17 paths and vary from 1 to 8 dB. For low antennas and distances less than 1000 km, the errors for frequencies above 4 MHz were less than 2 dB. At distances greater than 1000 km and antennas above 5 km, the errors increase considerably. To improve the accuracy of the predictions in these cases requires more effort to further expand and develop the model. It should be borne in mind that one of the objectives of this program was to develop a fast method to compute HF circuit performance. When trade-offs between speed and accuracy had to be made, the decision always favored speed.

5. CONCLUSIONS AND RECOMMENDATIONS

An HF propagation prediction program for rapid calculations of air-to-ground HF circuit parameters has been described. The program is optimized to enable the

Table 6. RMS Errors in Decibels for Air-to-Ground Loss Parameters for 17 HF Circuits, 4 Seasons, 2 Hours, and 1 Solar Activity

Ionospheric Wave Error

Skywave loss, L_{bf} : Less than 0.5 dB for each circuit.

Absorption loss, L_i : Less than 0.05 dB for each circuit.

Ground reflection loss, L_g: Less than 0.5 dB when not in a transition area.
Less than 7.0 dB in transition area.

Ground Wave

Frequency MHz	3	5	8	11	15	18	21	26
All circuits	6.3	4.4	4.3	5.8	4.5	4.6	4.7	4.7
Low antenna less than 1200 km distance	4.9	1.9	1.0	1.8	1.6	1.8	1.8	1.8
20 km antenna less than 1000 km distance	2.7	5.3	6.7	6.8	7.8	7.9	8.0	8.0

rapid calculation of a large number of circuits of various frequencies and lengths at the same universal time. The air-to-ground HF propagation program is derived from two propagation programs developed at the Institute for Telecommunication Sciences. The skywave portion of the air-to-ground HF propagation program follows from the HFMUFES program described by Barghausen et al. (1969). The groundwave portion of the air-to-ground propagation program is based upon the work of Berry (OT Technical Memorandum 78-247, January 1978). The air-to-ground model described herein is an order of magnitude faster than the anticedent programs.

Despite attempts to optimize the speed and accuracy of the calculations involved in the air-to-ground program, limitations to the program exist. As in the HFMUFES program, the ionization in the F1 layer is ignored. This could prove to be a significant limitation for circuits that are simulated for local summer conditions when the ionization in the F1 layer is a substantial fraction of that in the F2 region during the daytime. The F-layer ionization can effectively block radio waves from reaching the F2 region, thereby reducing the length of the propagation path for the frequencies reflected from the F1 layer.

The noise generated by aircraft operations is not included in the signal-to-noise ratio. Also, there is no height variation of the atmospheric noise and man-made noise in the program. These could prove to be substantial limitations to the accuracy of the simulated results for those cases involving platforms that are elevated above 5-10 km.

The accuracy of the predictions of the groundwave loss for distances greater than 1000 km and antenna heights above 5 km needs to be improved. This improvement may require using the exact equations. If this approach were adopted, it would come at considerable expense of the overall speed of the current air-to-ground program.

The limitations mentioned above should be removed by future work that is directed toward improving the HF air-to-ground propagation model.

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15. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

A radio propagation prediction computer code has been developed to permit rapid simulation of HF air-to-ground telecommunication circuits. This prediction program provides estimates of both skywave and groundwave HF propagation parameters. The skywave and groundwave propagation parameters can be obtained for radio circuits with transmitters and receivers on the surface of the earth or with one or both ends of the circuit elevated up to 50 km. When a large number of circuits in a given area are simulated for a single time, the program is an order of magnitude faster than its predecessors. This report provides a description of the air-to-ground HF propagation prediction program as well as illustrations of the results obtained from the program.

16. Key Words *(Alphabetical order, separated by semicolons)*

Air-to-ground propagation; groundwave propagation; HF predictions; ionospheric propagation; propagation predictions; skywave propagation

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