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Algorithms Used in ARROWS: Autodesign of Radio Relay Optimum Wideband Systems

L.G. Hause

U.S. DEPARTMENT OF COMMERCE
Malcolm Baldrige, Secretary

Alfred C. Sikes, Assistant Secretary
for Communications and Information

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ALGORITHMS USED IN ARROWS: AUTODESIGN OF RADIO RELAY OPTIMUM WIDEBAND SYSTEMS

L. G. Hause*

This report describes the mathematical models used in the ARROWS programs. These programs, which run on a desktop computer, automate the calculations involved in the design of line-of-sight microwave radio relay links. The programs calculate, tabulate, and plot information about Earth geometry, terrain profiles, ray paths, repeater-reflector geometry, median basic transmission loss, variablility of loss, equipment effects, and link performance. Each model is selected on the basis of its acceptance within the communications industry and the size and type of data base supporting the model. The computer hardware and software configurations are designed to be convenient to operate and to give the design engineer immediate access to calculated results corresponding to changes in design parameters. The programs corresponding to these algorithms are designed to be used interactively by persons having no experience in programming. The algorithms are applicable over a wide range of link parameters. The frequency range is from 1 GHz to 20 GHz. Path lengths should be less than 150 km.

Key words: computer software; digital radio; microwave radio; passive repeater; radio link performance; radio relay

1. INTRODUCTION

This report describes the algorithms used in the ARROWS program set. ARROWS is an acronym for Autodesign for Radio Repeater Optimum Wideband Systems. ARROWS is an automated, interactive set of desktop computer programs, that permit workers with moderate skill levels to perform the calculations necessary for the design of line-of-sight (LOS) microwave links for both FM/FDM and PCM/TDM systems. FM/FDM stands for "frequency modulation/frequency division multiplex" and PCM/TDM stands for "pulse code modulation/time division multiplex." Gathering and programming of these algorithms were sponsored by the

*The author is with the Institute for Telecommunication Sciences, National Telecommunications and Information Administration, U.S. Department of Commerce, Boulder, CO 80303-3328.

U.S. Army Information Systems Engineering Support Activity, Ft. Huachuca, AZ. The programs are written in HPL language and are provided with documentation that permits them to be conveniently operated, understood, modified, and updated. The primary use of the program set is the analysis of LOS links that may include up to three repeater sites. These programs calculate the optimum antenna and reflector orientation values from the Earth geometry parameter values of the terminal and repeater sites. They also calculate the performance of the link based on the reflector size, antenna gains, and other equipment parameters. Both atmospheric and terrain parameters are taken into account. ARROWS programs are used to prepare either active or passive repeater designs.

An example link is used to illustrate results produced by the ARROWS program set. These sites and paths exist in Europe, but equipment and communications channels attributed to them in the example do not exist. The sites were selected because their path and Earth geometry are typical, and the terrain-data set for these paths is conveniently available. The equipment selected to illustrate each path was not that which we felt was optimum for performance of the link, but that which we felt would illustrate the range and diversity of the ARROWS programs.

1.1 What are the Algorithms and What Do They Do?

The algorithms are given letter designations that correspond to the ARROWS individual subprogram letter designations as follows:

A. Repeater Link Earth Geometry
B. Path Profile Data and Effective Earth Radius
C. Primary Antenna Heights
D. Path Profiles and Ray Traces
E. Site Antenna or Reflector Layout
F. Repeater Site Loss and Antenna Gain
G. Median Basic Transmission Loss
H. Basic Transmission Loss Variability
I. Link Carrier-to-noise Ratio Probability Distribution
J. Analog Radio System Single-receiver Transfer Characteristic
K. FM/FDM Link Performance
L. PCM/TDM Link Performance.

The algorithms, by means of their corresponding programs, perform the following tasks:

1) "A" is used to calculate the coordinates of antennas and reflectors. It is also used to calculate the path distances and beam azimuths along the transmission paths. The map-crossing feature also helps in the preparation of terrain profiles.
2) "B" provides a convenient means of entering, editing, and manipulating path profile data. It is also used to calculate the effective-Earth-radius factor corresponding to atmospheric conditions.
3) "C" is used to calculate recommended minimum antenna height values.
4) "D" examines ray-path clearance and calculates fundamental atmospheric and geometric statistics about the propagation paths.
5) "E" is used to calculate the orientation of antennas and reflectors and the projected areas of flat reflectors. It is also used to determine shadowing effects of double flat reflectors.
6) "F" calculates losses and gains associated with antennas and reflectors.
7) "G" calculates the median basic transmission loss for each component path in the link. This loss has two components: the inverse square (free space) loss and atmospheric absorption.
8) "H" calculates the basic transmission loss variability for each path. The variability has two loss components: rain attenuation and multipath attenuation.
9) "I" incorporates equipment parameters in order to calculate the probability distribution of the link carrier-to-noise ratio.
10) "J" incorporates FM/FDM equipment parameters in order to calculate the single-receiver transfer characteristic function (worst-telephone-channel signal-to-noise ratio vs. radio frequency carrier-to-noise ratio).
11) "K" calculates FM/FDM link performance in terms of median signal quality and the fraction of time that the signal falls below a minimum acceptable quality.
12) "L" calculates PCM/TDM link performance in terms of the fraction of time that the signal falls below a minimum acceptable quality.

The subprograms do tasks besides those listed above. They provide graphs, pictorials, and tabulations in a report-ready format and store this data in a compact manner that makes it easy to locate, display, modify, and recalculate.

Because passive repeater links are usually made up of line-of-sight paths with adequate terrain clearance, line-of-sight analysis is used to calculate median signal level and path-loss variability. The programs were designed such that an ordinary one-path, line-of-sight link analysis is a special case of a repeater link analysis. This feature greatly expands the utility of the program set. The line-of-sight transmission loss algorithms that we have included are:

1) atmospheric absorption attenuation
2) atmospheric multipath attenuation
3) rain attenuation
4) inverse-square-law (free-space) loss.

The models described cover LOS links operating between 1 GHz and 50 GHz. The models do not cover links that include paths with marginal clearance. Distortion of digital transmissions due to multipath selective fading is not considered as a topic separate from multipath flat fading. This approach is reasonable if one of the following conditions exists:

1) Transmission bit rate on the link is less than 25 Mb/s.
2) Substantial multipath fading is not expected on any of the paths making up the link. Substantial fading is not expected on a path if it is shorter than 20 km, penetration angles of the beam through atmospheric layers are greater than 1°, or if antenna sites are elevated and the total path is over rough terrain.
3) The radios use adaptive equalizers (Smith, 1985, pp. 428-429) in combination with diversity and where the radio manufacturer's dispersive fade margin is greater than the flat fade margin.

Not all aspects of a system design can be automated, and such things as procedures for making a field survey of potential sites are much the same as described in MIL-HDBK-416 (Dept. of Defense, 1977a). These topics are not reexamined.

The use of a small computer system operating in a highly interactive mode permits the design engineer to evaluate many different system configurations, with immediate feedback in terms of system performance and tradeoffs. The benefits from this kind of automation are:

1) Days of tedious calculations are avoided.

2) Calculations are done systematically so that many types of errors are avoided.

3) Time is saved because batch processing is not necessary with the long turnaround times that are often involved with large computers.

4) More nearly optimum design choices result from the capability for the system designer to view the results of design changes immediately.

5) Report-ready formats cut overhead costs and expedite data checks and information dissemination.

1.2 Who Can Benefit from Using These Algorithms?

In the past, design of microwave systems was relegated to a few large organizations. Because of changes in the law and the economics involved in these systems, it is much more realistic for smaller organizations to provide their own wideband channel capabilities. This communications economy is not only a reality for businesses but also for governmental organizations, including many developing countries. Such organizations are often hard pressed to supply enough people, with suitable skill levels, to do the analysis required for planning of various components of the communication systems that they need. We believe that these algorithms not only reduce the period required for planning and installation of microwave links, but they also lead to link reliability that keeps operating costs in check.

2. ALGORITHM A: REPEATER LINK EARTH GEOMETRY

The principal purposes of this section are a) to discuss special considerations in the use of passive repeaters, and b) to determine the coordinates of all antennas or reflectors on the link and to calculate the path distances and beam azimuths along the component paths.

2.1 Passive Repeater Considerations

Although the ARROWS algorithms are used to design active and passive repeater links, a number of considerations must be taken into account when designing passive repeater systems. This section briefly discusses these considerations.

In mountainous terrain, access by maintenance personnel to active repeater stations is often a problem as is the primary power source, especially during winter months. A solution to this problem is often the use of a passive repeater that requires no power and little maintenance. With the passive repeater on a hilltop, the active repeater may be placed near an existing road, near reliable power, and at a low elevation. Although a passive repeater link generally exhibits more path loss than the direct line-of-sight link (were such a link available), the loss variability over the passive link is often less since beam angles of penetration through atmospheric layers are often steep. Other advantages often obtained using passive repeater systems are significant decreases in susceptib lity to interference and the capability of supporting wide bandwidths compared to diffraction paths, scatter paths, and many line-of-sight paths. The reasons for these advantages are very narrow beam angles, the resistance to multipath due to large penetration angles, and the flexibility of placing terminal sites in low terrain using short towers, thus sheltering the relatively wide-beam terminal antennas from interfering radio sources.

Full space diversity improvement is often very difficult to obtain especially on passive repeater links having one short leg. If a passive repeater is placed approximately midpath on a long path, space diversity may be used in both directions. Because of the space diversity restrictions, paths should be designed to minimize multipath if frequency diversity cannot be used. Multipath is minimized by either keeping the path short or by keeping the angles of penetration of the beam center through the atmospheric layers large (greater than 1°). Because of the ease with which high reflector gains are achieved using flat microwave reflectors, restraint must be exercised in the design of links using such reflectors. For flat, long paths containing beam penetration angles less than 0.5° through the atmospheric layers, large reflector gains (greater than 48 dB above isotropic) should generally not be used. For penetration angles greater than 1°, much larger gains may be used. Burrows and Attwood (1949, p. 146) state that, "Both theoretically and practically it has been found that the effects of nonstandard refraction are negligible for rays that leave the transmitter at an angle with the horizontal of more than about 1.5°. Rays that leave at an angle of less than 1.5°, and especially those emerging at angles with the horizontal of 0.5° or less, are strongly affected by nonstandard refraction."

2.2 Antennas

Each microwave mirror or antenna in the system is designated separately. An example of such designators for a link from ABC to XYZ (site designators) might be ABC, RA1, RB1, RB2, RC1, RC2, XYZ. Each repeater site may be given a nominal three-letter designator instead of R concatenated with a letter and an integer. The letters A, B, or C indicate the repeater site. The repeater antennas and mirrors at each site are lettered and numbered from the direction of the site having the designator that makes up the first three letters of the total link designator (for example, ABCXYZ). If mirrors or antennas are separated by less than 100 m, they are considered to be at the same site. The passive repeater system from end to end will be referred to as the link; the great circle distances (greater than 100 m) between adjacent repeaters will be referred to as paths, designated by concatenating the antenna designators on each end; for example, ABCRA1.

The following information must be obtained about each antenna or mirror: its type, location, size, orientation, operational bandwidth, polarization, losses, and gain. Initially we concern ourselves with only the first four pieces of information:

TYPE - Six types of antennas and mirrors are considered, and they are numbered as follows:

1) parabolic
2) parabolic horn
3) periscope
4) double antenna
5) single mirror
6) double mirror.

Particular sets of calculations in subsequent algorithms are done based on the antenna type.

LOCATION - Four pieces of information are needed for each location of an antenna or mirror aperture center:

1) latitude
2) longitude
3) elevation of the ground below the antenna center using mean sea level (msl) as reference
4) height of the antenna center above ground.

The coordinates of an antenna are often hand-entered but on occasion must be calculated from other information. A common type of information is a survey control point with an azimuth reference. When the position of an antenna cannot be hand entered directly, we use the procedure as follows:

1) Enter the antenna designator.
2) Enter the latitude, longitude, and elevation of the control point.
3) Enter the distance from the control point, D_{ca}, to the antenna center.
4) Enter the azimuth from the control point, A_{ca}, to the ground position under the antenna center.
5) Enter the height of the ground position above the control point.
6) Enter the height of the antenna center above the ground position.
7) Calculate the latitude, longitude, and elevation of the ground position under the antenna center.

The survey control point should not be more than 100 m from the antenna. The number of radians of latitude that a site is north of the control point is:

$$D_{ca} \cos(A_{ca}) / Z_p \qquad \text{(A-1)}$$

where Z_p is the polar Earth radius. The number of radians of longitude that a site is east of the control point is:

$$D_{ca} \cos(\text{control point latitude}) \sin(A_{ca}) / Z_e \qquad \text{(A-2)}$$

where Z_e is the equatorial Earth radius. These estimates of antenna center coordinates should be sufficiently accurate for our purposes as long as D_{ca} is less than 100 m.

SIZE - The shape of all parabolic and parabolic horn antenna apertures will be considered circular and the diameter must be introduced to determine the size. The size of periscope antenna is given in terms of its width and height. The size of mirror (flat) reflector is given in terms of its width and height. The size information is hand entered in Program C.

ORIENTATION - The orientation of antennas and flat reflectors is calculated from the antenna location information. The orientation of a flat reflector is defined in two parts: the azimuth of the normal to the reflecting surface and the elevation angle of the normal from horizontal. Orientation calculations are completed in Algorithm E. If the user is in doubt about where to place double mirrors, the program will automatically calculate suggested azimuths.

2.3 Path Distances and Azimuths

The model that we use to compute Earth geometry is unavoidably inexact but should be satisfactory for the engineering of passive-repeater links. Table 1 lists the equatorial and polar radii of spheroids in use today. The accuracy criteria for this model is an accuracy of 1 meter in position-geodetic length; latitude, longitude, and azimuth within .035 second over the longest possible hemispheroidal geodesies, but in any case, equaling the 1/100,000 distance and 1-second azimuth (Thomas, 1970, pp. 7 and 19).

This algorithm defaults to the International Spheroid, but provision is made to enter constants for other spheroids. These constants are the semimajor and minor axes (in kilometers) of the appropriate spheroid. A map showing which areas of the world are based on the various spheroids is contained in U.S. Army TM 5-241-1 (1967). Thus, for greatest accuracy, the applicable spheroid constants can be used in any particular area of the world. The spheroid used in preparing the maps from which profile values are selected should be entered.

The model used here is one proposed by Thomas (1970). The initial point latitude, λ_1, and longitude, ϕ_1, as well as the terminal point latitude, λ_2, and longitude, ϕ_2, are entered. The algorithm assumes positive values are north or east and negative values are south or west. The great circle path length, s (kilometers), azimuth from the initial point, α_{1-2}, and azimuth from the terminal point, α_{2-1}, are returned. The azimuth values are returned in degrees east of north.

Table 1. Earth Radii for Various Spheroids

Spheroid	Equatorial Radius (km)	Polar Radius (km)
International	6378.388	6356.912
Clark 1866	6378.2064	6356.5838
Clark 1880	6378.249145	6356.514869
Everest	6377.276345	6356.075415
Bessel	6377.397155	6356.078963
Australian National	6378.160	6356.7745
Airy	6377.563396	6356.256910
Fischer	6378.155	6356.77332
Malayan	6377.304063	6356.103039

2.4 Calculation of Map Crossings

Map crossings are calculated by successive approximations in which forward azimuth values (computed using the Thomas, 1970, model) are compared with the path forward azimuth to provide error values to measure convergence. If values of (λ_1, ϕ_1), (ϕ_2, λ_2) and λ_3 or ϕ_3 are given, calculate ϕ_3 or λ_3, respectively (Figures 1 and 2). In Figures 1 and 2, the symbols have the following definitions:

x = the distance east from the Prime Meridian to the point (x, y)

y = the distance north from the equator to (x, y)

ϕ = the longitude of (x, y)

λ = the latitude of (x, y)

α = the azimuth from Point 1 to (x, y) (from the Thomas model)

r = the distance from (x_1, y_1) to (x, y) (from the Thomas model)

e = $\alpha_{12} - \alpha$ (azimuth error)

Δs = the arc length

a = Earth radius (6370 km)

$\Delta\phi$ = the magnitude of the longitude error

$\Delta\lambda$ = the magnitude of the latitude error.

The equations that apply to Figure 1 are:

$$\Delta\lambda = \frac{180 \, \Delta y}{\pi a} \tag{A-3}$$

$$\Delta y \approx \frac{\Delta s}{\sin \alpha_{12}} \tag{A-4}$$

$$\Delta s \approx r_1 e_1 \frac{\pi}{180} . \tag{A-5}$$

Combining (A-3), (A-4), and (A-5),

$$\Delta\lambda \approx \frac{r_1 e_1}{a \sin \alpha_{12}} . \tag{A-6}$$

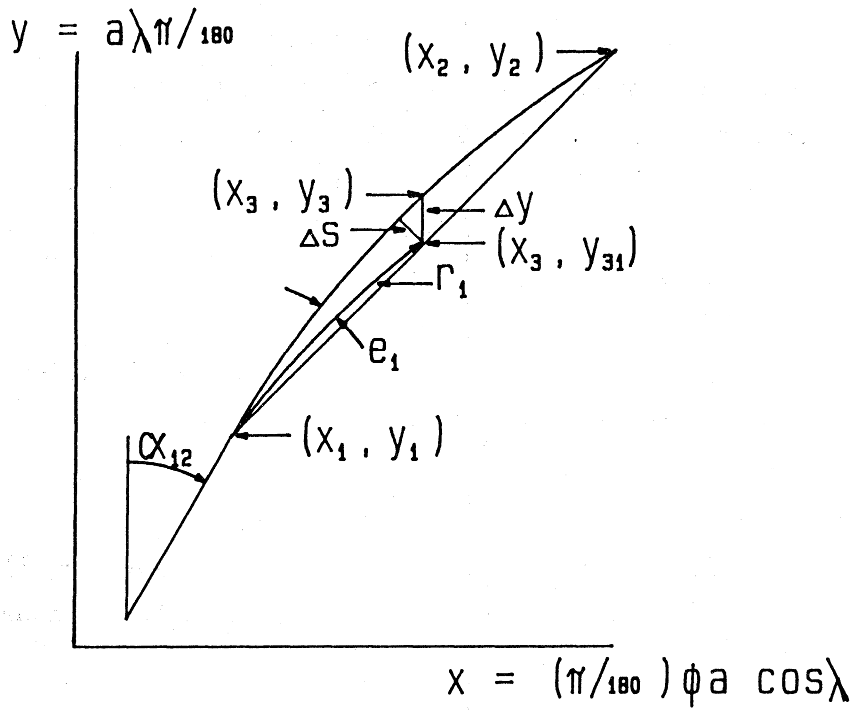

Figure 1. Geometry for calculating latitude for a given longitude.

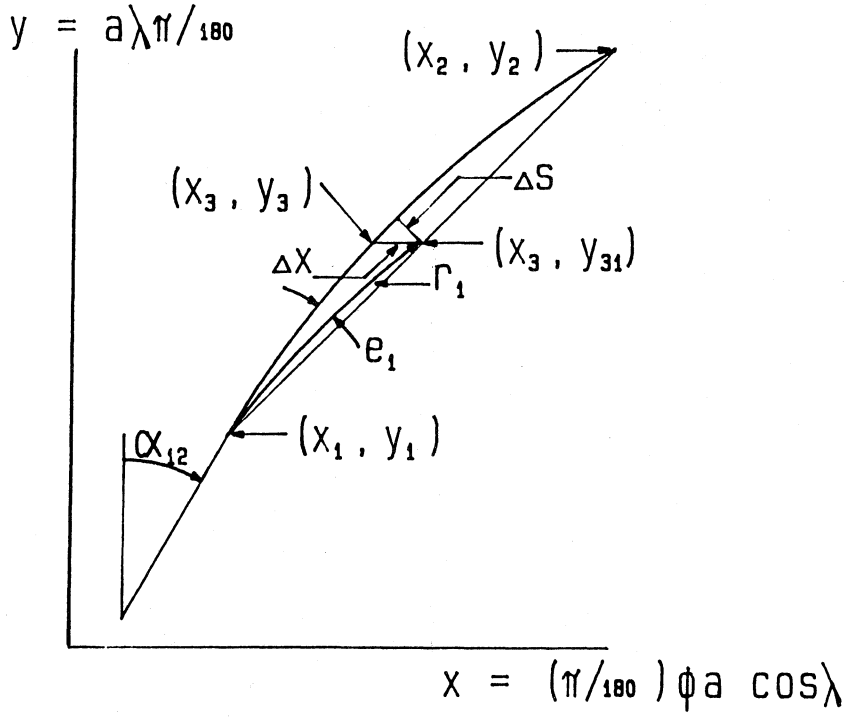

Figure 2. Geometry for calculating longitude for a given latitude.

The equations that apply to Figure 2 are:

$$\Delta\phi = \frac{180\ \Delta x}{\pi\ a \cos \lambda_1} \tag{A-7}$$

$$\Delta x \approx \frac{\Delta s}{\cos \alpha_{12}} \tag{A-8}$$

Combining (A-5), (A-7), and (A-8),

$$\Delta\phi \approx \frac{r_1 e_1}{a \cos \lambda_1 \cos \alpha_{12}} . \tag{A-9}$$

The algorithm for computing the map crossings is as follows:

1) Using the algorithm by Thomas (1970), calculate the azimuth, α_{1-2}, from (λ_1, ϕ_1) along the great circle path to (λ_2, ϕ_2).

2) Calculate the first estimate of λ_3 or ϕ_3, called λ_{31} and ϕ_{31} respectively, by linear interpolation:

$$\lambda_{31} = \lambda_1 + \frac{\phi_3 - \phi_1}{\phi_2 - \phi_1} (\lambda_2 - \lambda_1) \tag{A-10}$$

$$\phi_{31} = \phi_1 + \frac{\lambda_3 - \lambda_1}{\lambda_2 - \lambda_1} (\phi_2 - \phi_1) \tag{A-11}$$

3) Using the Thomas algorithm, calculate azimuth, α_{1-31} from (λ_1, ϕ_1) to (λ_3, ϕ_{31}) or to (λ_{31}, ϕ_3), whichever is applicable.

4) Calculate the azimuth error, e_1:

$$e_1 = \alpha_{1-31} - \alpha_{1-2}; \quad (e_n = \alpha_{1-3n} - \alpha_{1-2}) \tag{A-12}$$

5) Calculate the second estimate of ϕ_3 or λ_3 called $\phi_{3(n+1)}$ or $\lambda_{3(n+1)}$, respectively:

$$\phi_{3(n+1)} = \phi_{3n} - k_\phi \, e_n \qquad \text{where} \quad k_\phi = \frac{r_n}{a \cos \lambda_1 \cos \alpha_{1-n}} \qquad \text{(A-13)}$$

$$\lambda_{3(n+1)} = \lambda_{3n} - k_\lambda \, e_n \qquad \text{where} \quad k_\lambda = \frac{r_n}{a \sin \alpha_{1-n}} \qquad \text{(A-14)}$$

6) Calculate the azimuth, α_{1-32}; $\alpha_{1-3(n+1)}$.

7) Calculate the azimuth error e_2; e_{n+1}:

$$e_2 = \alpha_{1-2} - \alpha_{1-32}; \; e_{n+1} = \alpha_{1-2} - \alpha_{1-3(n+1)} \qquad \text{(A-15)}$$

8) Is $|e_1| > |e_2|$?; Is $|e_n| > |e_{n+1}|$?

9a) If yes, repeat the steps from Number 5 using the appropriate subscripts for each new step until $|e_n| < 0.01$ seconds

9b) If no, repeat the steps from Number 5, having changed the sign of k_ϕ or k_λ.

2.5 Earth Geometry Output Formats

An example of the output tabulation is presented in Table 2. The link diagram is shown in Figure 3.

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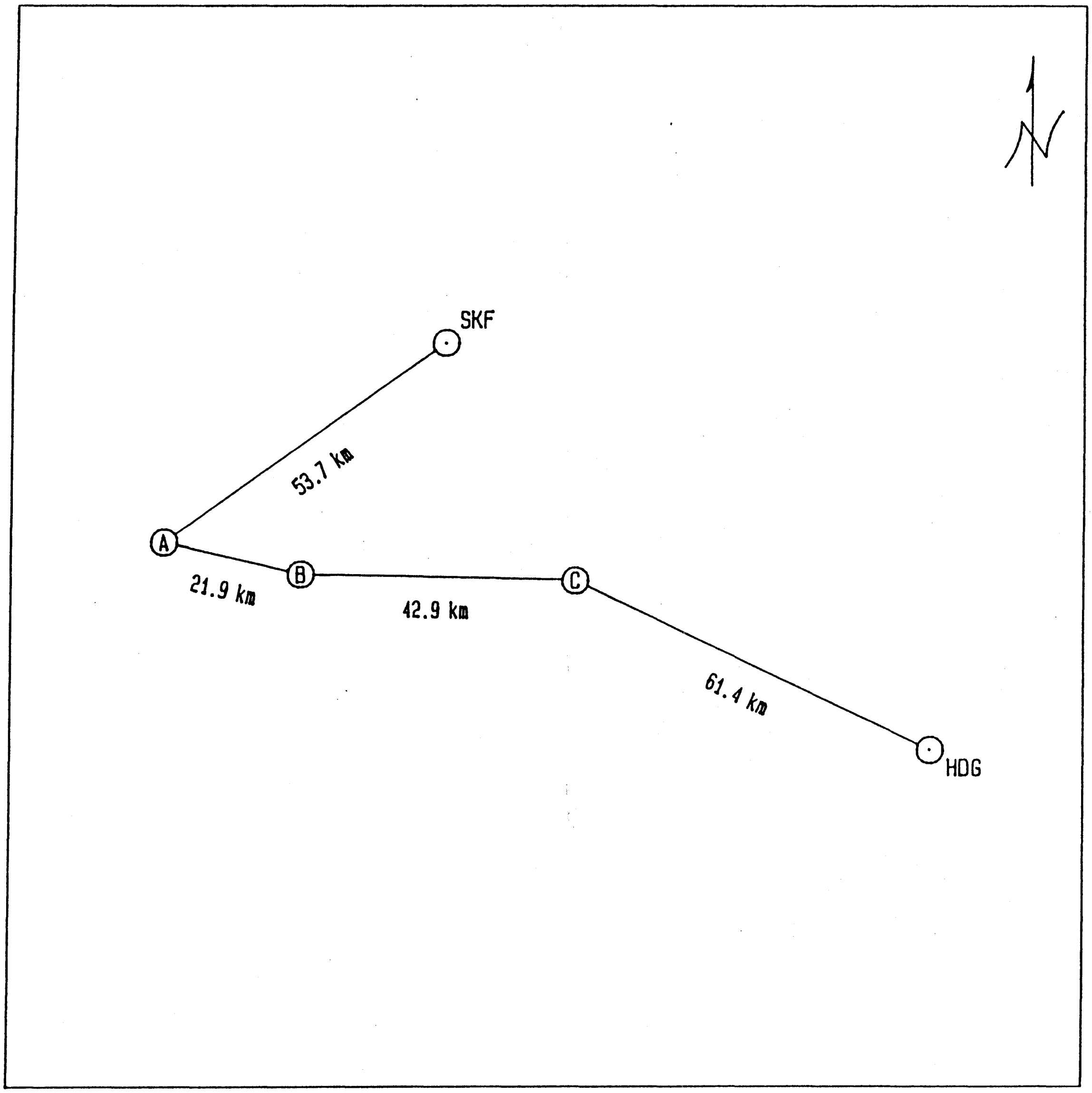


Designator	Name	Antenna Type
SKF	Shanzerkopf	Parabolic horn
MUL	Muhl	Single mirror
BHR	Baumholder	Double antenna
DON	Donnersberg	Double mirror
HDG	Heidelberg	Periscope

Link Configuration
Shanzerkopf to Heidelberg

Figure 3. Example link diagram.

Table 2. Example of Earth Geometry Data

Aug/21/1986

Link Earth Geometry
Shanzerkopf to Heidelberg

Link Information:

Earth Spheroid Name		International
Equatorial Radius	(km)	6378.388000
Polar Radius	(km)	6356.912000
Number of Paths in the Link		4

Site Information:

Site Name	Site Designator	Antenna or Reflector Configuration	Magnetic Declination from True North (d/m/s)
Shanzerkopf	SKF	Parabolic horn	5 00' 00.0"W
Muhl	MUL	Single mirror	5 00' 00.0"W
Baumholder	BHR	Double antenna	5 00' 00.0"W
Donnersberg	DON	Double mirror	5 00' 00.0"W
Heidelberg	HDG	Periscope	5 00' 00.0"W

	--------------------Survey Control Point--------------------			
Site Designator	Latitude (d/m/s)	Longitude (d/m/s)	Elevation above msl (m)	Azimuth Reference (d/m/s)
SKF	49 57' 37.0"N	7 38' 17.0"E	643.000	00' 00.0"
MUL	49 40' 50.0"N	7 01' 48.0"E	750.000	00' 00.0"
BHR	49 38' 08.0"N	7 19' 33.0"E	563.000	00' 00.0"
DON	49 37' 32.0"N	7 55' 10.0"E	685.000	00' 00.0"
HDG	49 23' 12.0"N	8 41' 00.0"E	108.000	00' 00.0"

Table 2. Example of Earth Geometry Data (Cont.)

Aug/21/1986

Link Earth Geometry (Continued)
Shanzerkopf to Heidelberg

Location of Antennas Relative to Control Points:

Antenna Designator	Azimuth from CP to Antenna Base Point (d/m/s)	Distance from CP to Antenna Base Point (m)	Height of Tower Base Above the CP (m)
SKF	00' 00.0"	0.000	0.000
MUL1	00' 00.0"	0.000	0.000
BHR1	00' 00.0"	0.000	0.000
BHR2	00' 00.0"	0.000	0.000
DON1	45 17' 00.0"	20.000	0.000
DON2	232 07' 00.0"	22.600	0.000
HDG	00' 00.0"	0.000	0.000

Antenna Center Information:

Antenna Designator	Latitude (d/m/s)	Longitude (d/m/s)	Tower Base Elevation Above msl (m)
SKF	49 57' 37.0"N	7 38' 17.0"E	643.000
MUL1	49 40' 50.0"N	7 01' 48.0"E	750.000
BHR1	49 38' 08.0"N	7 19' 33.0"E	563.000
BHR2	49 38' 08.0"N	7 19' 33.0"E	563.000
DON1	49 37' 32.5"N	7 55' 10.7"E	685.000
DON2	49 37' 31.5"N	7 55' 09.1"E	685.000
HDG	49 23' 12.0"N	8 41' 00.0"E	108.000

Intrasite Information:

Intrasite Path Designator	Antenna Seperation (m)	Forward Azimuth from True North (d/m/s)	Antenna Base Height Difference (m)
BHR1BHR2	0.000	00' 00.0"	0.000
DON1DON2	42.525	228 54' 31.6"	0.000

Table 2. Example of Earth Geometry Data (Cont.)

Aug/21/1986

Link Earth Geometry (Continued)
Shanzerkopf to Heidelberg

Intersite Information:

Intersite Path Designator	Path Length (km)	Forward Azimuth From True North (d/m/s)	Back Azimuth From True North (d/m/s)	Forward Azimuth From Magnetic North (d/m/s)	Back Azimuth From Magnetic North (d/m/s)
Path 1	53.6925	234 49' 09.3"	54 21' 16.9"	239 49' 09.3"	59 21' 16.9"
Path 2	21.9396	103 04' 28.2"	283 18' 00.0"	108 04' 28.2"	288 18' 00.0"
Path 3	42.9148	91 14' 24.3"	271 41' 33.0"	96 14' 24.3"	276 41' 33.0"
Path 4	61.3881	115 20' 28.5"	295 55' 20.5"	120 20' 28.5"	300 55' 20.5"

3. ALGORITHM B: PATH PROFILE DATA AND EFFECTIVE-EARTH RADIUS

The purpose of Algorithm B is to provide a convenient means of entering, editing, and manipulating path profile data. The normal effective-Earth-radius factor is also calculated.

The profile data consists primarily of terrain elevations in meters above mean sea level (msl) as a function of distance from the various antennas, starting with the first path making up a particular repeater link. For example, one of the component paths might be RB2RC1 (Figure 3). In this case, distances would be measured from Antenna RB2. In other words, when a path is named from the two primary antenna designators, RC1 and RB2, the path name should be entered using the antenna from which distances are measured as the first three characters in the path designator (RB2RC1). Once the starting site for a link has been selected, the direction along the link should be consistent. For example, in Figure 3, if ABC is selected as the first antenna for the first path, then the path designators should be ABCRA1, RA1RB1, RB2RC1, RC2XYZ. If XYZ were chosen as the first site, the repeater sites and antennas would be renumbered (Site A becoming Site C) and the path designators would be XYZRA1, RA2RB1, RB2RC1, AND RC1ABC. Due to the requirement for referencing distance to the first antenna on a path, provision is made to reverse the path by selecting the other antenna as the reference and calculating the correspondence of distances and elevations from the other end of the path. The reversing capability is necessary, since traffic in one direction may use a separate set of communication channel parameters than the traffic in the other direction uses. Two such parameters are carrier frequency and polarization.

Besides terrain elevation above msl, an obstacle type and height above ground level may be entered for a given distance; for example, at 21.7 km there are trees 10 m high.

In addition to the information about the terrain, average atmospheric refractivity and effective Earth-radius factor are calculated.

3.1 Path Profile Parameter Definitions

Heights in meters corresponding to distance, d (km), along the path from the first antenna are defined as follows:

h_m = the height of the terrain above mean sea level (msl) along the great-circle path. Values of h_m should be entered for values of d no greater than 5 km apart and no greater than 1 km apart on the first and last 5 km of the path. In the vicinity of high points and potential obstructions, points should be entered often enough to provide reasonable detail about the high points.

h_t = the height above ground level of obstacles on the path (trees, buildings, etc.).

3.2 Earth-Radius Factor

The ray path trajectory calculated in Algorithm C is dependent upon the value of the effective-Earth-radius factor, k. The concept of the "effective-Earth radius" is a convenient means of accounting for the bending of the radio rays caused by changes in the atmosphere's vertical refractivity. The Earth-radius factor $k = a/a_o$, where a is the effective-Earth radius in km and a_o is the actual Earth radius (6370 km). The surface refractivity reduced to sea level, N_o, can be used to obtain a value of k for estimating radio propagation effects (MIL-HDBK-417, pp. 4-82 to 4-89). The relationship between N_o and k is found by means of the parameter, N_s. A relation between N_s and k can be established for $250 < n_s < 400$ n-units:

$$k = [1 - 0.04665 \exp(0.005577 N_s)]^{-1} \qquad \text{(B-1)}$$

where N_s is the surface refractivity in n-units. Transmission loss calculation formulas have been predominantly based on N_s because more complete statistics of surface refractivity are available than are statistics for refractivity gradient.

The surface refractivity, N_s, is a function of temperature, pressure, and humidity, and decreases with elevation. Figure 4 is a map showing minimum monthly mean values of surface refractivity normalized to mean sea level, N_o. For a particular link, the applicable values of N_o are read from this map and converted to values of N_s by:

$$N_s = N_o[\exp(-0.1057\ h_{m1}) + \exp(-0.1057\ h_{m2})]1/2 \qquad \text{(B-2)}$$

where h_{m1} is the elevation of the first antenna site and h_{m2} is the elevation in km above msl of the second antenna site.

3.3 Profile Data Output Format

The output format for Program B is a series of tabulations (one for each path). Table 3 is an example of one of these profile data output tabulations.

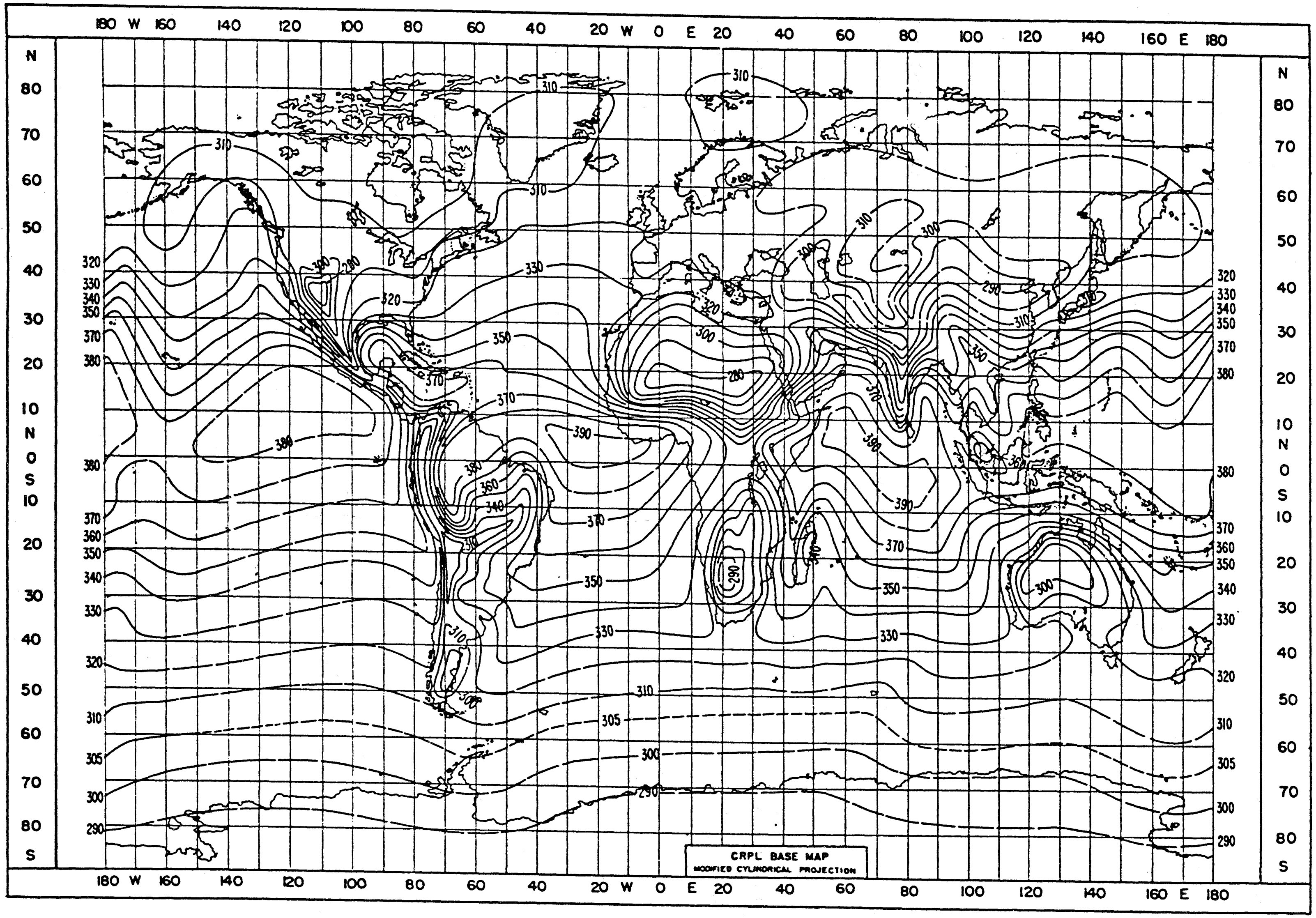


Figure 4. Minimum monthly surface refractivity, N_0, values normalized to mean sea level (Rice et al., 1967).

Table 3. Example of Profile Data

Aug/21/1986

Effective Earth's Radius Factor
Shanzerkopf to Heidelberg

For the SKFMUL Path:

Refractivity (Referred to msl), N[0]	(n-units)	320.00000
SKF Elevation Above msl, h[m1]	(m)	643.00000
MUL Elevation Above msl, h[m2]	(m)	750.00000
Average Surface Refractivity, N[S]	(n-units)	297.29263
Earth's Radius Factor, k		1.32425
Path Length, D	(km)	53.69250

For the MULBHR Path:

Refractivity (Referred to msl), N[0]	(n-units)	320.00000
MUL Elevation Above msl, h[m1]	(m)	750.00000
BHR Elevation Above msl, h[m2]	(m)	563.00000
Average Surface Refractivity, N[S]	(n-units)	298.56205
Earth's Radius Factor, k		1.32731
Path Length, D	(km)	21.93960

For the BHRDON Path:

Refractivity (Referred to msl), N[0]	(n-units)	320.00000
BHR Elevation Above msl, h[m1]	(m)	563.00000
DON Elevation Above msl, h[m2]	(m)	685.00000
Average Surface Refractivity, N[S]	(n-units)	299.58105
Earth's Radius Factor, k		1.32979
Path Length, D	(km)	42.91480

For the DONHDG Path:

Refractivity (Referred to msl), N[0]	(n-units)	320.00000
DON Elevation Above msl, h[m1]	(m)	685.00000
HDG Elevation Above msl, h[m2]	(m)	108.00000
Average Surface Refractivity, N[S]	(n-units)	307.00862
Earth's Radius Factor, k		1.34860
Path Length, D	(km)	61.38805

Table 3. Example of Profile Data (Cont.)

Aug/21/1986

P r o f i l e   D a t a
Path 4 (DONHDG)
Shanzerkopf to Heidelberg Link

Point No.	Metric Units Dist (km)	Elev (m)	Code	Height (m)	English Units Dist (mi)	Elev (ft)	Code	Height (ft)
DON	0.00	685			0.00	2247		
1	0.40	684	Obst		0.25	2244	Obst	
2	0.50	657			0.31	2156		
3	0.80	658			0.50	2159		
4	0.90	664	Tree	24	0.56	2179	Tree	79
5	1.10	665			0.68	2182		
6	1.40	645			0.87	2116		
7	1.50	615			0.93	2018		
8	1.90	462			1.18	1516		
9	2.20	384			1.37	1260		
10	2.80	345			1.74	1132		
11	3.00	294			1.86	965		
12	3.20	291			1.99	955		
13	3.50	294			2.17	965		
14	3.80	302			2.36	991		
15	4.00	300			2.49	984		
16	4.50	285			2.80	935		
17	5.90	255			3.67	837		
18	6.40	225			3.98	738		
19	6.50	217			4.04	712		
20	6.80	218			4.23	715		
21	6.90	226			4.29	742		
22	7.30	227			4.54	745		
23	7.90	211			4.91	692		
24	8.20	211			5.10	692		
25	9.50	272			5.90	892		
26	9.80	267			6.09	876		
27	10.20	266			6.34	873		
28	10.50	273			6.52	896		
29	10.80	268			6.71	879		
30	11.40	277			7.08	909		
31	11.75	277			7.30	909		
32	12.00	210			7.46	689		
33	12.50	195			7.77	640		
34	13.00	188			8.08	617		
35	14.10	195			8.76	640		

Table 3. Example of Profile Data (Cont.)

36	14.80	173			9.20	568		
37	15.15	177			9.41	581		
38	15.40	182			9.57	597		
39	15.80	246			9.82	807		
40	16.10	259			10.00	850		
41	16.50	323			10.25	1060		
42	16.70	325			10.38	1066		
43	16.90	324			10.50	1063		
44	19.00	183			11.81	600		
45	20.00	174			12.43	571		
46	21.30	144			13.24	472		
47	21.90	141			13.61	463		
48	22.60	145			14.04	476		
49	23.30	156			14.48	512		
50	23.60	156			14.66	512		
51	23.90	138			14.85	453		
52	24.10	138			14.98	453		
53	25.00	155	Tree	27	15.53	509	Tree	89
54	25.60	154	Tree	24	15.91	505	Tree	79
55	27.00	108	Tree	27	16.78	354	Tree	89
56	29.00	95	Tree	25	18.02	312	Tree	82
57	30.00	97			18.64	318		
58	31.50	94	Tree	27	19.57	308	Tree	89
59	33.00	96	Tree	26	20.51	315	Tree	85
60	35.80	93	Tree	27	22.25	305	Tree	89
61	37.00	95	Tree	27	22.99	312	Tree	89
62	39.00	95	Tree	27	24.23	312	Tree	89
63	42.00	90	Tree	27	26.10	295	Tree	89
64	45.50	90	Tree	27	28.27	295	Tree	89
65	46.00	91	Bldg	35	28.58	299	Bldg	115
66	46.80	91	Tree	27	29.08	299	Tree	89
67	49.30	102	Tree	25	30.63	335	Tree	82
68	50.80	103	Tree	26	31.57	338	Tree	85
69	51.00	101	Tree	25	31.69	331	Tree	82
70	52.00	101	Tree	24	32.31	331	Tree	79
71	52.70	104	Strt W		32.75	341	Strt W	
72	56.90	104	End W		35.36	341	End W	
73	58.50	106			36.35	348		
74	59.30	103	Tree	10	36.85	338	Tree	33
75	60.00	105			37.28	345		
76	61.00	105			37.90	345		
HDG	61.39	108			38.14	354		

4. ALGORITHM C: PRIMARY ANTENNA HEIGHTS

The purpose of Algorithm Set C is to calculate recommended minimum primary antenna height values. These values are based on the assumption that the costs of towers increase as the square of their heights and that these costs should be minimized. It is also assumed that various mitigating circumstances are not present, such as other factors that bear on costs, or various restrictions on tower heights due to such as those to accomodate the presence of aircraft. Two situations are considered. The first one assumes that both the first and second antenna heights (primary antenna heights on both ends of the path) are unknown. The second situation is one in which the antenna height on one end of the path is known.

4.1 Calculating Minimum Antenna Heights For Both Ends

The absolute minimum recommended antenna height of an antenna above ground is based on two considerations:

1) Minimum antenna heights for a path are the values that tend to minimize tower heights and at the same time provide six-tenths first Fresnel zone clearance when the ray path is calculated using the extreme subrefractive Earth-radius factor, k_e.

2) The absolute clearance within 1 km of each antenna is greater than 3 m plus one-half of the local antenna's vertical dimension plus the ray path clearance.

In order to calculate ray path location and Fresnel zone clearance values, two expressions are required. The expression for the ray path height, h_r, in meters above mean sea level (msl) is as follows:

$$h_r = d^2(12.75k)^{-1} + d\{(h_{22}-h_{21})D^{-1} - D(12.75k)^{-1}\} + h_{21} \qquad \text{(C-1)}$$

where h_{a1} = the first antenna height in m above msl at d = 0,

h_{a2} = the second antenna height in m above msl at d = D,

d = the distance along the path in km,

D = the length of the path in km, and

k = the Earth's radius factor.

The equation provided for calculating the first Fresnel zone radius in meters, R_f, on a plane perpendicular to the path center line is:

$$R_f = 17.3f^{-1/2}(dD-d^2)^{1/2}\ D^{-1/2} \qquad \text{(C-2)}$$

where f is the carrier frequency in GHz.

The algorithm for calculating optimum antenna heights proceeds in the following way. If the absolute clearance criteria are not met within the 1 km distance from the antennas, increase the height of the local antenna by the amount of the negative clearance (blockage, B_t, in meters). If the absolute clearance criteria within 1 km of the antennas are met, then increase the height of the antennas by the amount indicated in the following expressions:

$$I_{a1} = B_t(2d_b\ D^{-1} + 1)\ (1-d_b\ D^{-1}) \qquad \text{(C-3)}$$

$$I_{a2} = B_t\ d_b\ d^{-1}(3 - 2d_b\ D^{-1}) \qquad \text{(C-4)}$$

where B_t = the negative of the minimum Fresnel zone clearance in meters,

d_b = the distance fron the first antenna to the point of minimum Fresnel zone clearance in km,

D = the length of the path in km, and

I_{a1} and I_{a2} = the increases in tower heights.

These increases are calculated to maintain the required fractional Fresnel zone clearance while minimizing tower costs.

4.2 Calculating Minimum Antenna Height with One End Fixed

If for some reason the primary antenna height on one end of the path is fixed at a particular value, the other primary antenna height required for minimum clearance may be calculated using the following procedures:

1) If the absolute clearance within 1 km of the nonfixed antenna is not greater than 3 meters plus one half of the local antenna's vertical dimension plus the ray path clearance, increase the height of the local antenna until it does meet this criterion.

2) For distances more than 1 km from the antennas, check the minimum Fresnel zone clearance. If it is less than the fractional R_f, increase the height of the nonfixed antenna by B_t + 0.1 until it is less than the fractional R_f.

4.3 Recommended Antenna Heights Output Format

The output of Program "C" is a tabulation (Table 4) showing the recommended antenna heights. These recommendations ignore factors other than obstacles on the path being considered. Other considerations might include: existing tower heights, zoning regulations, etc. The output also shows alternative antenna height pairs that provide adequate clearance.

Table 4. Example Recommended Antenna Height Data

Aug/21/1986

Recommended Antenna Heights
Shanzerkopf to Heidelberg

Path 1 (Shanzerkopf to Muhl):

Primary Frequency	(GHz)	7.40000
Transmitting Antenna Aperture Vert Dimension	(m)	3.000
Receiving Antenna Aperture Vert Dimension	(m)	8.000
Recommended Xmit Ant Cntr Ht above Tower Base	(m)	32.621
Recommended Recv Ant Cntr Ht above Tower Base	(m)	11.143

Min Xmit Ant Ht (m)	Min Rec Ant Ht (m)	Min Xmit Ant Ht (m)	Min Rec Ant Ht (m)	Min Xmit Ant Ht (m)	Min Rec Ant Ht (m)
14.5	338.7	28.5	84.2	42.5	7.0
16.5	302.3	30.5	47.8	44.5	7.0
18.5	265.9	32.5	11.5	46.5	7.0
20.5	229.5	34.5	7.0	48.5	7.0
22.5	193.2	36.5	7.0	50.5	7.0
24.5	156.9	38.5	7.0	52.5	7.0
26.5	120.5	40.5	7.0	54.5	7.0

Path 2 (Muhl to Baumholder):

Primary Frequency	(GHz)	7.40000
Transmitting Antenna Aperture Vert Dimension	(m)	8.000
Receiving Antenna Aperture Vert Dimension	(m)	3.000
Recommended Xmit Ant Cntr Ht above Tower Base	(m)	7.000
Recommended Recv Ant Cntr Ht above Tower Base	(m)	4.500

Min Xmit Ant Ht (m)	Min Rec Ant Ht (m)	Min Xmit Ant Ht (m)	Min Rec Ant Ht (m)	Min Xmit Ant Ht (m)	Min Rec Ant Ht (m)
7.0	4.5	21.0	4.5	35.0	4.5
9.0	4.5	23.0	4.5	37.0	4.5
11.0	4.5	25.0	4.5	39.0	4.5
13.0	4.5	27.0	4.5	41.0	4.5
15.0	4.5	29.0	4.5	43.0	4.5
17.0	4.5	31.0	4.5	45.0	4.5
19.0	4.5	33.0	4.5	47.0	4.5

Table 4. Example Recommended Antenna Height Data (Cont.)

Aug/21/1986

Recommended Antenna Heights
Shanzerkopf to Heidelberg

Path 3 (Baumholder to Donnersberg):

Primary Frequency	(GHz)	7.40000
Transmitting Antenna Aperture Vert Dimension	(m)	3.000
Receiving Antenna Aperture Vert Dimension	(m)	12.000
Recommended Xmit Ant Cntr Ht above Tower Base	(m)	4.500
Recommended Recv Ant Cntr Ht above Tower Base	(m)	9.000

Min Xmit Ant Ht (m)	Min Rec Ant Ht (m)	Min Xmit Ant Ht (m)	Min Rec Ant Ht (m)	Min Xmit Ant Ht (m)	Min Rec Ant Ht (m)
4.5	9.0	18.5	9.0	32.5	9.0
6.5	9.0	20.5	9.0	34.5	9.0
8.5	9.0	22.5	9.0	36.5	9.0
10.5	9.0	24.5	9.0	38.5	9.0
12.5	9.0	26.5	9.0	40.5	9.0
14.5	9.0	28.5	9.0	42.5	9.0
16.5	9.0	30.5	9.0	44.5	9.0

Path 4 (Donnersberg to Heidelberg):

Primary Frequency	(GHz)	7.40000
Transmitting Antenna Aperture Vert Dimension	(m)	12.000
Receiving Antenna Aperture Vert Dimension	(m)	3.000
Recommended Xmit Ant Cntr Ht above Tower Base	(m)	27.305
Recommended Recv Ant Cntr Ht above Tower Base	(m)	4.691

Min Xmit Ant Ht (m)	Min Rec Ant Ht (m)	Min Xmit Ant Ht (m)	Min Rec Ant Ht (m)	Min Xmit Ant Ht (m)	Min Rec Ant Ht (m)
9.0	858.7	23.0	4.8	37.0	4.5
11.0	724.4	25.0	4.8	39.0	4.5
13.0	589.9	27.0	4.7	41.0	4.5
15.0	455.5	29.0	4.6	43.0	4.5
17.0	321.1	31.0	4.5	45.0	4.5
19.0	186.6	33.0	4.5	47.0	4.5
21.0	52.2	35.0	4.5	49.0	4.5

5. ALGORITHM D: PATH PROFILES AND RAY TRACES

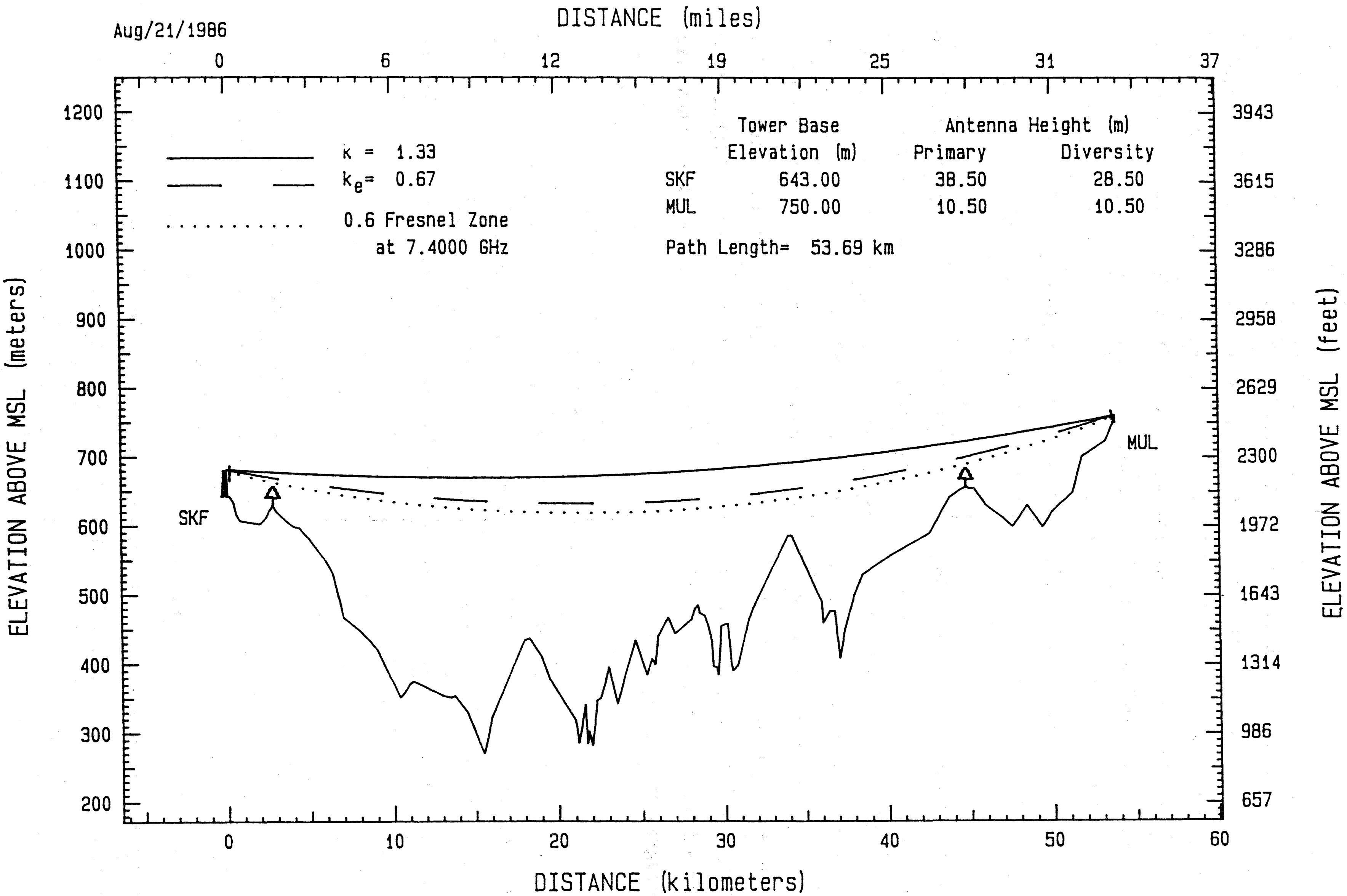
The purpose of Algorithm Set "D" is to provide an interactive,automated method of examining ray path clearance by calculating and documenting fundamental statistics about the microwave propagation paths. These statistics are the foundation information for accurately estimating the radio link reliability. Much of the data used in "D" is obtained from Algorithms "A," "B," and "C." A recommended value for average Earth-radius factor, k, is calculated in Algorithm "B," but this value's use is not required in "D."

On a microwave link, there may be from one to four tandem paths with two to five microwave sites. The outputs of this program consist of a profile set (Figure 5) and a tabulation set (Table 5) that corresponds to each of the paths. The figure shows the path profile and ray paths. Other information pertinent to meteorological and geometric parameters along the link is provided in the table. Information about recommended minimum line-of-sight (LOS) antenna heights for each path based on clearance calculations is available from the output of Program "C," but these values must be hand entered if they are used in Program Set "D."

5.1 Terrain Profile and Ray Paths

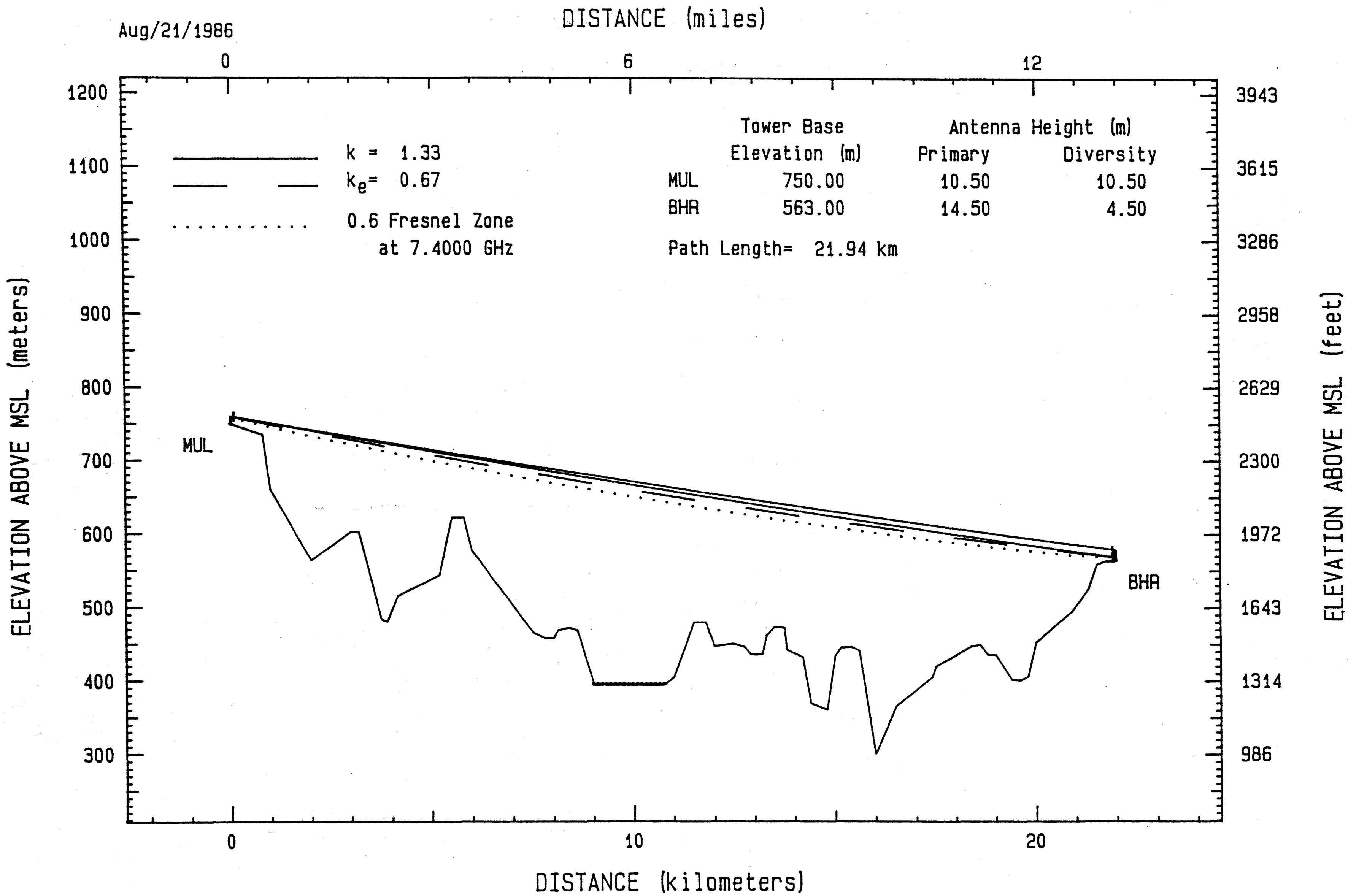
In preparing Figure 5, the path profiles are drawn and ray paths (which include the effect of the Earth's curvature) are calculated and plotted. The ray paths include ones for a space-diversity configuration (where applicable). The path profile is plotted in terms of terrain height in meters above mean sea level (msl) as a function of distance from the first antenna site (see Algorithm B).

Ray paths may be plotted for various antenna heights and Earth-radius factors, k. For one of the ray paths, the six tenths first Fresnel zone clearance location set can also be plotted. In order to calculate ray path trajectory and Fresnel zone clearance values, two expressions are required. They are the expression for the ray path height, h_r, in meters above mean sea level (msl), and the expression for first Fresnel zone radius (C-1 and C-2).



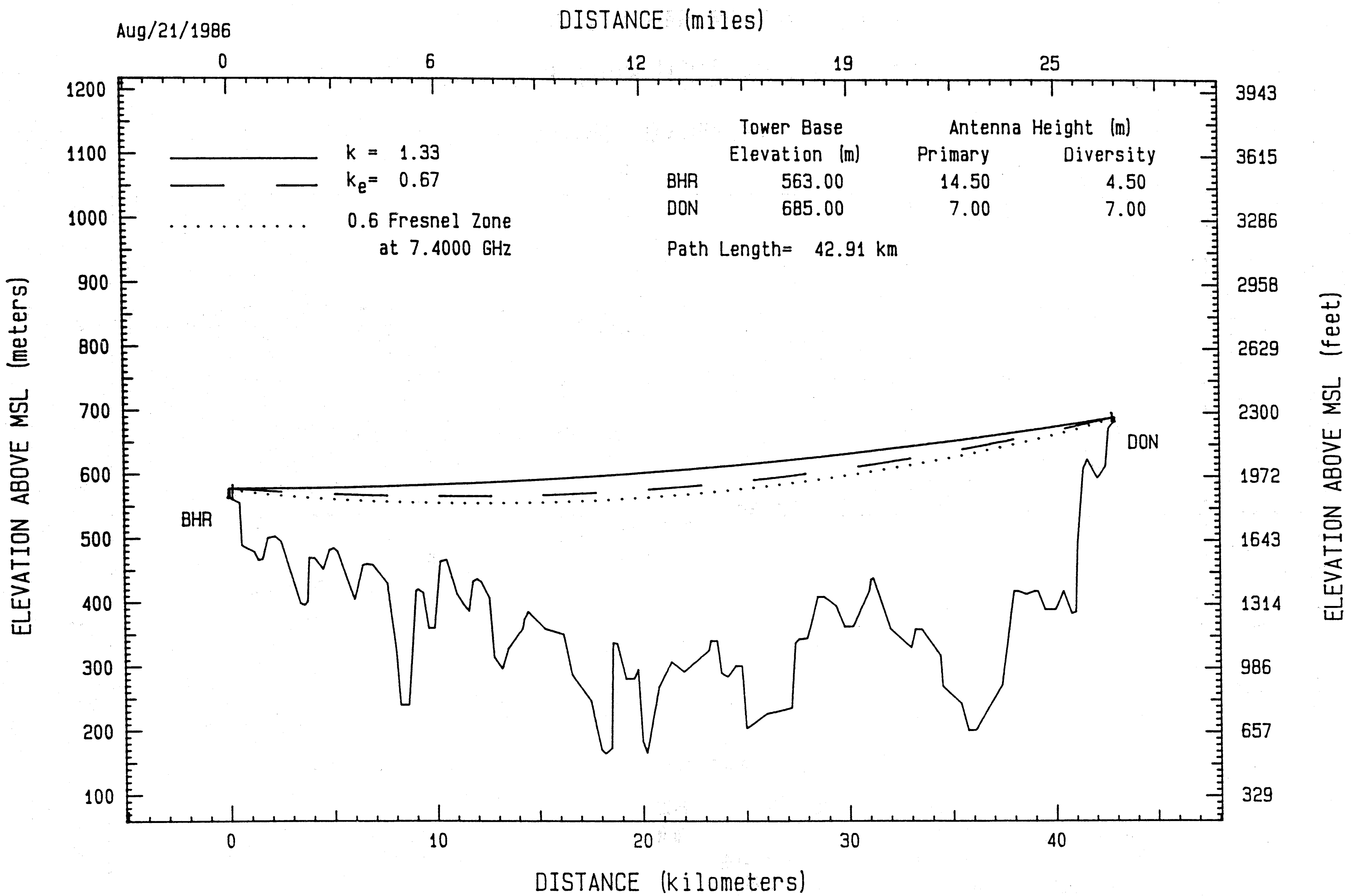
Path Profile from Shanzerkopf to Muhl

Figure 5. Example terrain profiles.



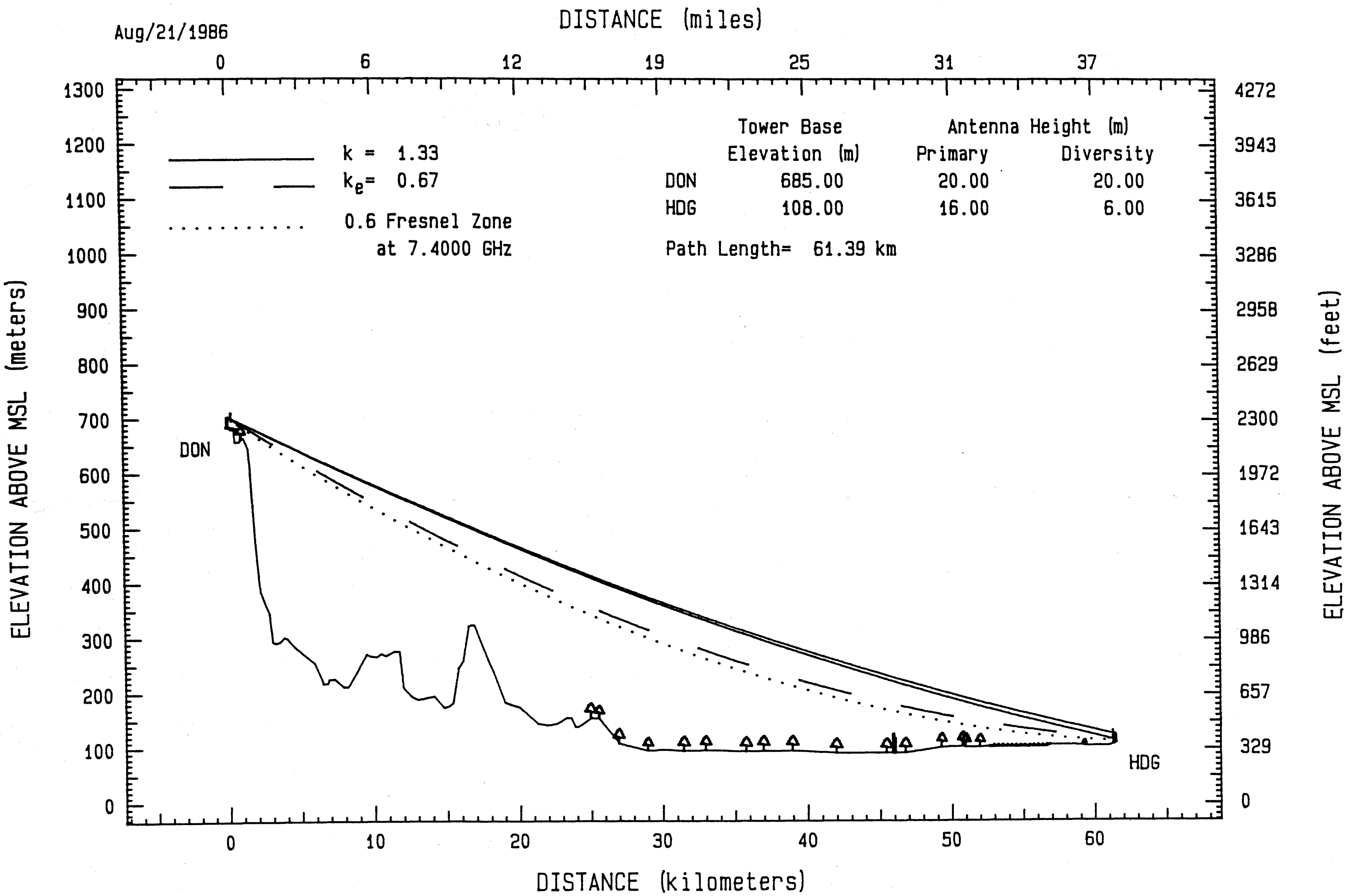
Path Profile from Muhl to Baumholder

Figure 5. Example terrain profiles. (Cont.)



Path Profile from Baumholder to Donnersberg

Figure 5. Example terrain profiles. (Cont.)



Path Profile from Donnersberg to Heidelberg

Figure 5. Example terrain profiles. (Cont.)

Table 5. Example Path Geometry and Meteorological Output

Aug/21/1986

Path Geometry and Meteorological Information
Shanzerkopf to Heidelberg

For the SKFMUL Path

Path Length	(km)	53.6925
Carrier Frequency	(GHz)	7.4000000
Transmitting Primary Antenna Height Above Ground	(m)	38.500
Receiving Primary Antenna Height Above Ground	(m)	10.500
Mean Terrain Elevation	(m)	494.467
Standard Deviation of Elevations	(m)	112.047
Path Azimuths from True North:		
SKF to MUL	(d/m/s)	234 49' 09.3"
MUL to SKF	(d/m/s)	54 21' 16.9"
Path Azimuths from Magnetic North:		
SKF to MUL	(d/m/s)	239 49' 09.3"
MUL to SKF	(d/m/s)	59 21' 16.9"
Primary Antenna Values For Average Earth's Radius Factor:		
Average Earth's Radius Factor		1.3300000
Transmitting Antenna Elevation Angle	(d/m/s)	-05' 49.6"
Receiving Antenna Elevation Angle	(d/m/s)	-15' 56.6"
Effective Path Length	(km)	53.6925
Minimum Ray Path Absolute Clearace Distance	(km)	2.8000
Minimum Ray Path Absolute Clearance	(m)	20.216
Minimum Ray Path 1st Fresnel Zone Clearance Distance	(km)	2.8000
Minimum Ray Path 1st Fresnel Zone Clearance	(1st Rad)	1.9513
Mean Atmospheric Pressure on the Ray Path	(kPa)	93.2077680
Mean Ray Path Height Above Ground	(m)	194.328
Primary Antenna Values For Extreme Subrefractive Earth's Radius Factor:		
Extreme Subrefractive Earth's Radius Factor		0.6666667
Minimum Ray Path Absolute Clearance Distance	(km)	2.8000
Minimum Ray Path Absolute Clearace	(m)	11.855
Minimum Ray Path 1st Fresnel Zone Clearance Distance	(km)	44.8000
Minimum Ray Path 1st Fresnel Zone Clearance	(1st Rad)	0.955
General Link Information:		
Estimated Annual Worst Month Average Snow Depth at SKF	(m)	3.000
Estimated Annual Worst Month Average Snow Depth at MUL	(m)	2.000

Tree growth at SKF is estimated at 0.500 m per year.
Tree growth at MUL is estimated at 0.400 m per year.

Table 5. Example Path Geometry and Meteorological Output (Cont.)

Aug/21/1986

Path Geometry and Meteorological Information
Shanzerkopf to Heidelberg

For the MULBHR Path

Path Length	(km)	21.9396
Carrier Frequency	(GHz)	7.4000000
Transmitting Primary Antenna Height Above Ground	(m)	10.500
Receiving Primary Antenna Height Above Ground	(m)	14.500
Mean Terrain Elevation	(m)	480.159
Standard Deviation of Elevations	(m)	85.051
Path Azimuths from True North:		
MUL to BHR	(d/m/s)	103 04' 28.2"
BHR to MUL	(d/m/s)	283 18' 00.0"
Path Azimuths from Magnetic North:		
MUL to BHR	(d/m/s)	108 04' 28.2"
BHR to MUL	(d/m/s)	288 18' 00.0"
Primary Antenna Values For Average Earth's Radius Factor:		
Average Earth's Radius Factor		1.3300000
Transmitting Antenna Elevation Angle	(d/m/s)	-33' 07.3"
Receiving Antenna Elevation Angle	(d/m/s)	24' 13.6"
Effective Path Length	(km)	21.9396
Minimum Ray Path Absolute Clearace Distance	(km)	0.3000
Minimum Ray Path Absolute Clearance	(m)	13.615
Minimum Ray Path 1st Fresnel Zone Clearance Distance	(km)	5.8000
Minimum Ray Path 1st Fresnel Zone Clearance	(1st Rad)	6.4402
Mean Atmospheric Pressure on the Ray Path	(kPa)	84.9608541
Mean Ray Path Height Above Ground	(m)	179.922
Primary Antenna Values For Extreme Subrefractive Earth's Radius Factor:		
Extreme Subrefractive Earth's Radius Factor		0.6666667
Minimum Ray Path Absolute Clearance Distance	(km)	0.3000
Minimum Ray Path Absolute Clearace	(m)	13.234
Minimum Ray Path 1st Fresnel Zone Clearance Distance	(km)	5.8000
Minimum Ray Path 1st Fresnel Zone Clearance	(1st Rad)	6.022
General Link Information:		
Estimated Annual Worst Month Average Snow Depth at MUL	(m)	3.200
Estimated Annual Worst Month Average Snow Depth at BHR	(m)	1.000

Tree growth at MUL is estimated at 0.300 m per year.
Tree growth at BHR is estimated at 1.100 m per year.

Table 5. Example Path Geometry and Meteorological Output (Cont.)

Aug/21/1986

Path Geometry and Meteorological Information
Shanzerkopf to Heidelberg

For the BHRDON Path

Path Length	(km)	42.9148
Carrier Frequency	(GHz)	7.4000000
Transmitting Primary Antenna Height Above Ground	(m)	14.500
Receiving Primary Antenna Height Above Ground	(m)	7.000
Mean Terrain Elevation	(m)	359.965
Standard Deviation of Elevations	(m)	94.057
Path Azimuths from True North:		
BHR to DON	(d/m/s)	91 14' 24.3"
DON to BHR	(d/m/s)	271 41' 33.0"
Path Azimuths from Magnetic North:		
BHR to DON	(d/m/s)	96 14' 24.3"
DON to BHR	(d/m/s)	276 41' 33.0"
Primary Antenna Values For Average Earth's Radius Factor:		
Average Earth's Radius Factor		1.3300000
Transmitting Antenna Elevation Angle	(d/m/s)	00' 28.3"
Receiving Antenna Elevation Angle	(d/m/s)	-17' 52.3"
Effective Path Length	(km)	42.9148
Minimum Ray Path Absolute Clearace Distance	(km)	42.6500
Minimum Ray Path Absolute Clearance	(m)	15.627
Minimum Ray Path 1st Fresnel Zone Clearance Distance	(km)	10.5000
Minimum Ray Path 1st Fresnel Zone Clearance	(1st Rad)	6.5575
Mean Atmospheric Pressure on the Ray Path	(kPa)	85.6008416
Mean Ray Path Height Above Ground	(m)	252.055
Primary Antenna Values For Extreme Subrefractive Earth's Radius Factor:		
Extreme Subrefractive Earth's Radius Factor		0.6666667
Minimum Ray Path Absolute Clearance Distance	(km)	42.6500
Minimum Ray Path Absolute Clearace	(m)	14.965
Minimum Ray Path 1st Fresnel Zone Clearance Distance	(km)	10.5000
Minimum Ray Path 1st Fresnel Zone Clearance	(1st Rad)	5.442
General Link Information:		
Estimated Annual Worst Month Average Snow Depth at BHR	(m)	1.000
Estimated Annual Worst Month Average Snow Depth at DON	(m)	1.000

Tree growth at BHR is estimated at 0.100 m per year.
Tree growth at DON is estimated at 0.100 m per year.

Table 5. Example Path Geometry and Meteorological Output (Cont.)

Aug/21/1986

Path Geometry and Meteorological Information
Shanzerkopf to Heidelberg

For the DONHDG Path

Path Length	(km)	61.3881
Carrier Frequency	(GHz)	7.4000000
Transmitting Primary Antenna Height Above Ground	(m)	20.000
Receiving Primary Antenna Height Above Ground	(m)	16.000
Mean Terrain Elevation	(m)	161.211
Standard Deviation of Elevations	(m)	103.612
Path Azimuths from True North:		
DON to HDG	(d/m/s)	115 20' 28.5"
HDG to DON	(d/m/s)	295 55' 20.5"
Path Azimuths from Magnetic North:		
DON to HDG	(d/m/s)	120 20' 28.5"
HDG to DON	(d/m/s)	300 55' 20.5"
Primary Antenna Values For Average Earth's Radius Factor:		
Average Earth's Radius Factor		1.3300000
Transmitting Antenna Elevation Angle	(d/m/s)	-44' 58.7"
Receiving Antenna Elevation Angle	(d/m/s)	20' 05.5"
Effective Path Length	(km)	61.3881
Minimum Ray Path Absolute Clearace Distance	(km)	0.9000
Minimum Ray Path Absolute Clearance	(m)	5.272
Minimum Ray Path 1st Fresnel Zone Clearance Distance	(km)	59.3000
Minimum Ray Path 1st Fresnel Zone Clearance	(1st Rad)	2.5974
Mean Atmospheric Pressure on the Ray Path	(kPa)	96.8165062
Mean Ray Path Height Above Ground	(m)	201.135
Primary Antenna Values For Extreme Subrefractive Earth's Radius Factor:		
Extreme Subrefractive Earth's Radius Factor		0.6666667
Minimum Ray Path Absolute Clearance Distance	(km)	0.9000
Minimum Ray Path Absolute Clearace	(m)	2.077
Minimum Ray Path 1st Fresnel Zone Clearance Distance	(km)	52.0000
Minimum Ray Path 1st Fresnel Zone Clearance	(1st Rad)	1.696
General Link Information:		
Estimated Annual Worst Month Average Snow Depth at DON	(m)	4.000
Estimated Annual Worst Month Average Snow Depth at HDG	(m)	2.000

Tree growth at DON is estimated at 0.200 m per year.
Tree growth at HDG is estimated at 0.300 m per year.

5.2 Path Geometry and Meteorological Information

In Table 5, information is grouped by path. For each path the following information is provided:

1) Earth-radius factors
2) antenna azimuths and elevation angles
3) actual and effective path lengths
4) minimum ray path terrain clearance
5) antenna heights above ground
6) mean atmospheric pressure on the ray path
7) mean path height above ground
8) terrain constants
9) estimated expected snow depths
10) operator comments.

Either the recommended average Earth-radius factor, k, calculated in algorithm "B" or some other value of "k" may be used in algorithm "D." The value of "k" selected will have a significant influence on most of the other values calculated in algorithm "D." A "k" value of 4/3 is often used as the average value.

5.3 Antenna Elevation Angle

Antenna beam elevation angle, E_{11}, which is often called the takeoff angle, is the angle between the horizontal plane and the tangent to the ray path at the antenna. At the first antenna (the end of the path where d = 0), the value of E_{11} is obtained using the expression:

$$E_{11} = \arctan\{(h_{a2} - h_{a1})\ (1000\ D)^{-1} - D(12750k)^{-1}\} \qquad \text{(D-1)}$$

This equation and the following one were obtained by deriving the slope from (C-1), and the same variable definitions are applicable. At the second antenna (where d = D), the value of E_{12} is obtained using the following expression:

$$E_{12} = -\arctan\{(h_{a2} - h_{a1})(1000\ D)^{-1} + D(12750k)^{-1}\}. \qquad (D\text{-}2)$$

5.4 Effective Path Length

The concept of effective path length, D_e, is used in the multipath fading calculations. D_e is a function of penetration angle of the beam center line and atmospheric layers, which results in a function in terms of antenna heights above msl and the total path length [see variable definitions for (C-1)]. The expression for D_e is based upon one year of measurements made by the author on five long paths in Italy (unpublished data). The value of the effective path length is obtained from the following expressions:

$$\text{if} \quad d_o = 0.5D - 8.49\,|h_{a2} - h_{a1}|\,D^{-1} + 163 \qquad (D\text{-}3)$$

$$\text{then} \quad D_e = D \text{ if } d_o > D \qquad (D\text{-}4)$$

$$\text{or} \quad D_e = d_o \text{ if } 0 <= d_o <= D \qquad (D\text{-}5)$$

$$\text{or} \quad D_e = 0 \text{ if } d_o < 0 \qquad (D\text{-}6)$$

$$\text{or} \quad D_e = 326 \text{ if } d_o > 326. \qquad (D\text{-}7)$$

For variable definitions, see (C-1).

5.5 Minimum Ray Path Terrain Clearance

The minimum ray path terrain clearance is the minimum distance between the center line of the beam and the bare terrain or the obstacles directly beneath the beam. This distance can be measured in terms of absolute clearance in meters, or in units of first Fresnel zone radii, R_F. Since R_F varies as a function of distance along the path (C-2), the absolute clearance minimim will sometimes not occur at the same distance from the first antenna as the Fresnel clearance, C_f, minimum. Fresnel clearnace minimums are not meaningful at distances near the antennas. For this reason, Fresnel clearance values within 1 km of an antenna are not considered in calculating the first Fresnel zone clearance minimum.

5.6 Antenna Heights Above Ground

The absolute minimum antenna height (for a path to qualify as LOS) of an antenna above ground is determined by two conditions:

1. Minimum antenna heights for a path are the values that tend to minimize tower heights and at the same time provide six tenths first Fresnel zone clearance when the ray path is calculated using the extreme subrefractive Earth-radius factor, k_e.
2. The absolute clearance within 1 km of each antenna is greater than 3 meters plus one half of the local antenna's vertical dimension.

Recommended values of minimum primary antenna heights are calculated in Algorithm "C" and if they are applicable, they may be used as actual antenna heights in Algorithm "D."

5.7 Mean Atmospheric Pressure on the Ray Path

To calculate the mean atmospheric pressure along the path, we use the expression for pressure, P_a, as a function of altitude above mean sea level provided in List (1951, pp. 266):

$$P_a = 101.3\ (1 - 2.26 h_r \times 10^{-5})^{5.2553} \qquad \text{(D-8)}$$

where P_a = the atmospheric pressure in kilopascals (kPa).

h_r = the height of the ray path above msl in m where $-100 < h_r < 10^5$.

The mean atmospheric pressure, P_{am}, is obtained by averaging ten values of P_a calculated for ten approximately equidistant points along the path calculated using the average value of Earth-radius factor, k.

5.8 Mean Path Height Above Ground

The mean ray path height above ground, h_{rg}, in meters, is given by the expression:

$$h_{rg} = D^{-1} \sum_{n=1}^{n=p} (h_r - h_e)(d_{n+1} - d_{n-1})/2 \qquad \text{(D-9)}$$

where h_r = ray path height above msl (m)

h_e = terrain height above msl plus obstacle height (m)

D = path length (km)

d = distance from the first antenna to a point (km)

n = the number of the profile point

p = the number of profile points.

5.9 Mean Terrain Elevation

Mean terrain elevation, h_{me}, in meters, is given by the expression:

$$h_{me} = \frac{\sum_{n+1}^{n=p} (d_{n+1} - d_n) \frac{h_n + h_{(n+1)}}{2}}{\sum_{n=1}^{n=p} (d_{n+1} - d_n)} \qquad \text{(D-10)}$$

where h_n = the height of the terrain above msl at point "n."

5.10 Standard Deviation of Terrain Elevations

The standard deviation of terrain elevations, S_1, in meters, is given by the expression:

$$S_1 = \left\{ \frac{\sum_{n=1}^{n=p} (d_{n+1} - d_n)[(h_{me} - (\frac{h_{(n+1)} + h_n}{2})]^2}{\sum_{n=1}^{n=p} (d_{n+1} - d_n)} \right\}^{1/2} . \qquad \text{(D-11)}$$

Antenna sites are excluded from the profile points when calculating S_1.

6. ALGORITHM E: SITE ANTENNA OR REFLECTOR LAYOUT

The purpose of this algorithm set is to provide diagrams and tabulations showing the spatial relationships of antennas and reflectors. This information is especially useful for the design of repeater sites when plane mirror passive repeaters are used. Some of the information provided for each site is:

1) azimuth and elevation angle of the incoming antenna beam to a site
2) azimuth and elevation angle of the outgoing antenna beam
3) the forward azimuth and elevation angle of the intrasite beam when a double-plane mirror passive repeater is used
4) the azimuth and elevation angle of the normal to the reflecting surface of the plane mirrors that are used
5) the projected area of a reflector normal to the direction of the radio beam
6) antenna or reflector height and width as well as its height above the tower base in meters.

In this set of algorithms, all azimuths are referred to true north.

Diagrams showing plan views are used to depict repeater sites and side views are used for terminal sites. The spatial displacement relationships between antennas or reflectors and towers are not to scale on the diagrams; tower sizes are not to scale. Most of the information is obtained from the outputs of Program Sets "A" and "D." The orientation angles of plane reflectors are calculated in this algorithm.

6.1 Plane Mirror Orientation

The reflection surface's normal elevation angle, N_{el}, and its azimuth, N_{az}, are calculated as follows:

Using spherical coordinates, the azimuth and elevation angles of the incoming and reflected beam are used to calculate unit vectors from the mirror center along each beam. The unit vectors are added, giving a vector which bisects the angle between them. From the components of this vector, the angle of elevation and azimuth of the normal are derived using spherical coordinates.

6.2 Projected Area

The projected areas in the direction of the incoming and outgoing antenna beams are needed to calculate the reflector aperture gain. To calculate the projected area, the total area of the reflector is multiplied by the cosine of the angle between the reflector normal and antenna beam center line. The cosine of this angle is equal to a sum divided by a product. The sum is that of the three products obtained by multiplying the two corresponding rectangular coordinate components of the normal vector and the outgoing ray unit vector. The product is that of the magnitudes of the normal vector and the outgoing ray vector. This relationship may be found in most modern analytic geometry books.

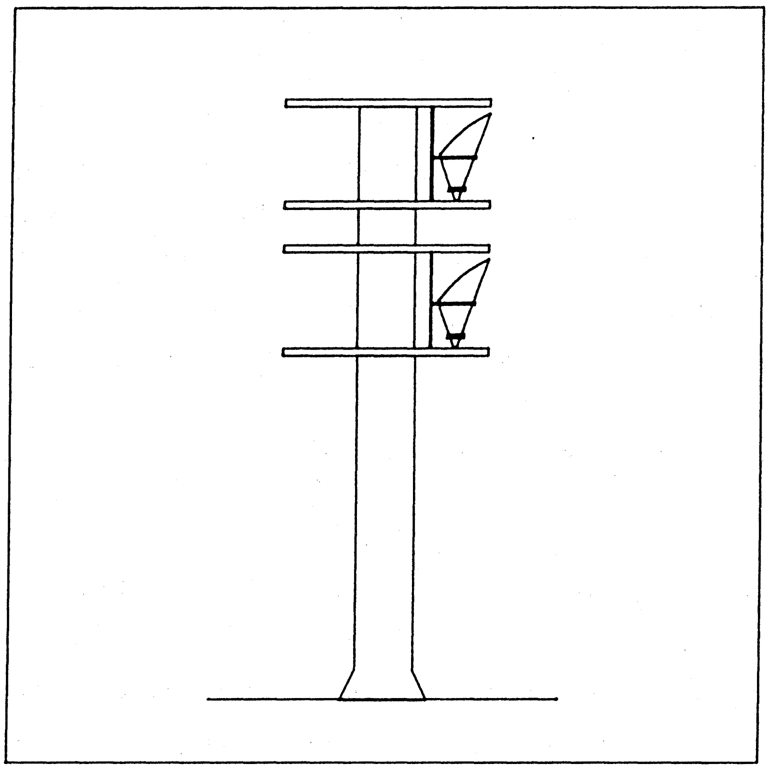
6.3 Shadowing

In the case of a double mirror at a repeater site (see Figure 9), it is possible to have shadowing. Shadowing occurs when one of the mirrors obstructs either the incoming or outgoing beam of the other mirror, thus reducing the projected area and the reflector aperture gain. If shadowing does occur, the word "SHADOWING" is printed in the bottom left corner of the diagram. The presence of shadowing is calculated by finding the intersections of the incoming beams, the outgoing beams, and the planes of the mirrors. If certain of these intersection points exist, then shadowing exists.

Shadowing can usually be overcome by moving the mirrors farther apart. If this does not cure the problem, then other placement of the mirrors relative to the control point must be considered.

6.4 Layout Output Format

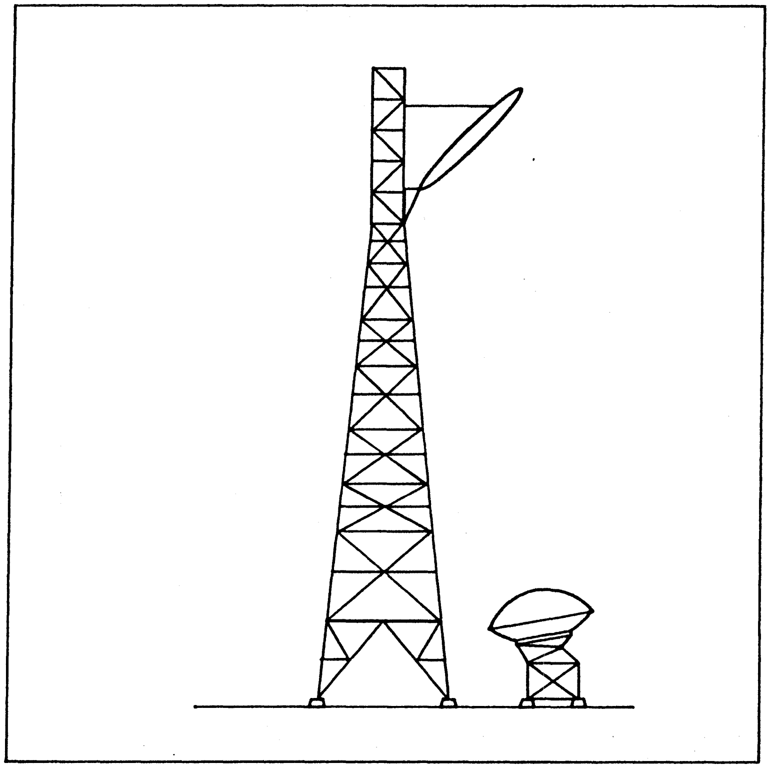
A diagram of the antenna site with tabulated data about the antennas is the primary output of Program "E." The diagram for terminal sites is a side view representation (Figures 6 through 8). For repeater sites, a plan view representation is provided (Figures 9 through 11). These diagrams are not to scale and do not necessarily represent the actual antenna and tower structure being used. The diagrams should provide most of the information needed for antenna alignment.



1. Primary Frequency	GHz	7.4000
2. Polarization		Vertical
3. Latitude	d/m/s	49 57' 37.0"N
4. Longitude	d/m/s	7 38' 17.0"E
5. Tower Base Elevation Above msl	m	643.00
6. Beam Azimuth at SKF to MUL	d/m/s	234 49' 09.3"
7. Beam Magnetic Azimuth at SKF to MUL	d/m/s	239 49' 09.3"
8. Primary Beam Elev Angle at SKF to MUL	d/m/s	-05' 49.6"
9. Primary Antenna Vertical Dimension	m	3.00
10. Diversity Antenna Vertical Dimension	m	3.00
11. Prim Ant Center Ht Above Tower Base	m	38.50
12. Diver Ant Center Ht Above Tower Base	m	28.50

Antenna Diagram For Shanzerkopf

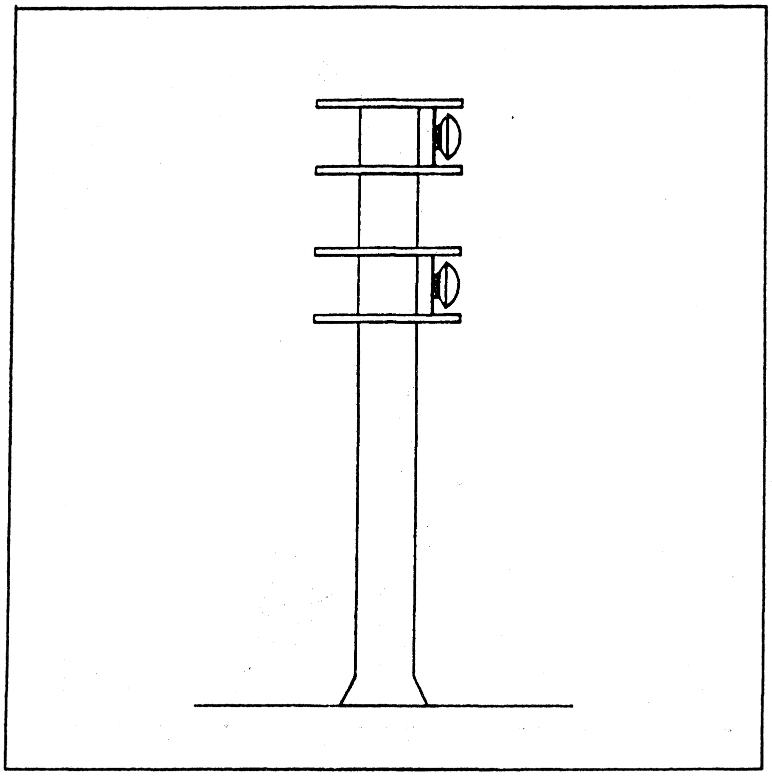
Figure 6. Example parabolic horn configuration.



1.	Primary Frequency	GHz	7.4000
2.	Polarization		Vertical
3.	Reflector Center Latitude	d/m/s	49 23' 12.0"N
4.	Reflector Center Longitude	d/m/s	8 41' 00.0"E
5.	Tower Base Elevation Above msl	m	108.00
6.	Feed Antenna Height Above Tower Base	m	1.50
7.	Feed Antenna Diameter	m	3.00
8.	Beam Azimuth From Feed Ant To Refl	d/m/s	49 32' 00.0"
9.	Beam Elev Angle From Feed Ant To Refl	d/m/s	80 00' 00.0"
10.	Beam Azimuth at HDG to DON	d/m/s	295 55' 20.5"
11.	Beam Magnetic Azimuth at HDG to DON	d/m/s	300 55' 20.5"
12.	Beam Elevation Angle at HDG to DON	d/m/s	20' 05.5"
13.	Reflector Vertical Dimension	m	4.11
14.	Reflector Horizontal Dimension	m	3.00
15.	Reflector Center Ht Above Tower Base	m	16.00
16.	Reflection Surface Normal Azimuth	d/m/s	287 27' 38.5"
17.	Reflection Surface Normal Elev Angle	d/m/s	-42 09' 22.6"
18.	Angle Between Normal and Beam Center	d/m/s	43 10' 16.3"
19.	Projected Area	sq m	7.07

Antenna Diagram For Heidelberg

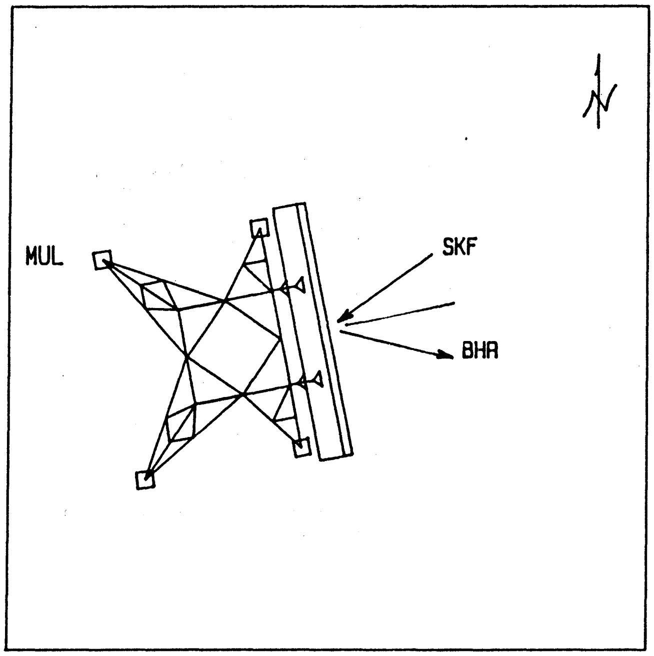
Figure 7. Example periscope antenna configuration.



1.	Primary Frequency	GHz	8.7000
2.	Polarization		Vertical
3.	Latitude	d/m/s	49 57' 37.0"N
4.	Longitude	d/m/s	7 38' 17.0"E
5.	Tower Base Elevation Above msl	m	643.00
6.	Beam Azimuth To MUL	d/m/s	234 49' 09.3"
7.	Beam Magnetic Azimuth To MUL	d/m/s	239 49' 09.3"
8.	Primary Beam Elev Angle Toward MUL	d/m/s	-05' 49.6"
9.	Primary Antenna Diameter	m	3.00
10.	Diversity Antenna Diameter	m	3.00
11.	Prim Ant Center Ht Above Tower Base	m	38.50
12.	Diver Ant Center Ht Above Tower Base	m	28.50

Antenna Diagram For Shanzerkopf

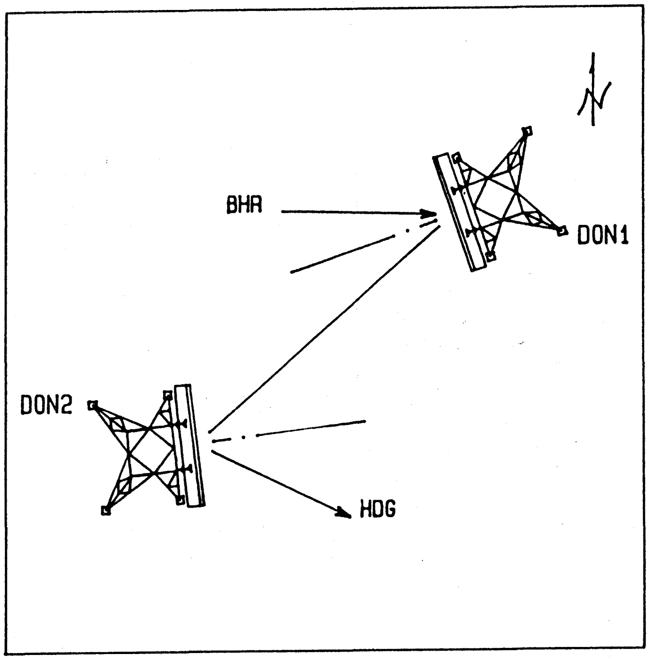
Figure 8. Example parabolic antenna configuration.



1.	Reflector Center Latitude	d/m/s	49 40' 50.0"N
2.	Reflector Center Longitude	d/m/s	7 01' 48.0"E
3.	Tower Base Elevation Above msl	m	750.00
4.	Beam Azimuth To SKF	d/m/s	54 21' 16.9"
5.	Beam Magnetic Azimuth To SKF	d/m/s	59 21' 16.9"
6.	Primary Beam Elev Angle Toward SKF	d/m/s	-15' 56.6"
7.	Beam Azimuth To BHR	d/m/s	103 04' 28.2"
8.	Beam Magnetic Azimuth To BHR	d/m/s	108 04' 28.2"
9.	Primary Beam Elev Angle Toward BHR	d/m/s	-33' 07.3"
10.	Reflector Vertical Dimension	m	8.00
11.	Reflector Horizontal Dimension	m	16.00
12.	Reflector Center Ht Above Tower Base	m	10.50
13.	Reflector Surface Normal Azimuth	d/m/s	78 42' 50.9"
14.	Reflector Surface Normal Elev Angle	d/m/s	-26' 55.8"
15.	Angle Between Normal and Beam Center	d/m/s	24 21' 34.7"
16.	Projected Area	sq m	116.60

Reflector Diagram For Muhl

Figure 9. Example single mirror repeater configuration.



DON1 Receiving Reflector Data:

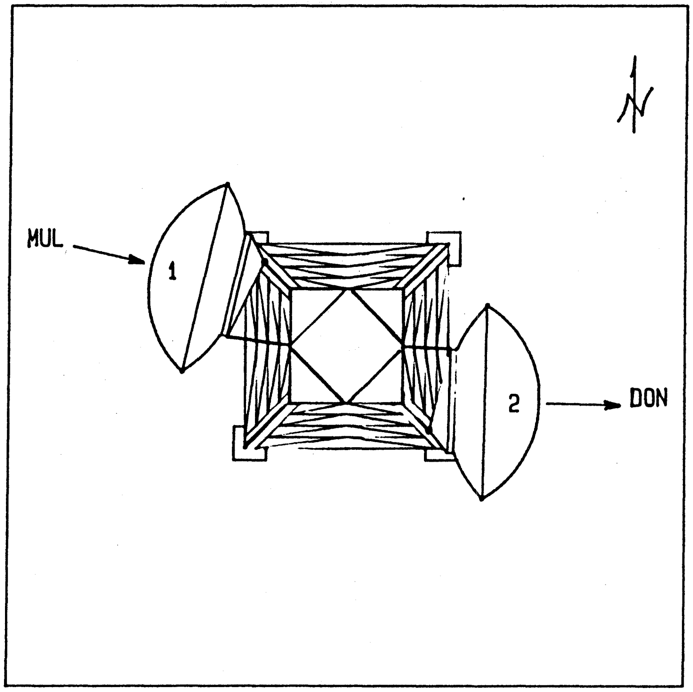
1.	Reflector Center Latitude	d/m/s	49 37' 32.5"N
2.	Reflector Center Longitude	d/m/s	7 55' 10.7"E
3.	Tower Base Elevation Above msl	m	685.00
4.	Beam Azimuth To BHR	d/m/s	271 41' 33.0"
5.	Beam Magnetic Azimuth To BHR	d/m/s	276 41' 33.0"
6.	Primary Beam Elev Angle Toward BHR	d/m/s	-17' 52.3"
7.	Reflector Vertical Dimension	m	12.00
8.	Reflector Horizontal Dimension	m	15.00
9.	Reflector Center Ht Above Tower Base	m	7.00
10.	Reflection Surface Normal Azimuth	d/m/s	250 48' 06.1"
11.	Reflection Surface Normal Elev Angle	d/m/s	8 57' 29.6"
12.	Angle Between Normal and Beam Center	d/m/s	22 46' 23.8"
13.	Projected Area	sq m	165.97

DON2 Receiving Reflector Data:

1.	Reflector Center Latitude	d/m/s	49 37' 31.5"N
2.	Reflector Center Longitude	d/m/s	7 55' 09.1"E
3.	Tower Base Elevation Above msl	m	685.00
4.	Beam Azimuth To HDG	d/m/s	115 20' 28.5"
5.	Beam Magnetic Azimuth To HDG	d/m/s	120 20' 28.5"
6.	Primary Beam Elev Angle Toward HDG	d/m/s	-44' 58.7"
7.	Reflector Vertical Dimension	m	12.00
8.	Reflector Horizontal Dimension	m	15.00
9.	Reflector Center Ht Above Tower Base	m	20.00
10.	Reflection Surface Normal Azimuth	d/m/s	82 57' 40.2"
11.	Reflection Surface Normal Elev Angle	d/m/s	-10 34' 12.8"
12.	Angle Between Normal and Beam Center	d/m/s	33 38' 32.3"
13.	Projected Area	sq m	149.85

Reflector Diagram For Donnersberg

Figure 10. Example double mirror repeater configuration.



BHR1 Receiving Antenna Data:

1. Primary Freqency	GHz	7.4000
2. Polarization		Vertical
3. Latitude	d/m/s	49 38' 08.0"N
4. Longitude	d/m/s	7 19' 33.0"E
5. Tower Base Elevation Above msl	m	563.00
6. Beam Azimuth To MUL	d/m/s	283 18' 00.0"
7. Beam Magnetic Azimuth To MUL	d/m/s	288 18' 00.0"
8. Primary Beam Elev Angle Toward MUL	d/m/s	24' 13.6"
9. Primary Antenna Diameter	m	3.0
10. Prim Ant Center Ht Above Tower Base	m	14.5
11. Diver Ant Center Ht Above Tower Base	m	4.5

BHR2 Transmitting Antenna Data:

1. Primary Freqency	GHz	7.4000
2. Polarization		Vertical
3. Latitude	d/m/s	49 38' 08.0"N
4. Longitude	d/m/s	7 19' 33.0"E
5. Tower Base Elevation Above msl	m	563.00
6. Beam Azimuth To DON	d/m/s	91 14' 24.3"
7. Beam Magnetic Azimuth To DON	d/m/s	96 14' 24.3"
8. Primary Beam Elev Angle Toward DON	d/m/s	00' 28.3"
9. Primary Antenna Diameter	m	3.0
10. Prim Ant Center Ht Above Tower Base	m	14.5
11. Diver Ant Center Ht Above Tower Base	m	4.5

Antenna Diagram For Baumholder

Figure 11. Example double antenna repeater configuration.

7. ALGORITHM F: REPEATER SITE LOSS AND ANTENNA GAIN

The basic purpose of this algorithm is to calculate repeater site loss in dB, L_{rs}. For flat repeaters, L_{rs} is equal to 10 times the common logarithm of the ratio of the site's actual effective radiated power to the power that would be radiated using antennas, of the same gains, that are interconnected with a lossless transmission line. To calculate L_{rs}, it is necessary to use various procedures depending upon the antenna configuration used at the repeater site. The three configurations are double antennas, single mirror, and double mirrors. A second purpose of this algorithm is to calculate antenna and reflector gains at each site in the link.

7.1 Terminal Site Antenna Gains

There are three types of antennas that may be specified for a terminal site (parabolic, parabolic horn, and periscope). The gain of a parabolic antenna, G_{pa}, is derived from its diameter in meters, D_a, the aperture efficiency (0.55), and the carrier frequency, f_c, in GHz:

$$G_{pa} = 20 \log(7.772\ D_a\ f_c) \qquad \text{(F-1)}$$

This equation is obtained from MIL-HDBK-417 (Department of Defense, 1977b, p. 4-215). The gain of a parabolic horn, G_{ph}, is also obtained from (F-1). The periscope antenna gain, G_{ps}, is derived from the feed antenna gain, G_f, and diameter, D_f, the reflector projected aperture area, A_{pp}, and the distance, d_{fr}, between the feed antenna and the reflector.

$$G_{ps} = G_f + G_r \qquad \text{(F-2)}$$

where G_f is obtained from Equation F-1 and the reflector gain, G_r, is obtained from an empirical equation, which was derived from empirical curves in Johnson and Jasik, (1984, pp. 17-24 to 17-27). The expression for reflector gain is:

$$G_r = -20P_r - 2.098 - (k_1/k_2)\log\{10^{[k_2(-p_r + k_3)]} + 1\} \quad \text{(F-3)}$$

where $$P_r = \log \frac{0.23561 d_{fr}}{f_c\, A_{pp}} \quad \text{(F-4)}$$

$$k_1 = 20 + 4\log\{10^{(-8R_a + 6.4)} + 1\} \quad \text{(F-5)}$$

$$k_2 = -1.35R_a + 3.7 + 0.095\log\{1+(R_a/0.8)^{10}\} \quad \text{(F-6)}$$

$$k_3 = 0.68R_a - 0.71 - 0.08\log\{1 + (R_a/0.89)^{10}\} \quad \text{(F-7)}$$

$$R_a = 0.8862\, D_f\, A_{pp}^{-0.5} \;. \quad \text{(F-8)}$$

7.2 Site Loss for Double Antennas

For the double antenna configuration, the power gain of each antenna in decibels above isotropic is obtained using Equation F-1. The site loss, L_{rs}, is equal to zero for the double antenna case. The final amplifier power and the feeder line lengths are entered in Program "F," but line losses and transmitter antenna terminal output power are calculated and applied in Algorithm "I."

7.3 Site Loss for a Single Mirror Configuration

For the far field case, site loss, L_{rs}, is zero and the transmitting and receiving antenna gains equal the single reflector aperture gain, G_{SRA}, which is obtained from the expression:

$$G_{SRA} = 10\log(138\, A_{pa}\, f_c^2) \quad \text{(F-9)}$$

where A_{pa} is the projected aperture area, in square meters, which was calculated in Algorithm E.

For the near field case, the single reflector aperture gain is obtained from (F-9) but L_{rs} is not equal to zero. The near field expressions must be applied if the shortest of the two paths to the single mirror is less than 0.01 A_{pa} f_c. The value of L_{rs} is given by the expression:

$$L_{rs} = -92.45 - 20\log(d_{fr} f_c) + 2G_{SRA} + 2G_f - G_r \qquad \text{(F-10)}$$

The variables in this expression have been defined for (F-1) through (F-9). In this case, d_{fr} is the length of the shortest of the two paths to the mirror. G_f is the gain of the antenna at the opposite end of the short path from the mirror.

7.4 Site Loss for Double Mirrors

Projected aperture gains of each reflector are equal to those of the reflector with the smallest projected aperture area (effective area). The gain is obtained from (F-9). Site loss, L_{rs}, for the double mirror depends upon several variables: the separation distance, d_s, between mirror centers at the site; the smaller effective area, A_{pas}; the larger effective area, A_{pal}; and the carrier frequency, f_c. The model used to to calculate L_{rs} is based on a paper by Yang (1957). To calculate L_{rs}, we first define the parameters $1/K_d^2$ and b/a using the expressions:

$$\frac{1}{K_d^2} = (600d_s)/(f_c a^2) \quad \text{where} \quad 0 < \frac{1}{K_d^2} < 5 \qquad \text{(F-10)}$$

$$\text{and} \quad \frac{b}{a} \quad \text{where } b = A_{pal}^{.5} \quad \text{and} \quad a = A_{pas}^{.5} \qquad \text{(F-11) and (F-12)}$$

If $\frac{1}{K_d^2} < 2$ and $\frac{b}{a} >= 2$ or if $\frac{1}{K_d^2} < 0.6$ and $1 <= \frac{b}{a} < 2$, then

$$L_{rs} = 0 \text{ or } -1.923 \log\left(\frac{1}{K_d^2}\right) + 7.5 \frac{b}{a} - 9.923 , \qquad \text{(F-13)}$$

whichever is less.

For all other conditions within $0 < \frac{1}{K_d^2} < 5$ and $1 <= \frac{b}{a} < 5$,

L_{rs} is given by the following expression:

$$L_{rs} = 20 \log\{0.5 K_d^{-2} [U_c^2 + V_s^2] \qquad \text{(F-14)}$$

where $U_c = \int_p^q C(t)dt$ and $V_s = \int_p^q S(t)dt$, (F-15) and (F-16)

$$p = K_d(1 - \frac{b}{a}) \text{ and } q = K_d(1 + \frac{b}{a}), \qquad \text{(F-17) and (F-18)}$$

C(t) and S(t) are the cosine and sine Fresnel integrals. To evaluate U_c and V_s we use the series expansions of C(t) and S(t) given in Abramowitz and Stegun (1964).

Integrating the expansions, we obtain:

$$U_c \Big]_0^x = \sum_{n=0}^{n=m} \frac{(-1)^n(\ \ /2)^{2n}\ X^{4n+2}}{(2n)\ (4n+3)\ (4n+4)} \qquad \text{(F-19)}$$

$$V_s \Big]_0^x = \sum_{n=0}^{n=m} \frac{(-1)^n(\ \ /2)^{2n+1}\ X^{4n+4}}{(2n+1)\ (4n+3)\ (4n+4)} \qquad \text{(F-20)}$$

where m increases without bound.

From these two expressions, we obtain:

$$U_c = U_c \Big]_0^q - U_c \Big]_0^p \quad \text{and} \quad V_s = V_s \Big]_0^q - V_s \Big]_0^p \qquad \text{(F-21) and (F-22)}$$

In the algorithm, the series are evaluated with a large enough value of "n" to obtain a value of L_{rs} within $\pm$ 0.01 dB of the exact theoretical value.

7.3 Site Loss and Antenna Gain Output Format

The output of Program "F" is a tabulation of repeater site gain and antenna gain information (Table 6).

Table 6. Example Repeater Site Gain and Antenna Gain Data

Aug/21/1986

Repeater Site Gain and Antenna Gain
Shanzerkopf to Heidelberg

Transmitter Terminal Site SKF		
Antenna Type		Parabolic horn
Transmitting Frequency	(GHz)	7.4000
Transmitter Antenna Gain	(dBi)	44.7377
Repeater Site MUL		
Antenna Type		Single mirror
Receiving Frequency	(GHz)	7.4000
Primary Receiving Antenna Gain	(dBi)	59.4506
Diversity Receiving Antenna Gain	(dBi)	
Transmitting Frequency	(GHz)	7.4000
Primary Transmitting Antenna Gain	(dBi)	59.4506
Transmitter Power	(dBm)	0.0000
Transmitter Line Lengths	(m)	0.0000
Receiver Line Length	(m)	0.0000
Near Field Condition?		No
Site Loss	(dB)	0.0000
Repeater Site BHR		
Antenna Type		Double antenna
Receiving Frequency	(GHz)	7.4000
Primary Receiving Antenna Gain	(dBi)	44.7377
Diversity Receiving Antenna Gain	(dBi)	44.7377
Transmitting Frequency	(GHz)	7.4000
Primary Transmitting Antenna Gain	(dBi)	44.7377
Transmitter Power	(dBm)	43.0000
Transmitter Line Lengths	(m)	15.0000
Receiver Line Length	(m)	15.0000
Near Field Condition?		No
Site Loss	(dB)	0.0000
Repeater Site DON		
Antenna Type		Double mirror
Receiving Frequency	(GHz)	7.4000
Primary Receiving Antenna Gain	(dBi)	60.5401
Diversity Receiving Antenna Gain	(dBi)	
Transmitting Frequency	(GHz)	7.4000
Primary Transmitting Antenna Gain	(dBi)	60.5401
Transmitter Power	(dBm)	0.0000
Transmitter Line Lengths	(m)	0.0000
Receiver Line Length	(m)	0.0000
Near Field Condition?		No
Site Loss	(dB)	0.0000
Receiving Terminal Site HDG		
Antenna Type		Periscope
Receiving Frequency	(GHz)	7.4000
Primary Receiving Antenna Gain	(dBi)	44.7377
Diversity Receiving Antenna Gain	(dBi)	

8. ALGORITHM G: MEDIAN BASIC TRANSMISSION LOSS

The model for calculating median basic transmission loss is similar to the model in MIL-HDBK-416 (Dept. of Defense, 1977a). It is based on the inverse square law and a gas absorption model. Terrain reflections are not a part of this model, although for low antennas and particularly smooth terrain, reflections can strongly influence the median received signal level. Over the frequency range of interest here (1 to 50 GHz), the adverse effects of terrain reflections on signal level are usually overcome by using space diversity. For this reason, we are not including terrain reflection effects in the median basic transmission loss calculation. We do not, however, want to imply that terrain reflection effects should be ignored in the design of a system. Aside from affecting received signal level, reflections may cause a delayed-signal distortion of the desired signal; therefore, reflections should be avoided if possible. Another factor that will affect median basic transmission loss is partial blocking of the ray path by an obstacle. Such an obstacle produces a diffracted field. This model assumes that terrain clearance is adequate and that diffraction losses can be ignored.

8.1 Free-Space Basic Transmission Loss (Inverse Square Loss)

The free-space basic transmission loss, L_{bf}, is calculated as follows:

$$L_{bf} = 92.45 + 20 \log f_{GHz} + 20 \log d_{km} \quad \text{(dB)} \qquad \text{(G-1)}$$

where d_{km} is the distance in km and f_{GHz} is frequency in GHz.

8.2 Atmospheric Absorption

The atmospheric absorption loss component due to oxygen is dependent primarily upon air density and path length and is fairly stable as a function of time. The component due to water vapor absorption, on the other hand, varies with air density, temperature, and humidity which requires a more complicated model to predict a median value. The first water vapor line occurs at 22 GHz with substantial effects at frequencies above 15 GHz. The graph often used to estimate water vapor absorption assumes a value of absolute humidity of about 10 g/m^3 (Dept. of Defense, 1977a, p. 4-49). In many parts of the world absolute humidity will remain between 20 and 30 g/m^3 for weeks at a time; therefore, a better model than the one used in MIL-HDBK-416 (Dept. of Defense, 1977a) is required. The model that we use for calculating atmospheric absorption is one prepared by H. J. Liebe and G. G. Gimmestad (1978). Atmospheric absoption, A_{abs}, is calculated by adding the components corresponding to oxygen and water vapor:

$$A_{abs} = d_{km}(a_o + a_w) \tag{G-2}$$

To calculate O_2 absorption per unit length, a_o, to 50 GHz:

$$a_o = \frac{0.626 \times 10^{-6} f^2 p^2 t^{2.9}}{f^2 + 3.14 \times 10^{-5} p^2 t^{1.8}} + 0.1820 f \sum_{a=1}^{a=36} S_a F_a'' \tag{G-3}$$

$$S_a = A_1 pt^3 \exp [A_2(1 - t)] \tag{G-4}$$

$$F_a'' = \frac{f}{f_a} \left(\frac{y_a - (f_a - f) I_a}{(f_a - f)^2 + y_a^2} + \frac{y_a - (f_a + f) I_a}{(f_a + f)^2 + y_a^2}\right) \tag{G-5}$$

$$y_a = A_3 (p + 1.3 p_W) t^{0.9} \tag{G-6}$$

$$I_a = A_4 pt^2 \tag{G-7}$$

f = frequency in GHz. $(1 < f < 50)$ (for $f < 1$, let $A_{abs} = 0$)
f_a = line frequency (see Tables 7 and 8)

$$t = \frac{300}{T + 273.16} \quad \text{where } T = \text{temperature in °C.} \quad -98 < T < 37. \tag{G-8}$$

T is the median path air temperature.

For the value of T, a world map of mean temperature values is provided (Figure 13). A default value[1] is T = 20°C.

$$p = p_m - p_w \qquad (60 < p_m < 101.3) \qquad \text{(G-9)}$$

p_m is the mean air pressure on the radio path. It is provided as an output of the path profile and ray path algorithm. A default value is p_m = 101.3 kPa (pressure at mean sea level).

$$p_w = 0.00046151\, q_w(T + 273.16) \qquad \text{(G-10)}$$

q_w = air water vapor density in g/m^3, $(0 < q_w < 40)$.

For the value of q_w, a world contour map is provided (Figure 12). A default value for water vapor density is q_w = 15 g/m^3. For values of f_a, A_1, A_2, A_3 and A_4, see Table 7.

To calculate water vapor absorption per unit length, a_w, to 50 GHz:

$$a_w = 0.1820\, f \left[\sum_{b=1}^{b=6} S_b F_b'' \right] + 0.1820\, f N_w'' \qquad \text{(G-11)}$$

$$S_b = B_1\, p_w\, t^{3.5} \exp\left[B_2(1 - t)\right] \quad \text{(see Eq. G-8)} \qquad \text{(G-12)}$$

$$F_b'' = \frac{f y_b}{f_b} \left(\frac{1}{(f_b - f)^2 + y_b^2} + \frac{1}{(f_b + f)^2 + y_b^2} \right) \qquad \text{(G-13)}$$

---

[1] The term "default value" as used here means a value for making an estimate when a more accurate value is not available.

Table 7. Oxygen Lines

Frequency f_a (GHz)	Strength A_1 (kHz/kPa)	A_2	Width A_3 (GHz/kPa)	Interference A_4 (1/kPa)
50.9873	.00000244	8.69	.0087	.0055
51.50302	.00000604	7.74	.0089	.0056
52.02117	.0000141	6.84	.0092	.0055
52.54223	.0000308	6.00	.0094	.0057
53.06680	.0000637	5.22	.0097	.0053
53.59572	.000124	4.48	.0100	.0054
54.12997	.0002256	3.81	.0102	.0048
54.67116	.0003893	3.19	.0105	.0048
55.22136	.0006274	2.62	.01079	.00417
55.78380	.0009471	2.11	.01110	.00375
56.26478	.0005453	0.0138	.01646	.00774
56.36339	.001335	1.66	.01144	.00297
56.96818	.001752	1.255	.01181	.00212
57.61249	.002126	0.910	.01221	.00094
58.32389	.002369	0.621	.01266	-.00053
58.44660	.001447	0.0827	.01449	.00597
59.16422	.002387	0.0386	.01319	-.00244
59.59098	.002097	0.207	.01360	.00344
60.30604	.002109	0.207	.01382	-.00435
60.43478	.002444	0.386	.01297	.00132
61.15057	.002486	0.621	.01248	-.00036
61.80017	.002281	0.910	.01207	-.00159
62.41122	.001919	1.255	.01171	-.00266
62.48626	.001507	0.0827	.01468	-.00503
62.99800	.001492	1.66	.01139	-.00334
63.56854	.001079	2.11	.01108	-.00417
64.12778	.0007281	2.62	.001078	-.00448
64.67892	.0004601	3.19	.0105	-.0051
65.22408	.0002727	3.81	.0102	-.0051
65.76474	.000152	4.48	.0100	-.0057
66.30206	.0000794	5.22	.0097	-.0055
66.83677	.0000391	6.00	.0094	-.0059
67.36951	.0000181	6.84	.0092	-.0056
67.90073	.00000795	7.74	.0089	-.0058
68.4308	.00000328	8.69	.0087	-.0057
118.75034	.0009341	0.0138	.01592	-.00044

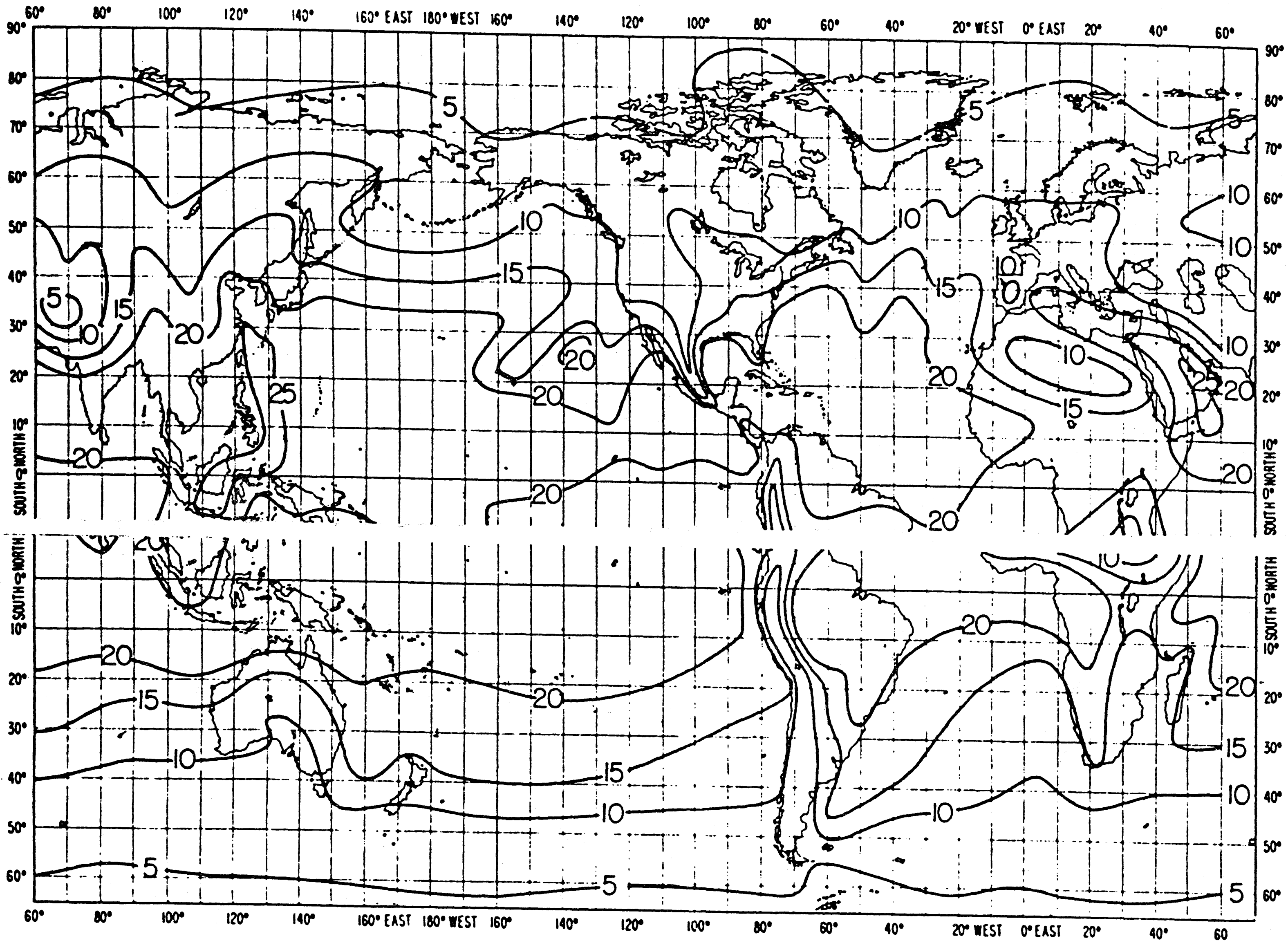
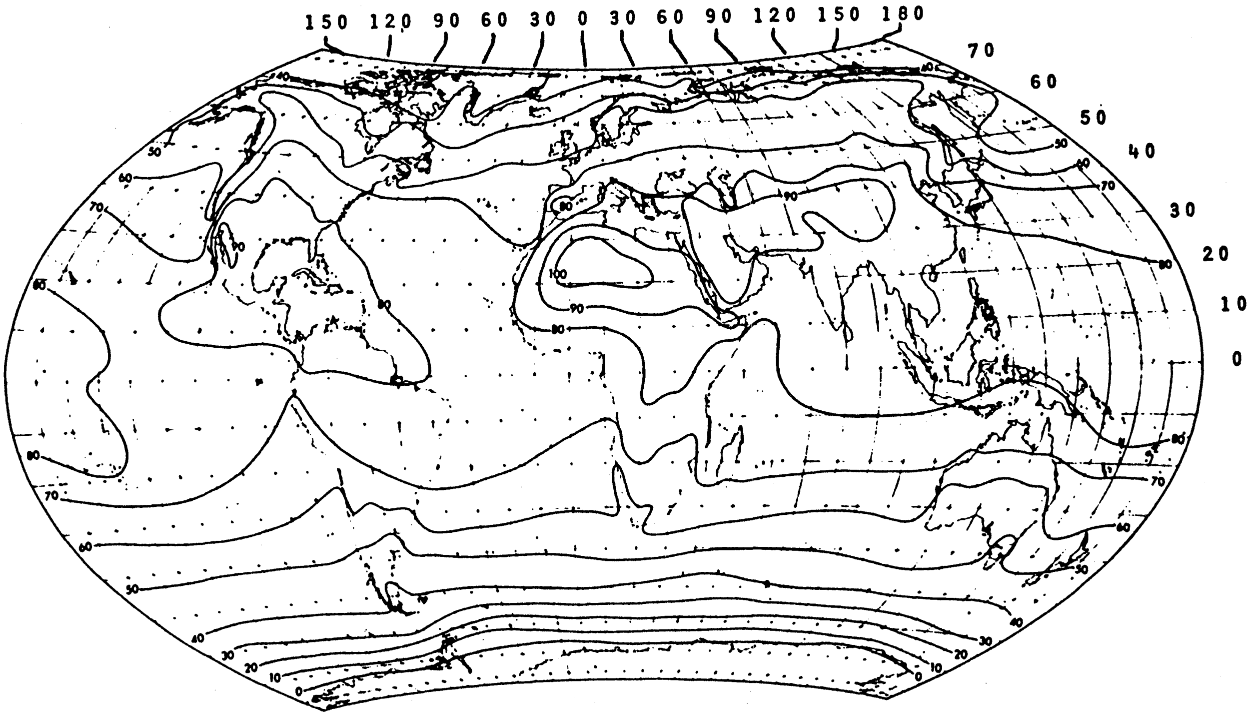


Figure 12. Contours of average absolute humidity (g/m^3) for a summer month (August for the northern hemisphere and February for the southern hemisphere) (Bean and Dutton, 1966).

AVERAGE JULY TEMPERATURE (F°)



Degrees Celsius = $\frac{5}{9}$ (°F-32)

AVERAGE JANUARY TEMPERATURE (F°)

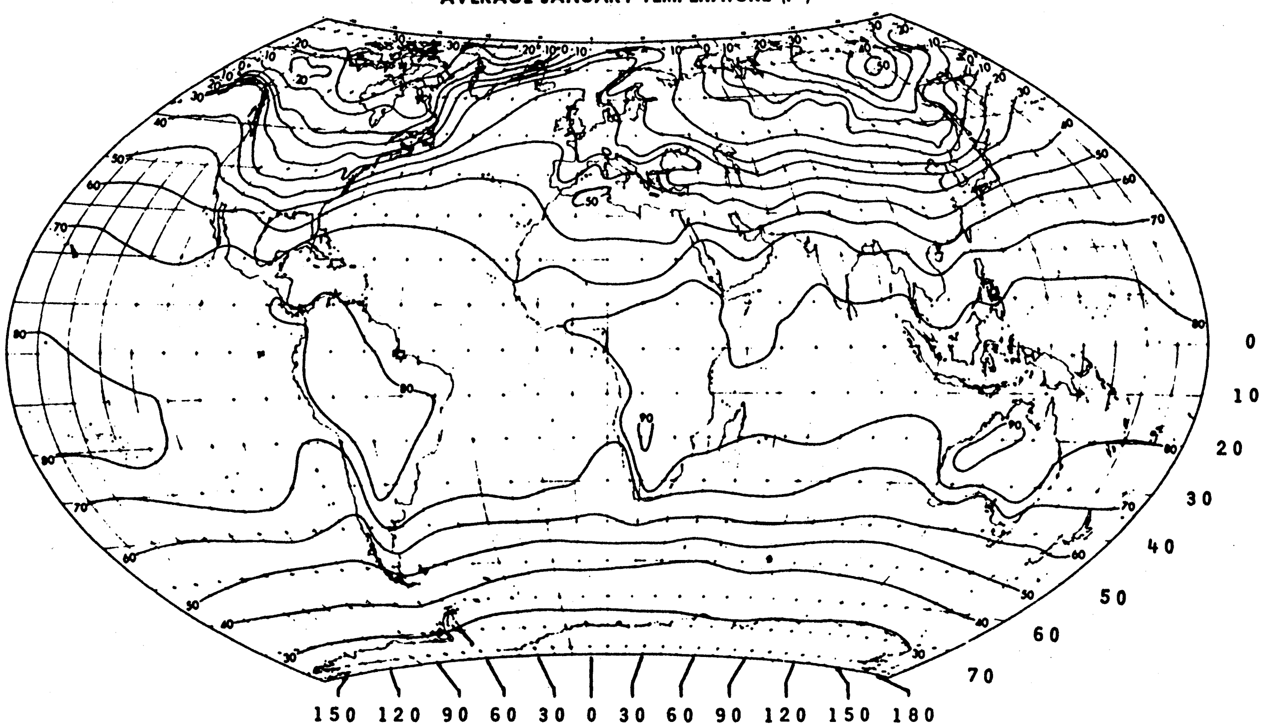


Figure 13. Mean temperature values (ESSA, 1969).

$$y_b = B_3 \ (p + 4.80 \ p_w) \ t^{0.6} \tag{G-14}$$

$$N_w'' = 1.87 \times 10^{-6} \ p \ p_w \ t^{3.1} \ f \tag{G-15}$$

For values of f_b, B_1, B_2, B_3 and B_4, see Table 8.

Table 8. Water Vapor Lines

f_b	B_1	B_2	B_3	B_4
22.23508	0.112	2.143	.0281	0
68.052	0.018	8.75	.028	0
183.31009	2.41	0.653	.0282	0
321.22564	0.044	6.16	.022	0
325.15292	1.59	1.52	.029	0
380.19737	12.40	1.02	.0285	0

8.3 Median Basic Transmission Loss Output Format

The output from Program "G" is a tabulation (Table 9) showing input and output variable values for each path in the link.

Table 9. Example Median Basic Transmission Loss Output

Aug/21/1986

Median Basic Transmission Loss
Shanzerkopf to Heidelberg

Path 1 Shanzerkopf to Muhl		
Path Length	(km)	53.693
Primary Frequency	(GHz)	7.4000
Average Summer Temperture	(Celsius)	26.7
Mean Path Pressure	(kPa)	93.2078
Absolute Humidity	(gm/cu. m)	12.00
Oxygen Absorption	(dB)	0.302
Water-Vapor Absorption	(dB)	0.225
Total Atmospheric Absorption	(dB)	0.527
Free Space Basic Transmission Loss	(dB)	144.433
Total Path Median Basic Transmission Loss	(dB)	144.960
Path 2 Muhl to Baumholder		
Path Length	(km)	21.940
Primary Frequency	(GHz)	7.4000
Average Summer Temperture	(Celsius)	26.7
Mean Path Pressure	(kPa)	84.9609
Absolute Humidity	(gm/cu. m)	12.00
Oxygen Absorption	(dB)	0.102
Water-Vapor Absorption	(dB)	0.084
Total Atmospheric Absorption	(dB)	0.186
Free Space Basic Transmission Loss	(dB)	136.659
Total Path Median Basic Transmission Loss	(dB)	136.845
Path 3 Baumholder to Donnersberg		
Path Length	(km)	42.915
Primary Frequency	(GHz)	7.4000
Average Summer Temperture	(Celsius)	26.7
Mean Path Pressure	(kPa)	85.6008
Absolute Humidity	(gm/cu. m)	12.00
Oxygen Absorption	(dB)	0.203
Water-Vapor Absorption	(dB)	0.166
Total Atmospheric Absorption	(dB)	0.369
Free Space Basic Transmission Loss	(dB)	142.487
Total Path Median Basic Transmission Loss	(dB)	142.855
Path 4 Donnersberg to Heidelberg		
Path Length	(km)	61.388
Primary Frequency	(GHz)	7.4000
Average Summer Temperture	(Celsius)	26.7
Mean Path Pressure	(kPa)	96.8165
Absolute Humidity	(gm/cu. m)	12.00
Oxygen Absorption	(dB)	0.373
Water-Vapor Absorption	(dB)	0.267
Total Atmospheric Absorption	(dB)	0.640
Free Space Basic Transmission Loss	(dB)	145.596
Total Path Median Basic Transmission Loss	(dB)	146.236

9. ALGORITHM H: BASIC TRANSMISSION LOSS VARIABILITY

The purpose of Algorithm Set "H" is to calculate the component probability distributions of path transmission loss due to rain attenuation and multipath fading. These distributions are combined using diversity considerations to obtain the probability distribution of basic transmission loss, L_b, not exceeded more than a particular fraction of a year.

9.1 Path Attenuation Caused by Rain

For the locations listed in Table 10, the algorithm for rain attenuation developed at NTIA/ITS by Mr. E. J. Dutton (1984) is used. For other areas of the world, the model described in CCIR (1982) and Crane (1982) is applied.

9.2 Dutton Rain Attenuation Model

$P_{PA}(A > A_{PA})$ is the probability that a particular value of attenuation, A_{PA}, is exceeded during a particular fraction of a year on a given path at a given frequency for a particular fraction, Q, of all years. The purpose of the Dutton (1984) model is to provide a relationship between P_{PA} and A_{PA} given by the expression:

$$P_{PA}(A > A_{PA}) = F_P \, P_{PO} \qquad \text{(H-1)}$$

P_{PA} may be obtained by multiplying P_{PO} by the probability modification factor, F_P, where P_{PO} is the probability that a particular value of attenuation per kilometer, A_{PO}, is exceeded at a point at a given frequency for a particular value of Q.

9.3 Probability Modification Factor

The idea of a probability modification factor, F_P, may be used for terrestrial paths where the path elevation angle is assumed to be equal to zero although F_P was originally defined for use with satellite paths. F_P is defined as the ratio, P_{PA}/P_{PO}.

If F_P is calculated and found to be greater than 1, a value of 1 is assigned to F_P. If $P_{PO} >= .0001$, the expression for F_P is:

$$F_P = 128.64 \frac{(f/15)^2}{D_P^2 \; A_{PO}} (h_{TOP})^{.5} \qquad \text{(H-2)}$$

where h_{TOP} is the height of thunderstorm tops given by the expression:

$$h_{TOP} = K_{1c} \; R^{K_{2c}} \qquad \text{(H-3)}$$

D_P is the path length in km and R is the point rain rate. If the path length is greater than 30 km, then $D_P = 30$ km. The subscript "c" designates the climate zones (see Figure 14) for which there are eight unique thunderstorm top regions (see Tables 10 and 11).

If $P_{PO} < .0001$, then F_P is calculated in accordance with Dutton et al. (1982, p. 1365) using the expression:

$$F_p = \left(\frac{\bar{R}_{.001\%}}{\bar{R}_{.01\%}}\right)\left(\frac{R_{.01\%}}{R_{.001\%}}\right) F_P[P_{PO} = .01\%] \qquad \text{(H-4)}$$

$$\text{where } \bar{R} = \frac{0.28355}{D_P} [1.689R^{1.64} - (1.227R^{0.64} - D\;)^{0.25625}] \qquad \text{(H-5)}$$

and if D_P is greater than $1.227R^{0.64}$ then $\bar{R} = \frac{0.28355}{D_P} (1.698\; R^{1.64})$

D_P is the path length in km or 30 km, whichever is less, and R is the value of point rain rate in mm/h.

Table 10. Rain Rate Input Data Sources for the Dutton Model

Location	Storm Top Region Number	NTIA Report 84-148 Page No. M	U	D	S_{R1}	$S_{R.1}$	$S_{R.01}$
Central America	6	97	99	98	107	108	109
Federal Republic of Germany	3	42	44	43	57	58	59
Okinawa	6	61	61	61	61	61	61
Republic of Korea	3	63	65	64	73	74	75
Southeast Asia	6	134	136	135	144	145	146
Southwest Asia		78	80	79	93	94	95
Aden	7						
Afghanistan	4						
Bahrain	7						
Cyprus and India (Northwest)	3						
India (Southwest)	6						
Iran	3						
Iraq	7						
Israel, Jordan and Lebanon	3						
Muscat and Oman	7						
Pakistan	3						
Qatar and Saudi Arabia	7						
Syria	3						
Trucial Oman	7						
Turkey and the U.S.S.R	3						
Yemen	7						
United States (Fig. H-1)		112	114	113	127	128	129
Zone 1	6						
Zones 2, 4 and 5	8						
Zones 3, 6 and 7	3						
Zones 8 and 10	4						
Zones 9 and 13	5						
Zones 11, 12 and 14	7						
Zones 15 and 16	2						
Zone 17	1						
Zones 18 and 19	6						

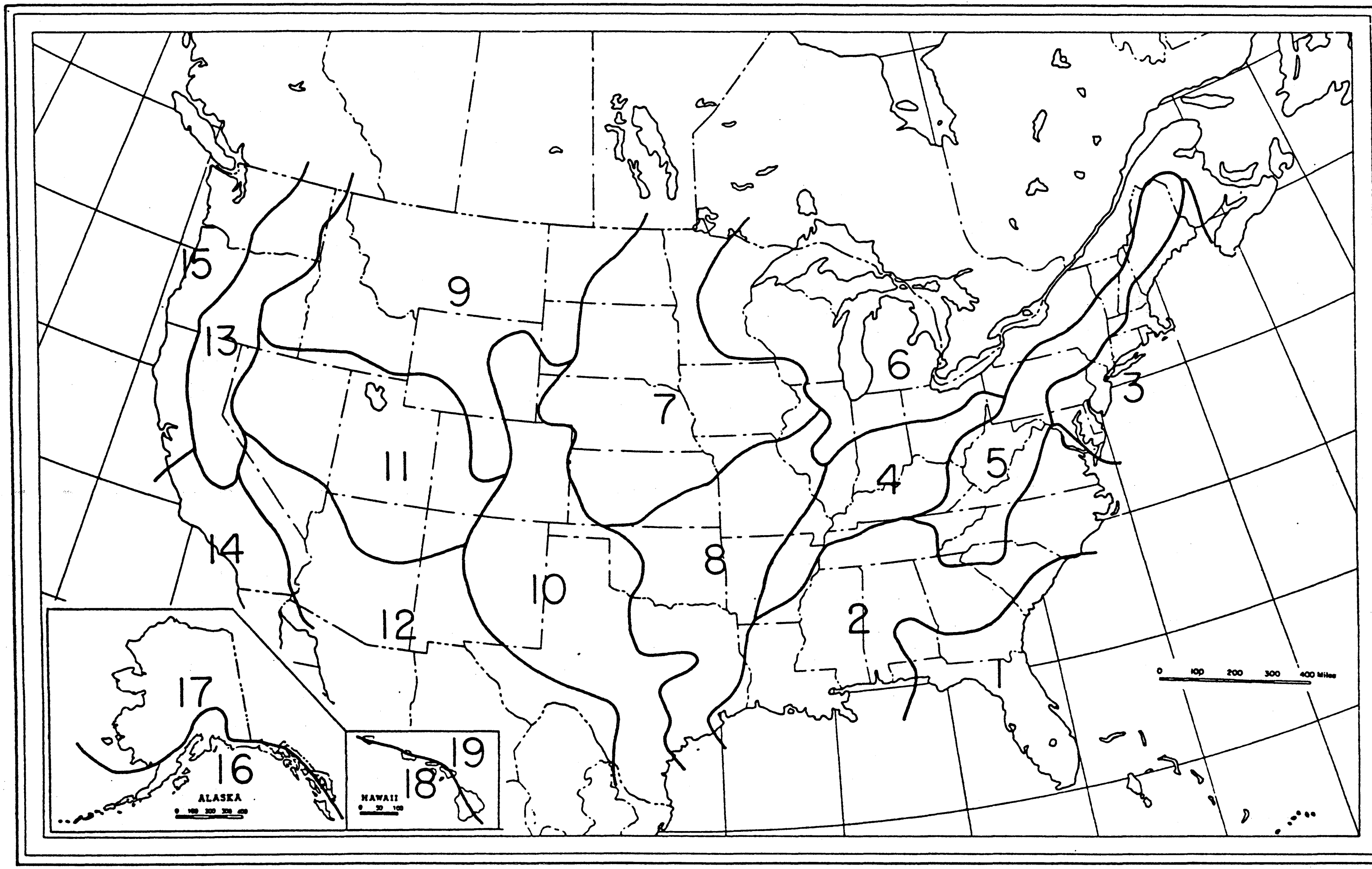


Figure 14. Rainfall climatic zones in the USA (Dutton, 1977, p6).

Table 11. Storm Top Constant Values

Storm Top Region No.	K_{1c}	K_{2c}
1	11.480	0.34414
2	9.466	0.18218
3	10.444	0.14192
4	14.911	0.07659
5	10.638	0.10010
6	14.035	0.06909
7	5.687	0.21356
8	11.681	0.11000

9.4 Rain Attenuation Coefficient

The point attenuation coefficient in dB/km, A_{PO}, may be obtained from the carrier frequency, polarization and point rain rate values using the expression:

$$A_{PO}[f] = a\,R^{b} \qquad \text{(H-6)}$$

where "a" and "b" are obtained from the expressions in CCIR (1982b, Rep. 721, pp. 170-171) as follows:

$$a = [k_H + k_V + (k_H - k_V)\cos X \cos^2 2Y]/2 \qquad \text{(H-7)}$$

$$b = [k_H C_H + k_V C_V + (k_H C_H - k_V C_V)\cos^2 X \cos 2Y]/2a \qquad \text{(H-8)}$$

where X is the path elevation angle and Y is the polarization tilt angle relative to the horizontal. For terrestrial links X is approximately equal to zero. For horizontal polarization, Y = 0. Y = 90° for vertical polarization. k_H, k_V, C_H and C_V, which were obtained by curve fitting data in CCIR (1982b, Report 721), are functions of frequency, f, and are given by the expressions:

$$k_H = 10^{E_{XH}} \qquad \text{(H-9)}$$

$$E_{XH} = 2.02 \text{ logf} - 4.459 + 0.151 \log(10^{(10 \text{ logf} - 7.5)} + 1)$$

$$-0.142 \log(10^{(10 \text{ logf} - 12)} + 1)$$

$$k_V = 10^{E_{XV}} \qquad \text{(H-10)}$$

$$E_{XV} = 2.02 \text{ logf} - 4.398 + 0.15 \log(10^{(10 \text{ logf} - 7.5)} + 1)$$

$$-0.284 \log(10^{(5 \text{ logf} - 6)} + 1)$$

$$C_H = 0.1694 \text{ logf} + 0.912 + 0.1116 \log(10^{(8 \text{ logf} - 3.857)} + 1) \qquad \text{(H-11)}$$

$$- 0.03827 \log(10^{(30 \text{ logf} - 24.12)} + 1)$$

$$- 0.03035 \log(10^{(20 \text{ logf} - 18.59)} + 1)$$

$$+ 0.01371 \log(10^{(20 \text{ logf} - 23.52)} + 1)$$

$$- 0.01256 \log(10^{(20 \text{ logf} - 29)} + 1)$$

$$C_V = 0.1428 \text{ logf} + 0.88 + 0.1337 \log(10^{(7 \text{ logf} - 3.399)} + 1) \qquad \text{(H-12)}$$

$$- 0.03712 \log(10^{(30 \text{ logf} - 24.67)} + 1)$$

$$- 0.03869 \log(10^{(20 \text{ logf} - 18.90)} + 1)$$

$$+ 0.02928 \log(10^{(15 \text{ logf} - 18)} + 1)$$

$$- 0.01079 \log(10^{(20 \text{ logf} - 29.54)} + 1)$$

9.5 Probability of a Particular Point Rain Rate Value

Using an equation from Dutton (1978, p. 2), which was derived from Rice and Holmberg (1973), we may obtain the fraction of time, P_{PO}, that a particular rain rate, R, is exceeded at a point location during one half of all years. P_{PO} is given by the expression:

$$P_{PO}[R,0.5] = 0.0001141\{T_{11}\exp(-R/R_{11}) + 0.35T_{21}\exp(-0.45307R/R_{21}) + 0.65T_{21}\exp(-2.857143R/R_{21})\} \quad \text{(H-13)}$$

Using the definitions from Dutton et al. (1974, p. C-1 and C-2) we have the expressions for T_{11}, T_{21}, R_{11}, and R_{21} as follows:

$$T_{11} = (\frac{U}{D})M/R_{11} \quad \text{(H-14)}$$

$$T_{21} = (1 - \frac{U}{D})M/R_{21} \quad \text{(H-15)}$$

$$R_{11} = 1 + 33.48\ \exp(-\frac{U\ M}{D\ 8766}) \quad \text{(H-16)}$$

$$R_{21} = \frac{(1 - \frac{U}{D})\ M}{24\ D[0.165 + k_A\ \exp(-k_B)]} \quad \text{(H-17)}$$

where $k_A = 0.121\ \exp(k_B/1440)$ (H-18)

and $k_B = 1444\ \ln(\frac{3017}{D} - 7.772)$ (H-19)

"M" is the average annual precipitation in mm for the average year. "U" is the average annual number of days with thunderstorms for the average year. "D" is the average annual number of days with precipitation greater than 0.01 inches (0.25 mm) for the average year. The values of M, U and D are found using the contour maps printed in Dutton (1984). These maps are found on the pages listed in Table 10.

9.6 Rain Rate Distribution Confidence Bands

To calculate the confidence limits (the annual rain rate probability distribution where rates are not exceeded for more than some fraction, Q, of all years), we use the maps from Dutton (1984) showing the standard deviation, S_R, for three values of rain rate corresponding to average annual probability, P_{PO}. These values of P_{PO} are 0.01, 0.001 and 0.0001. From these standard deviation values and assuming a normal distribution or a truncated normal distribution for the confidence band values, an expression for the confidence limit is calculated.

To use the Dutton (1984) method, a continuous expression is required for standard deviation, S_R, values from rain rate, R, for an average year. The function is obtained by fitting a curve to the three values of S_R provided in Dutton (1984). The three values of S_R correspond to P_{PO} = 1%, .1%, and .01% (Table 10). The expression for S_R is:

$$S_R = M_1 R + (M_2 - M_1) \log[10^{(R - R_{1\%})} + 1] \qquad \text{(H-20)}$$

$$+ (M_3 - M_2) \log[10^{(R - R_{.1\%})} + 1]$$

where $M_1 = \dfrac{S_{R1\%}}{R_{1\%}}$, $M_2 = \dfrac{S_{R.1\%} - S_{R1\%}}{R_{.1\%} - R_{1\%}}$ and $M_3 = \dfrac{S_{R.01\%} - S_{R.1\%}}{R_{.01\%} - R_{.1\%}}$.

Using equations H-13, H-20, and the expression for the inverse normal distribution function, $N_P[Q]$, the value of $R_{PO}[P_{PO},Q]$ is obtained using the expression:

$$R_{PO}[P_{PO},Q] = R_{PO}[P_{PO},0.5] + S_R[R]\ N_P[Q]. \qquad \text{(H-21)}$$

An excellent approximation for 1 - $N_P[Q]$ is given in Abramowitz and Stegun (1964, p. 933, equation 26.2.23).

9.7 Path Rain Attenuation Probability Distribution

Using point rain rate as a parameter and (H-1) through (H-21), we may calculate four sets of corresponding values of path attenuation in dB, A_{PA}, and probability that A_{PA} is exceeded, $P_{PA}[Q]$. Using these coordinate pairs, $(A_{PA}[P_{PA},Q],P_{PA})$, we then curve fit an expression for A_{PA} as a function of $P_{PA}[Q]$. The expression is:

$$A_{PA}[P_{PA},Q] = \sum_{I=1}^{I=4} (m_1 - m_{I-1}) \log(10^{(-\log P_{PA} - I)} + 1) \qquad \text{(H-22)}$$

where in functional notation:

$$m_0 = 0;\ m_1 = A_{PA}[.01,Q];\ m_2 = A_{PA}[.001,Q] - A_{PA}[.01,Q]$$

$$m_3 = A_{PA}[.0001,Q] - A_{PA}[.001,Q]$$

$$m_4 = A_{PA}[.00001,Q] - A_{PA}[.0001,Q].$$

9.8 CCIR Rain Rate Zone Model

A rain rate zone is picked from one of the three zone maps (Figures 15, 16, and 17), then, using Table 12 which is based on rain rates from CCIR (1982b, Rep. 563-2, p. 117, Table 1), a rain rate probability distribution function may be calculated for an average year.

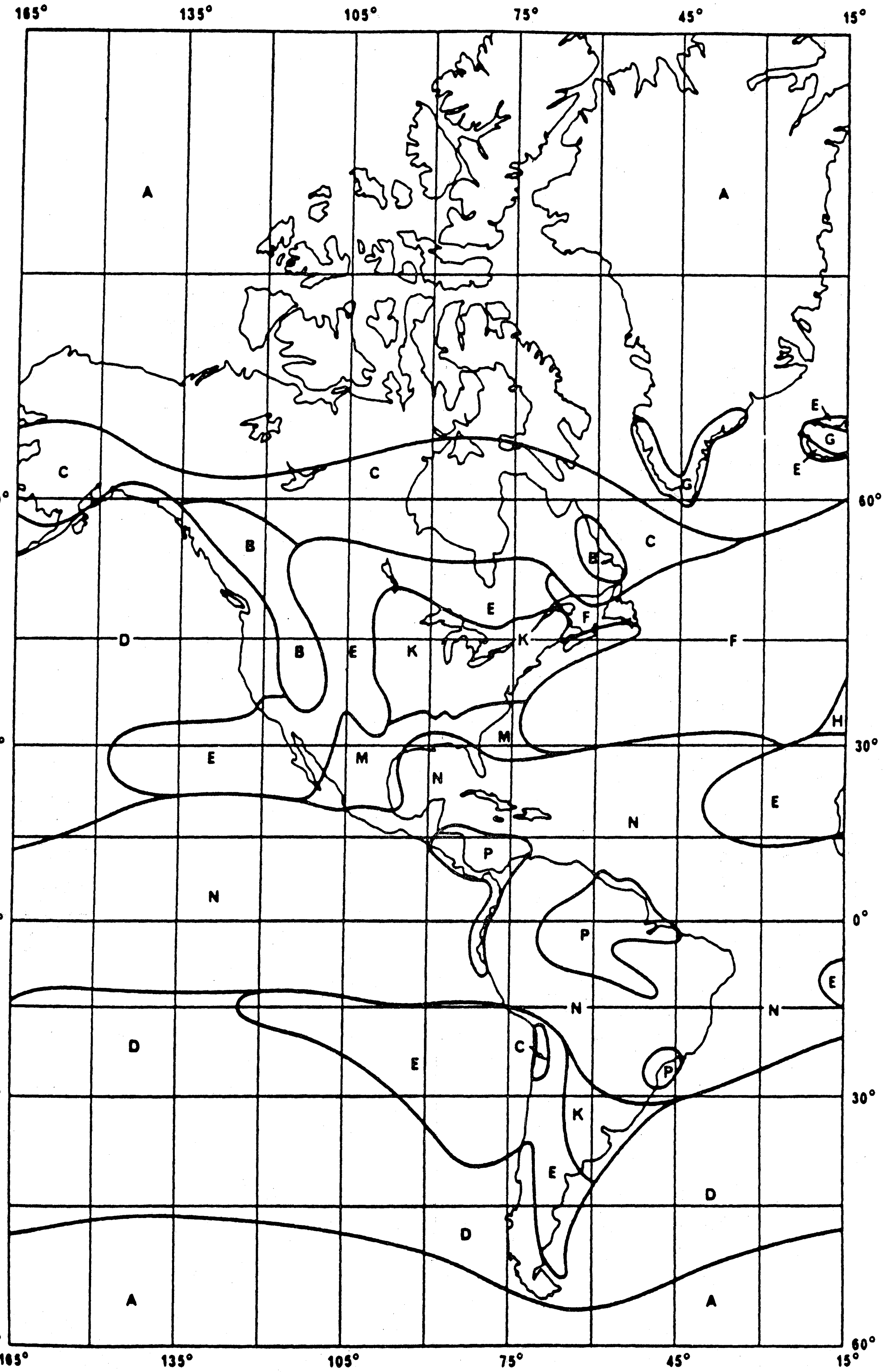


Figure 15. Rain rate zones for North and South America.

Figure 16. Rain rate zones for Europe, Africa and Western Asia.

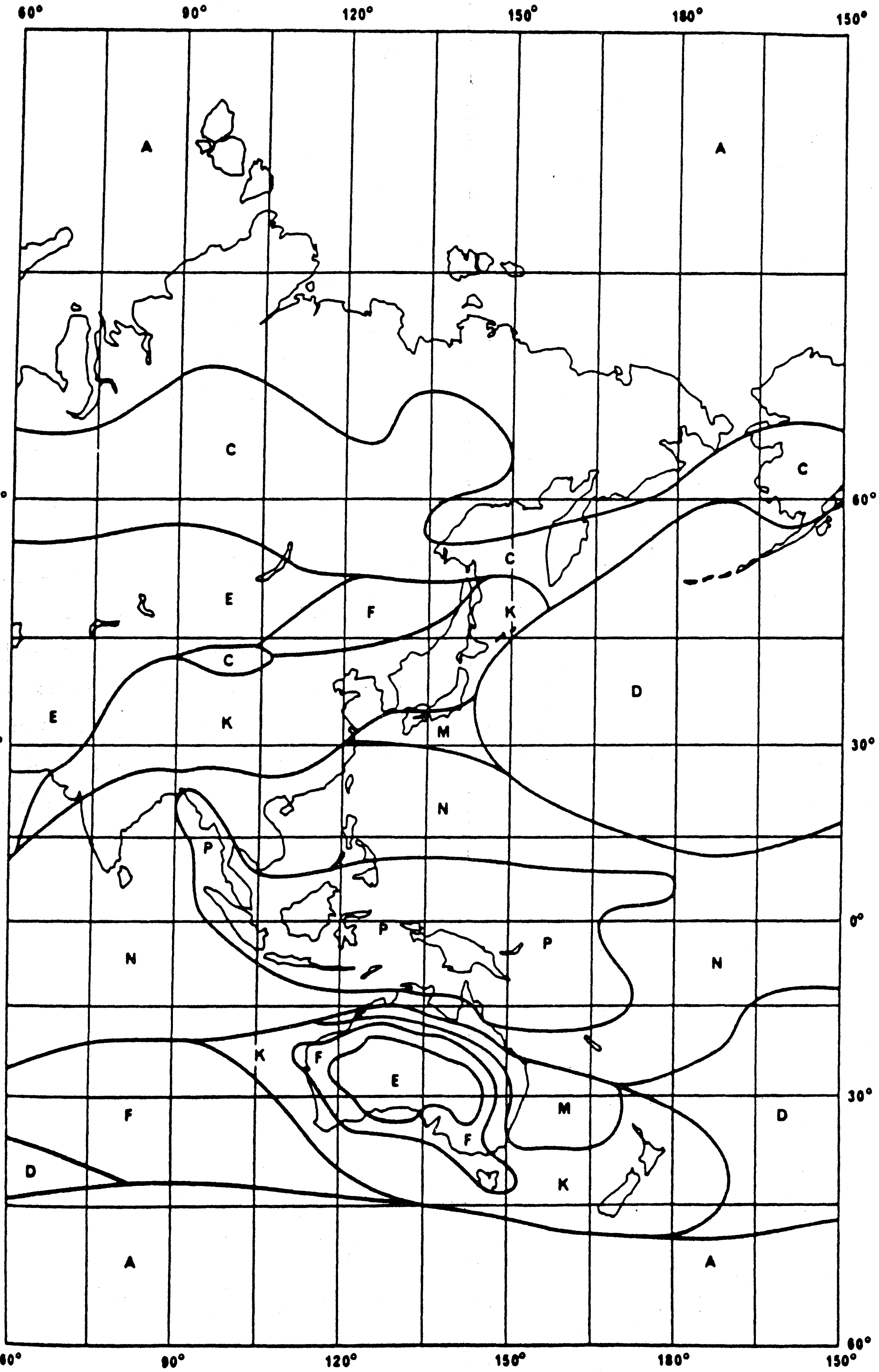


Figure 17. Rain rate zones for East Asia and Australia.

Table 12. Rainfall Intensity Exceeded (mm/h) - CCIR Rain Climatic Zones

Fraction of ave year	Climatic Zone No.													
	A	B	C	D	E	F	G	H	I	J	K	L	M	N
0.01	.01	1	.01	3	1	2	.01	.01	.01	2	.01	4	5	12
0.001	2	3	5	8	6	8	12	10	20	12	15	22	35	65
0.0001	8	12	15	19	22	28	30	32	35	42	60	63	95	145
0.00001	22	32	42	42	70	78	65	83	55	100	150	120	180	250

Crane (1982, p. 1381) suggests year-to-year standard deviation values corresponding to various rain rates in terms of average year probability values (S_R = .29R[.001], S_R = .29R[.0001], S_R = .36R[.01] and S_R = .36R[.00001]). Using the relationships from (CCIR, 1982b, pp. 170-171) with values for frequency and rain rate (Equations H-6 through H-12), the point attenuation is calculated. The expression for estimating the effective path length, rD, is given in CCIR (1982b, Rep. 338-4, p. 291, eq. 8). The total attenuation on a path is obtained from the expression:

$$A_{PA} = A_{PO} rD \qquad \text{(H-23)}$$

where A_{PO} is the point rain attenuation in dB per km, D is the path length in km, and r is the reduction factor. The reduction factor is given by the expression:

$$r = 90/(90 + 4D) \qquad \text{(H-24)}$$

The path attenuation probability distribution can be obtained using the curve fitting expressions from the previous section.

9.9 Radome Loss

The layer of water formed on an antenna weather cover during a rain storm produces a few decibels of attenuation (Hogg et al., 1977, pp. 1579). The amount of attenuation depends upon several factors:

- o rain rate
- o wind direction
- o condition of the radome surface; i.e., roughness, weathering, composition, etc.
- o the shape of the radome, i.e., flat or curved
- o the microwave frequency.

Measurements produced 4 to 8 dB attenuation at 20 GHz and 3 to 6 dB at 11 GHz (Hogg et al., 1977). An equation for estimating radome attenuation, A_W, for each antenna is:

$$A_W = 0.2\ f \qquad 5 < f < 50\ \text{GHz} \qquad \text{(H-25)}$$

where f is the carrier frequency in GHz and A_W is the wet radome attenuation in decibels. This estimate is for a parabolic antenna with a flat weather cover. If a path is less than or equal to 20 km, $2A_W$ is added to A_{PA} to give the total rain attenuation on the path. For longer paths the total rain attenuation is equal to $A_W + A_{PA}$.

9.10 Multipath Fading Distribution

This multipath fading analysis is applicable to LOS paths. The analysis is primarily based on the procedures described in CCIR (1982b, Report 338-4, p. 284). The CCIR describes a procedure for obtaining the multipath fading distribution for the worst fading month. It is valid for fading depths greater than 15 dB where atmospheric structures (not surface reflections) are the primary cause of the fading. This distribution is applicable to paths with adequate clearance. The distribution is given by the expression:

$$P_r(W) = P_m\ K_c Q_T (W/W_o)(1000f)^B D^C \qquad \text{(H-26)}$$

where

D = the path length in km

f = frequency in GHz

K_c = factor for climatic conditions

Q_T = factor for terrain conditions

W = received power in watts

W_o = long-term received power during nonfading conditions in watts

P_m = an adjustment for the probability that deep fading will occur

P_r = the probability that W is less than a particular value.

A modification of this distribution is used. In this modification, the following assumptions are made:

1) All factors except W/W_o, when multiplied together, are defined as the occurrence factor, F_o, of a path. For a particular path, F_o is a constant for any short-term median value of combined loss, L_b, provided that the short-term median is less than 15 dB below the long-term median. For more than 15 dB, Rayleigh fading is assumed in the short-term periods. The value of W_o is related to L_b and the respective long-term median value, W_{om} and L_{bm}, by the expression:

$$10 \log (W_{om}/W_o) = L_b - L_{bm} \tag{H-27}$$

2) The value of F_o is never greater than 1.
3) The number of worst months (the length of the multipath fading season) is assumed to be a function of median annual temperature and effective path length, d_e, which was derived in Algorithm D.
4) The effective path length is assumed to be a function of the penetration angles (the angles between the beam center line and atmospheric layers). A function results which is expressed in terms of antenna heights above mean sea level and the total path length. Assumptions 3 and 4 are based on one year of measurements made by the author on five long paths in Italy (unpublished data).
5) We assume that the exponent $B = 1$ and $C = 3$ (CCIR, 1982b, report 338-4, p. 286).

Based on these assumptions, the value of P_r (for the worst month) is given by the expression:

$$P_r = P_m K_c Q_T f d_e^3 10^{-(M_f/10)} \quad \text{(H-28)}$$

where M_f is the fading depth in dB below the long-term median value of combined loss, L_b. For inland paths,

$$P_m K_c Q_T = S_1^{-1.3} 10^{-5} \quad \text{(H-29)}$$

and for coastal paths (a coastal path must have at least one point on the path within 300 km of a very large body of water),

$$P_m K_c Q_T = 3.6 S_1^{-1.3} 10^{-5} \quad \text{(H-30)}$$

where S_1 is the standard deviation of terrain elevations in meters.

The fading season, Y_a, (worst fraction of a year) is given by:

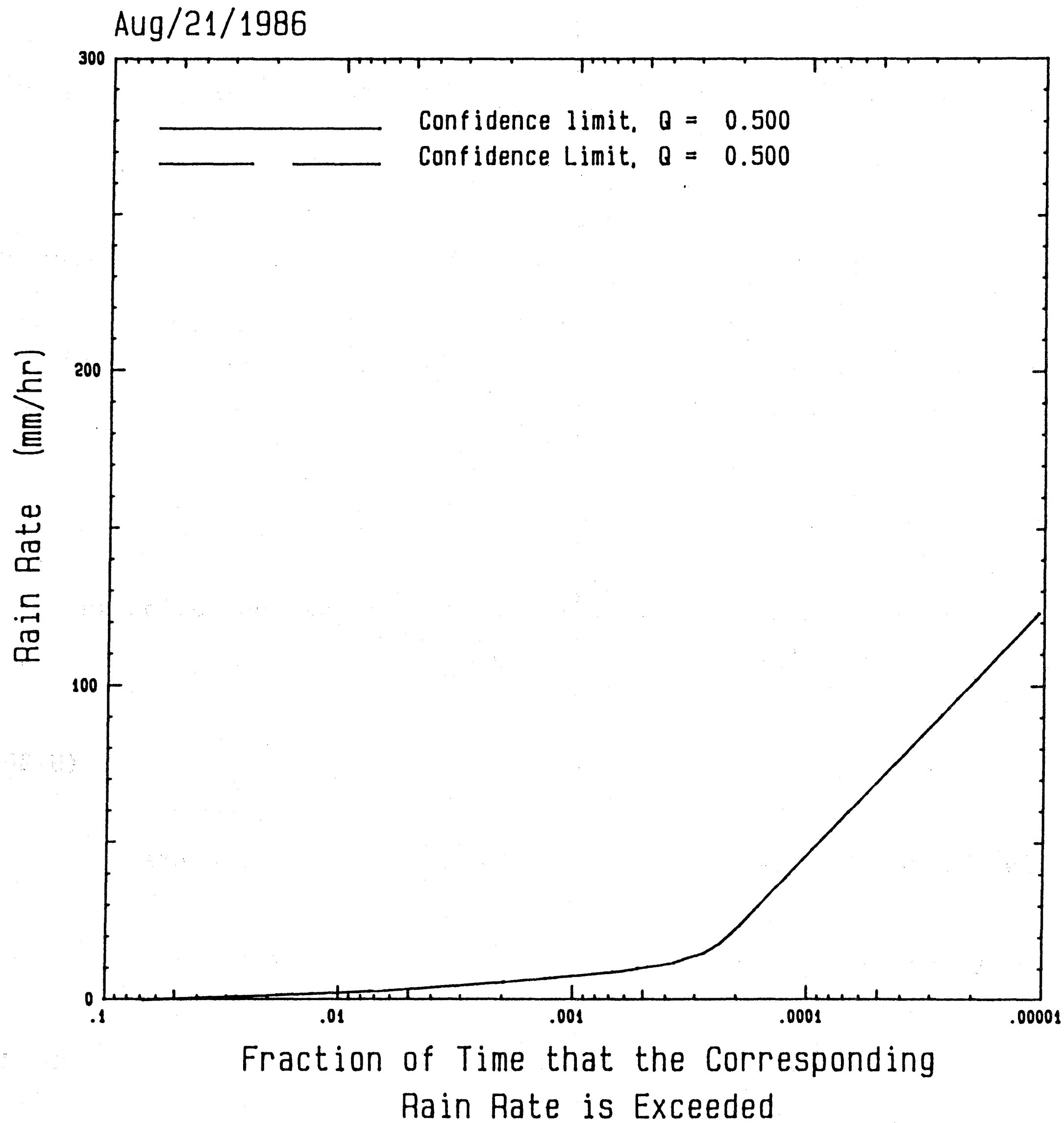
$$Y_a = (9T_o + 5 d_e + 160) \times 10^{-3} \quad \text{(H-31)}$$

where $Y_a <= 1$ and T_o is the mean annual temperature in degrees C. Since F_o is the occurrence factor for the worst month, the annual occurrence factor, F_{oa}, is given by the expression:

$$F_{oa} = Y_a F_o . \quad \text{(H-32)}$$

9.11 Variability Data Outputs

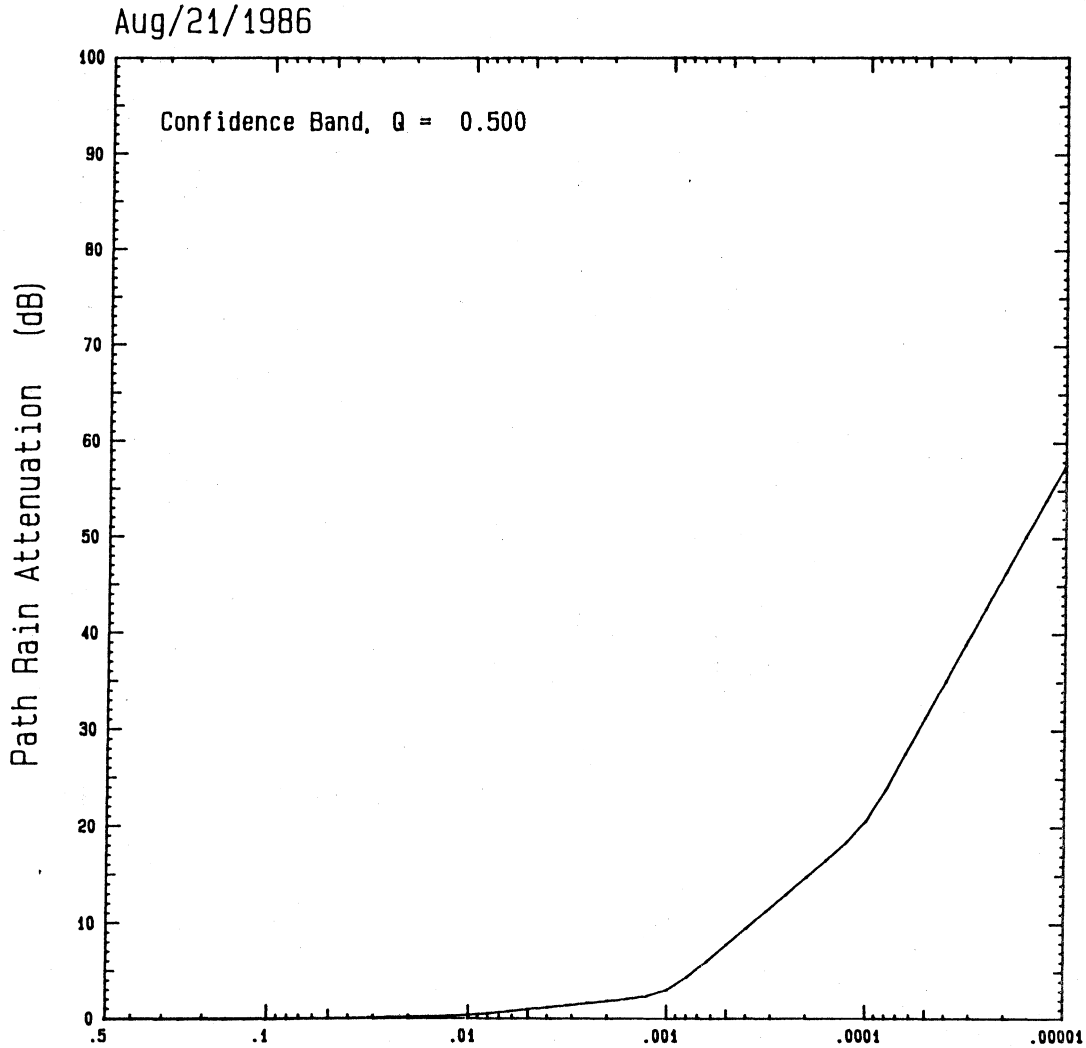
There are three types of outputs from Program Set "H." One is a plot of the rain rate probability distribution (Figure 18) plotted on a log scale. A second plot (Figure 19) shows graphs of path rain attenuation distributions on a Rayleigh scale. The third plot (Figure 20) shows an example of a multipath attenuation distribution on a Rayleigh scale.



Rain Attenuation Model		Dutton 1984
World Rain Rate Zone		5
Path Length	km	53.693
Primary Frequency	GHz	7.400
Polarization		Vertical
Median Basic Transmission Loss	dB	144.960
Thunderstorm Top Region		3
Mean Annual Precipitation	mm	700.0
Number of Thunderstorm Days per Year		25
Number of Rainy Days per Year		150
Radome Loss	dB	1.480

Rain Rate Probability for the Path
Shanzerkopf to Muhl

Figure 18. Example rain-rate probability distributions.

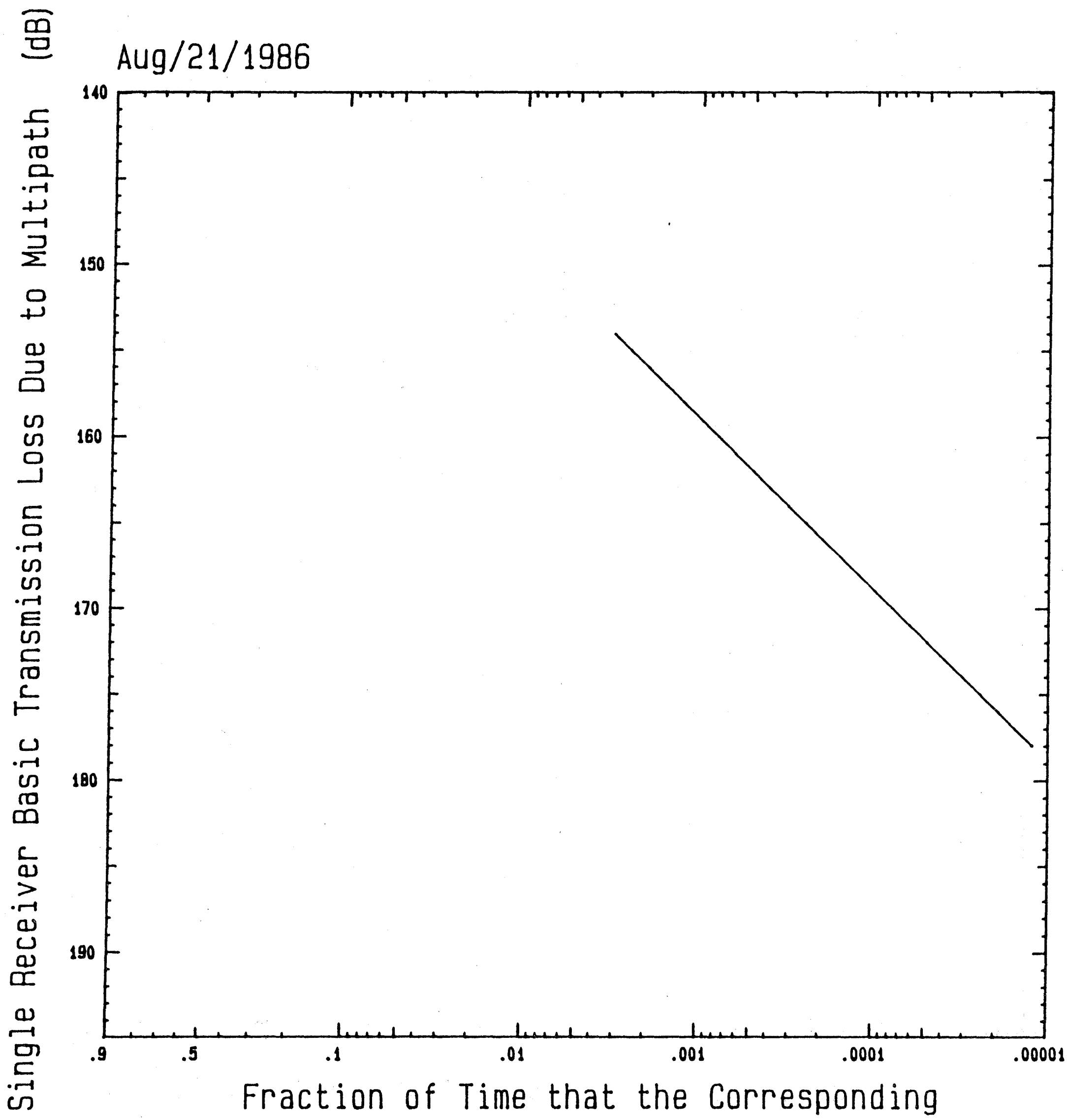


Fraction of Time that the Corresponding
Path Rain Attenuation is Exceeded

Rain Attenuation Model		Dutton 1984
World Rain Rate Zone		5
Path Length	km	53.693
Primary Frequency	GHz	7.400
Polarization		Vertical
Median Basic Transmission Loss	dB	144.960
Thunderstorm Top Region		3
Mean Annual Precipitation	mm	700.0
Number of Thunderstorm Days per Year		25
Number of Rainy Days per Year		150
Radome Loss	dB	1.480

Rain Attenuation Probability for the Path
Shanzerkopf to Muhl

Figure 19. Example path rain attenuation distribution.



Path Length	km	53.693
Effective Path Length	km	53.693
Primary Frequency	GHz	7.400
Polarization		Vertical
Median Basic Transmission Loss	dB	144.960
Std Deviation of Terrain Elev	m	112.047
Average Annual Temperture	Celsius	12.778
Region		Inland
Annual Occurance Factor		0.01349

Multipath Attenuation for the Path
Shanzerkopf to Muhl

Figure 20. Example multipath attenuation distribution.

10. ALGORITHM I: LINK CARRIER-TO-NOISE RATIO PROBABILITY DISTRIBUTION

To estimate the performance of a microwave link, it is useful to calculate the time distribution of carrier-to-noise ratio at receivers at the ends of the link. To do these calculations, information about the following parameters is required:

- o median basic transmission loss across the path
- o variability of the basic transmission loss
- o antenna gains
- o passive repeater efficiency
- o transmitter power output
- o transmission (feeder) line loss
- o diplexer and power splitter losses
- o receiver bandwidth
- o receiver noise figure
- o type and configuration of the diversity and combining system
- o reliability of equipment and support systems.

Calculation of equipment and support system reliability is considered separately from the other parameters. Usually a given amount of allotted outage time is assigned to equipment and support systems failure and it is often several times the amount of time allotted to outages associated with propagation anomalies. Median basic transmission loss values were calculated in Algorithm G. Variability of basic transmission loss was calculated in Algorithm H. Antenna gains and passive repeater efficiency were calculated in Algorithm F. Except for equipment and support systems reliability, values associated with the other parameters are considered in this algorithm.

The purpose of this set of algorithms is to calculate the link carrier-to-noise ratio probability distribution. To make these calculations, transmission loss data from previously executed programs is entered automatically, and certain equipment data must be hand entered. Assumptions must also be made concerning how fading occurs on the paths and how amplifiers with or without frequency converters at the repeater sites contribute to the path carrier-to-noise ratio (C/N). The assumptions are:

1. Fading on each component path of the link occurs at a different time than does significant fading on any of the other paths. This assumption permits the addition of time fractions corresponding to particular C/N values not exceeded on each path to give a composite C/N probability distribution for the whole link. This assumption is generally good for deep fading (greater than 15 dB).
2. Multipath fading on a path does not occur on a path at the same time that rain attenuation fading is happening (measurements indicate that this assumption is reasonable).
3. Final amplifiers used at the active repeater sites have a constant carrier output power level which is independent of the input level or these amplifiers have a constant gain.
4. No significant signal distortion occurs on the repeater paths or at the repeater sites. This assumption is reasonable on paths where data rates are low or on paths with little multipath fading.

10.1 Path Carrier-To-Noise Ratio

In order to calculate the combined received carrier-to-noise probability distribution $P[C/N_r]$ for the total number of paths in the link (up to 4 paths), we must treat each path a component source of noise. The particular path for which we are calculating noise will be called the nth path. We must have a set of variable values for each path as follows:

A_1 = path rain attenuation in dB for P_{pa} = 0.01
A_2 = path rain attenuation in dB for P_{pa} = 0.001
A_3 = path rain attenuation in dB for P_{pa} = 0.0001
A_4 = path rain attenuation in dB for P_{pa} = 0.00001
A_{pa} = path rain attenuation for probability, P_{pa}, and confidence, Q
A_w = the rain radome loss due to rain in dB ($A_w = 0$ if $A_{pa} < .01$)
B = combiner switching threshold power ratio in dB
B_r = the receiver bandwidth in MHz
C/N_{mx} = median C/N at the transmitter (for the first path, C/N_{x1} = 60 dB)
C/N_t = the thermal C/N at the receiver output
D = the path length in km
D_{rf} = the receiver feeder line length in dB
D_{xf} = the transmitter feeder line length in m

f_c = the primary carrier frequency in GHz

f_{dc} = the diversity carrier frequency in GHz

F_r = the receiver noise figure in dB

F_{oa} = the annual multipath fading occurrence factor

G_a = the active repeater site constant gain amplifier in dB

G_{dr} = the diversity receiver antenna gain in dBi

G_r = the primary receiver antenna gain in dBi

G_x = the transmitter antenna gain in dBi

I_{of} = the frequency diversity improvement in dB

I_{os} = the space diversity improvement in dB

K_{rf} = the receiver feeder line loss per 100 m in dB

K_{xf} = the transmitter feeder line loss per 100 m in dB

L_{mb} = the median basic transmission loss across the path in dB (Basic transmission loss across the path is the theoretical loss between isotropic radiators.)

L_{rd} = the receiver diplexer or power splitter loss in dB

L_{rf} = the receiver feeder line loss in dB

L_{rs} = the site loss on the receiver end of the path in dB

L_{vb} = the variable component of basic transmission loss in dB

L_{xf} = the transmitter feeder line loss path in dB

L_{xd} = the transmitter diplexer or power splitter loss in dB

M_{pa} = the multipath fade depth for the probability, P_m

N_t = receiver thermal noise in dBm

(at 20 C, $N_t = -113 + 10 \log B_r + F_r$)

P_b = the probability that a fade depth from any cause is exceeded

$P_{C/N}$ = the probability that C/N_r at the end of the link is not exceeded

P_m = the probability that M_{pa} is exceeded

P_{pa} = the probability that A_{pa} is exceeded

Q = Fraction of years A_{pa} is exceeded more than P_{pa} of the time

s_d = the vertical diversity spacing in m

T_r = the receiver site type

T_x = the transmitter site type

W_{fa} = The transmitter final amplifier power output in dBm

W_r = the received signal level for the path in dBm.

W_x = transmitter power at the antenna terminals in dBm (P_x=P_{fa} - L_{xf})

For values of C/N not exceeded for the link and less than the mean value, the C/N probability distribution for the link is given by the expression:

$$P[C/N_r] = P[C/N_{r1}] + P[C/N_{r2}] + \ldots + P[C/N_{rn}] \qquad \text{(I-1)}$$

when $C/N_r = C/N_{r1} = C/N_{r2} = C/N_{rn}$

and $$C/N_{rn} = -10 \log[10^{-.1C/N_{xn}} + 10^{-.1C/N_{tn}}] \qquad \text{(I-2)}$$

and $$C/N_{xn} = C/N_{r(n-1)} \qquad \text{(I-3)}$$

and $$C/N_{tn} = W_{rn} - N_{tn}. \qquad \text{(I-4)}$$

Thermal noise at the nth receiver output, N_{tn} is obtained from the expression:

$$N_{tn} = -113 + 10 \log B_{rn} + F_{rn}. \qquad \text{(I-5)}$$

Signal level at the input to the nth receiver, $W_{rn,}$ is obtained from I-6.

$$W_{rn} = W_{xn} + G_{xn} + G_{rn} - L_{rfn} - L_{rdn} - L_{rsn} - L_{mbn} - L_{vbn}. \qquad \text{(I-6)}$$

Transmission line loss values are calculated from line lengths and from the curves shown in Figure 21. Diplexer and power splitter losses other than zero should be entered when they are applicable (applicability depends upon where receiver and transmitter power measurement reference points are located in the system).

For passive repeater sites, the value of $W_{x(n+1)}$ (the next path output power) must be obtained for calculating $P[C/N_{r(n+1)}]$. $W_{x(n+1)}$ is obtained from the expression:

$$W_{x(n+1)} = W_{rn} - L_{xf(n+1)} \qquad \text{(I-7)}$$

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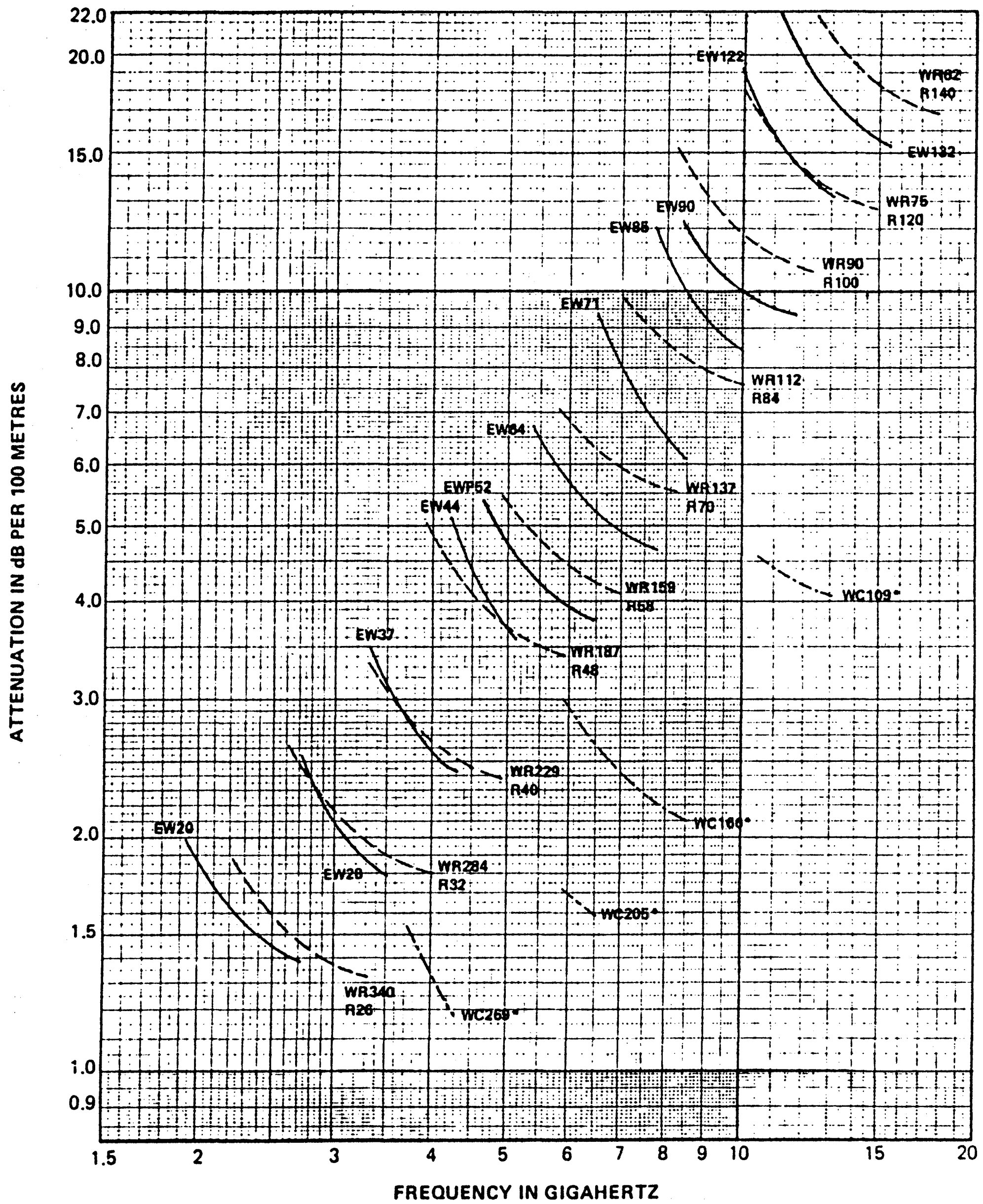


Attenuation curves based on:
VSWR 1.0
Ambient Temperature 24°C (75°F)
High-Conductivity Copper

The above attenuation curves are guaranteed within ±5%.

Figure 21. Microwave waveguide attenuation.

For active repeater sites with constant power output, use the expression:

$$W_{x(n+1)} = W_{fa(n+1)} - L_{xf(n+1)} - L_{xd(n+1)} . \tag{I-8}$$

For active repeater sites with constant gain amplifier, use the expression:

$$W_{x(n+1)} = W_{rn} - L_{xf(n+1)} + G_{a(n+1)} . \tag{I-9}$$

The probability corresponding to each value of the variable component of basic transmission loss is obtained from the following expression:

$$P_{bn}[L_{vbn}] = P_{mn} + P_{pan} \tag{I-10}$$

when $L_{vbn} = M_{pan} = A_{pan}$

$$\text{and} \quad P_{pan} = 10^{X} \tag{I-11}$$

$$\text{where} \quad X = -1 - \sum_{I=1}^{I=4} 0.025(M_I - M_{I-1}) \log(10^{(40(\log A_{pa} - \log A_{I-1})} + 1)$$

with $A_0 = 1$; other values of A_I were calculated in Algorithm H.

Without diversity improvement,

$$P_{mn} = F_{oan}\, 10^{-.1M_{pan}} \qquad \text{if} \quad M_{pan} > 15 \text{ dB}. \tag{I-12}$$

With diversity improvement,

$$P_{mn} = \frac{F_{oan}}{I}\, 10^{-.1M_{pan}} \qquad \text{if } M_{pan} > 15 \text{ dB}. \tag{I-13}$$

Calculation of vertical space diversity improvement, I_{os}, (with switch combining) is based on a model provided by Vigants (1975, pp. 110-112). If we let T_m be the time that the signal from the main antenna remains below a given signal level and if we let T_s be the simultaneous time that the signal from both antennas is below level, L, then I_{os} is defined as T_m/T_s. The Vigants (1975) expression for I_{os} is:

$$I_{os} = 0.001213\ f_c s_d^2\ D^{-1}\ 10^{0.1(G_{dr} - G_r + M_{pa})} \qquad \text{(I-14)}$$

where $s_d < 20$ m and $M_{pa} > 20$ dB.

For calculating frequency diversity improvement, I_{of}, we also use the model given in Vigants (1975):

$$I_{of} = 80.47\ |f_c - f_{dc}|\ f_c^{-2}\ D^{-1}\ 10^{0.1M_{pa}} \qquad \text{(I-15)}$$

where $|f_c - f_{dc}| < 0.5$ and $M_{pa} > 20$ dB.

The value of I_{ox}, as calculated for both space and frequency diversity is valid only if the diversity signal is at each instant the stronger of the two received signals. If switching only occurs when the off-line receiver has a signal level that exceeds the on-line receiver signal by some threshold power ratio, B, in dB, the actual diversity improvement is I where:

$$I = E_d I_{ox}. \qquad \text{(I-16)}$$

The efficiency factor, E_d, is given by:

$$E_d = 2/(\ 10^{B/10} + 10^{-B/10}\ ). \qquad \text{(I-17)}$$

For example, if B = 6 dB, then $E_d = 0.47$. Such threshold power ratios for switching are often built into combiner configurations to prevent excessive switching.

We may now select a number of probability values that represent the fraction of time that link C/N_r values are not exceeded. The probability values of interest are 0.5, 0.1, 0.01, 0.001, 0.0001, and 0.00001. Using these values and (I-1) through (I-16), corresponding values of C/N_r may be obtained. From these coordinate pairs, we apply curve fitting functions for calculating additional values of $C/N_r[P,Q]$ or $P[C/N_r,Q]$. C/N_r is given by the expression:

$$C/N_r = C/N_{mr} + \sum_{I=1}^{I=4} 0.1(m_I - m_{I-1})\log[10^{10(-\log P - I)} + 1] \qquad \text{(I-18)}$$

where $m_o = 0$

$m_1 = C/N_r[0.1] - C/N_r[0.5]$

$m_2 = C/N_r[0.01] - C/N_r[0.1]$

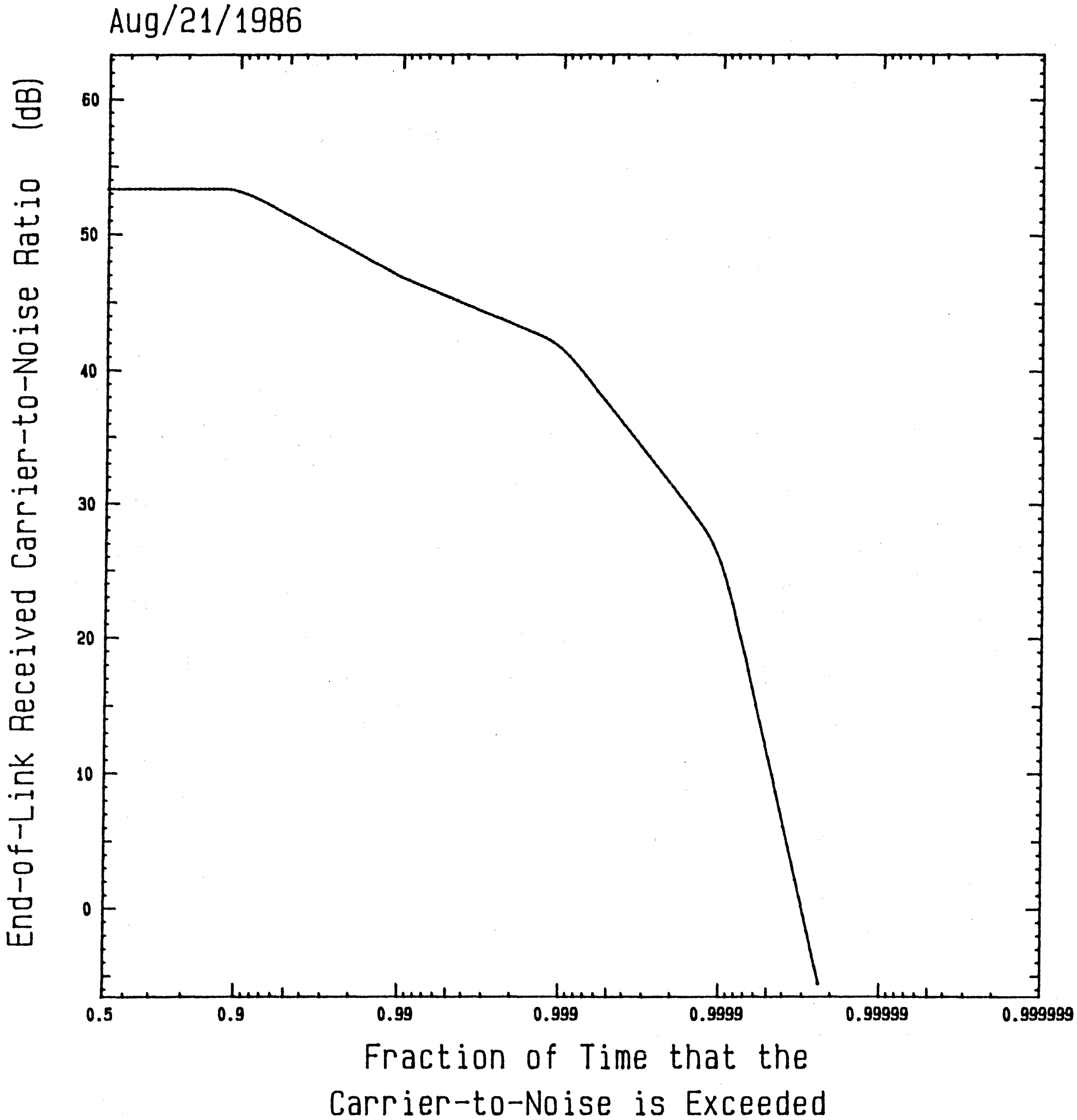
$m_3 = C/N_r[0.001] - C/N_r[0.01]$

$m_4 = C/N_r[0.0001] - C/N_r[0.001]$

$m_5 = C/N_r[0.00001] - C/N_r[0.0001]$.

10.2 Carrier-To-Noise Output Format

There are two output formats. The first one is a graph (Figure 22) of the link received carrier-to-noise ratio probability distribution. Note that the propability notation has been changed from "C/N that is not exceeded," as used in (I-1), to "C/N that is exceeded," as is used on graph scale. This change is made to give the availability value directly when performance threshold values from algorithms K and L are applied to this figure. The second output is a list of input and output parameters and their values (Table 13) that are used to calculate the C/N_r distribution.



Number of Paths in the Link		4
Rain Attenuation Confidence Band, Q		0.500
Median Received C/N at Heidelberg	dB	53.415

Link Received Carrier-to-Noise Distribution
Shanzerkopf to Heidelberg

Figure 22. Example of a link received carrier-to-noise probability distribution.

Table 13. Example Output of Carrier-to-Noise Ratio Data

Aug/21/1986

Carrier-to-Noise Probability Distribution Parameters
Shanzerkopf to Heidelberg

Path 1 Parameters - Shanzerkopf to Muhl

Path Length	(km)	53.693
Transmitter Antenna Type		Parabolic horn
Receiver Antenna Type		Single mirror
Transmitter Final Amplifier Type		Constant power
Primary Carrier Frequency	(GHz)	7.4000
Diversity Carrier Frequency	(GHz)	8.7000
Transmitter Antenna Gain	(dBi)	44.7377
Primary Receiver Antenna Gain	(dBi)	59.4506
Diversity Receiver Antenna Gain	(dBi)	
Site Loss on the Receiver End of the Path	(dB)	0.0000
Median Basic Transmission Loss Across the Path	(dB)	144.9600
Rain Attenuation for P=0.01	(dB)	0.4518
Rain Attenuation for P=0.001	(dB)	2.6670
Rain Attenuation for P=0.0001	(dB)	20.0562
Rain Attenuation for P=0.00001	(dB)	57.7263
Rain Radome Loss Due to Rain	(dB)	1.4800
Annual Multipath Fading Occurance Factor		0.0135
Diversity Type		Space
Vertical Diversity Spacing	(m)	0.000
Combiner Switching Threshold Power Ratio	(dB)	4.0000
Transmitter Feeder Line Length	(m)	20.0000
Transmitter Feeder Line Loss per 100 meters	(dB/100m)	10.0000
Transmitter Feeder Line Loss	(dB)	2.0000
Transmitter Diplexer Loss	(dB)	1.0000
Receiver Feeder Line Length	(m)	0.0000
Receiver Feeder Line Loss per 100 meters	(dB/100m)	0.0000
Receiver Feeder Line Loss	(dB)	0.0000
Receiver Diplexer Loss	(dB)	0.0000
Transmitter Final Amplifier Power Output	(dBm)	40.0000
Transmitter Power at the Antenna Terminals	(dBm)	37.0000
Receiver Noise Figure	(dB)	0.0000
Receiver Bandwidth	(MHz)	15.0000
Receiver Thermal Noise	(dBm)	-101.2391
Median Received Signal Level for the Path	(dBm)	-3.7716
Median Thermal C/N at the Receiver Output	(dB)	97.4674
Median C/N at the Transmitter	(dB)	60.0000
Median Path C/N at the Receiver Output	(dB)	59.9992

Table 13. Example Output of Carrier-to-Noise Ratio Data (Cont.)

Aug/21/1986

Carrier-to-Noise Probability Distribution Parameters (Continued)
Shanzerkopf to Heidelberg

Path 2 Parameters - Muhl to Baumholder

Path Length	(km)	21.940
Transmitter Antenna Type		Single mirror
Receiver Antenna Type		Double antenna
Transmitter Final Amplifier Type		Constant gain
Primary Carrier Frequency	(GHz)	7.4000
Diversity Carrier Frequency	(GHz)	8.7000
Transmitter Antenna Gain	(dBi)	59.4506
Primary Receiver Antenna Gain	(dBi)	44.7377
Diversity Receiver Antenna Gain	(dBi)	44.7377
Site Loss on the Receiver End of the Path	(dB)	0.0000
Median Basic Transmission Loss Across the Path	(dB)	136.8455
Rain Attenuation for P=0.01	(dB)	0.1846
Rain Attenuation for P=0.001	(dB)	1.0898
Rain Attenuation for P=0.0001	(dB)	11.4439
Rain Attenuation for P=0.00001	(dB)	29.2425
Rain Radome Loss Due to Rain	(dB)	1.4800
Annual Multipath Fading Occurance Factor		0.0009
Diversity Type		Space
Vertical Diversity Spacing	(m)	10.000
Combiner Switching Threshold Power Ratio	(dB)	4.0000
Transmitter Feeder Line Length	(m)	0.0000
Transmitter Feeder Line Loss per 100 meters	(dB/100m)	0.0000
Transmitter Feeder Line Loss	(dB)	0.0000
Transmitter Diplexer Loss	(dB)	0.0000
Receiver Feeder Line Length	(m)	15.0000
Receiver Feeder Line Loss per 100 meters	(dB/100m)	10.0000
Receiver Feeder Line Loss	(dB)	1.5000
Receiver Diplexer Loss	(dB)	1.0000
Transmitter Amplifier Gain	(dB)	0.0000
Transmitter Power at the Antenna Terminals	(dBm)	-3.7716
Receiver Noise Figure	(dB)	5.0000
Receiver Bandwidth	(MHz)	15.0000
Receiver Thermal Noise	(dBm)	-96.2391
Median Received Signal Level for the Path	(dBm)	-38.9288
Median Thermal C/N at the Receiver Output	(dB)	57.3103
Median C/N at the Transmitter	(dB)	59.9992
Median Path C/N at the Receiver Output	(dB)	55.4396

Table 13. Example Output of Carrier-to-Noise Ratio Data (Cont.)

Aug/21/1986

Carrier-to-Noise Probability Distribution Parameters (Continued)
Shanzerkopf to Heidelberg

Path 3 Parameters - Baumholder to Donnersberg

Path Length	(km)	42.915
Transmitter Antenna Type		Double antenna
Receiver Antenna Type		Double mirror
Transmitter Final Amplifier Type		Constant power
Primary Carrier Frequency	(GHz)	7.4000
Diversity Carrier Frequency	(GHz)	8.7000
Transmitter Antenna Gain	(dBi)	44.7377
Primary Receiver Antenna Gain	(dBi)	60.5401
Diversity Receiver Antenna Gain	(dBi)	
Site Loss on the Receiver End of the Path	(dB)	0.0000
Median Basic Transmission Loss Across the Path	(dB)	142.8554
Rain Attenuation for P=0.01	(dB)	0.3611
Rain Attenuation for P=0.001	(dB)	2.1316
Rain Attenuation for P=0.0001	(dB)	16.0303
Rain Attenuation for P=0.00001	(dB)	46.1389
Rain Radome Loss Due to Rain	(dB)	1.4800
Annual Multipath Fading Occurance Factor		0.0078
Diversity Type		None
Vertical Diversity Spacing	(m)	42.915
Combiner Switching Threshold Power Ratio	(dB)	4.0000
Transmitter Feeder Line Length	(m)	15.0000
Transmitter Feeder Line Loss per 100 meters	(dB/100m)	10.0000
Transmitter Feeder Line Loss	(dB)	1.5000
Transmitter Diplexer Loss	(dB)	1.0000
Receiver Feeder Line Length	(m)	0.0000
Receiver Feeder Line Loss per 100 meters	(dB/100m)	0.0000
Receiver Feeder Line Loss	(dB)	0.0000
Receiver Diplexer Loss	(dB)	0.0000
Transmitter Final Amplifier Power Output	(dBm)	43.0000
Transmitter Power at the Antenna Terminals	(dBm)	40.5000
Receiver Noise Figure	(dB)	0.0000
Receiver Bandwidth	(MHz)	15.0000
Receiver Thermal Noise	(dBm)	-101.2391
Median Received Signal Level for the Path	(dBm)	2.9224
Median Thermal C/N at the Receiver Output	(dB)	104.1614
Median C/N at the Transmitter	(dB)	55.4396
Median Path C/N at the Receiver Output	(dB)	55.43[illegible]5

Table 13. Example Output of Carrier-to-Noise Ratio Data (Cont.)

Aug/21/86

Carrier-to-Noise Probability Distribution Parameters (Continued)
Shanzerkopf to Heidelberg

Path 4 Parameters - Donnersberg to Heidelberg

Path Length	(km)	61.388
Transmitter Antenna Type		Double mirror
Receiver Antenna Type		Periscope
Transmitter Final Amplifier Type		Constant power
Primary Carrier Frequency	(GHz)	7.4000
Diversity Carrier Frequency	(GHz)	8.7000
Transmitter Antenna Gain	(dBi)	60.5401
Primary Receiver Antenna Gain	(dBi)	44.7377
Diversity Receiver Antenna Gain	(dBi)	
Median Basic Transmission Loss Across the Path	(dB)	146.2362
Rain Attenuation for P=0.01	(dB)	0.5254
Rain Attenuation for P=0.001	(dB)	3.0282
Rain Attenuation for P=0.0001	(dB)	22.7133
Rain Attenuation for P=0.00001	(dB)	65.7379
Rain Radome Loss Due to Rain	(dB)	1.4800
Annual Multipath Fading Occurance Factor		0.0239
Diversity Type		Space
Vertical Diversity Spacing	(m)	10.000
Combiner Switching Threshold Power Ratio	(dB)	4.0000
Transmitter Feeder Line Length	(m)	0.0000
Transmitter Feeder Line Loss per 100 meters	(dB/100m)	0.0000
Transmitter Feeder Line Loss	(dB)	0.0000
Transmitter Diplexer Loss	(dB)	0.0000
Receiver Feeder Line Length	(m)	15.0000
Receiver Feeder Line Loss per 100 meters	(dB/100m)	10.0000
Receiver Feeder Line Loss	(dB)	1.5000
Receiver Diplexer Loss	(dB)	1.0000
Transmitter Final Amplifier Power Output	(dBm)	0.0000
Transmitter Power at the Antenna Terminals	(dBm)	2.9224
Receiver Noise Figure	(dB)	3.0000
Receiver Bandwidth	(MHz)	15.0000
Receiver Thermal Noise	(dBm)	-98.2391
Median Received Signal Level for the Path	(dBm)	-40.5361
Median Thermal C/N at the Receiver Output	(dB)	57.7030
Median C/N at the Transmitter	(dB)	55.4396
Median Path C/N at the Receiver Output	(dB)	53.4152

11. ALGORITHM J: ANALOG RADIO SYSTEM SINGLE-RECEIVER TRANSFER CHARACTERISTIC

This algorithm is designed to calculate the response of the radio system to radio path distortion and received signal carrier-to-noise ratio (C/N). The calculation of this response is basically different for frequency modulation, frequency-division multiplex (FM/FDM) systems than it is for digital, time-division multiplex (TDM) systems. The FM/FDM system will be considered in this algorithm.

The quality of the FM/FDM system is evaluated in terms of the signal-to-noise ratio in the worst voice channel (usually the highest baseband channel). The calculations and algorithm outputs are obtained as follows:

1) input link and equipment parameters
2) calculate noise components
3) add the noise components and calculate the worst voice channel (highest in the baseband) signal-to-noise ratio (S/N)
4) tabulate the parameters and plot the transfer characteristic.

11.1 Noise Sources

In general, the noise types are <u>thermal</u> noise (due to the receiver front end and loss of rf energy in traversing the path), <u>echo</u> noise (which arises because the echo-delayed signals resemble modulated, interfering carriers of the same frequency caused by transmission line impedance mismatches), and <u>nonlinear</u> noise (due to modulator and demodulator nonlinearities and radio path frequency-selective fading and multipath effects). The units for noise in the voice channel are pW0, picowatts of noise that are measured at a zero dBm test tone level point in the channel.

The most significant parameter influencing radio link design is the voice channel signal-to-noise ratio, S/N. It is defined as 10 times the common logarithm of the ratio of an RMS single-tone signal power (usually 1000 Hz at such a level that the sine-wave voltage peaks are roughly equal to the voltage peaks in a signal developed by a telephone talker) to average noise power in a 300 to 3400 Hz bandwidth (over a period of several milliseconds).

In a wideband communication system in which many voice channels are frequency-division multiplexed into a baseband signal that extends over a large spectrum, it is necessary to be able to analyze the performance of any voice channel in the band. However, only the channel occupying the highest frequency position in the baseband is usually analyzed since its quality is expected to be the poorest of the channels because of its lower modulation index, even with preemphasis.

Because there is higher noise power in the upper voice channels of a radio-relay system than in the lower channels, compensation for this effect, called pre-emphasis, is applied in most radio-relay systems. This means that before frequency modulation is done, the level of the lower frequencies is decreased. This is done in such a way that the mean power of the baseband signal is the same with or without pre-emphasis. On these assumptions, the CCIR has standardized the frequency characteristic of the preemphasis, which is a common characteristic for all types of broadband systems (Recommendation 275-2). Between the lowest and the highest voice channel, the pre-emphasis (i.e., the difference in level) is 8 dB.

11.2 Thermal Noise Calculation

For all purposes of system noise calculations, thermal noise is defined as noise from all sources in a channel when there is no modulated signal present on any of the channels in the microwave system. By this definition, thermal noise includes atmospheric and cosmic noise, and all intrinsic and thermal noise produced in the equipment when no modulation is present. Thermal noise is measured in a channel with all modulation removed from all channels of the system.

The signal-to-thermal noise ratio in an FDM-FM system is related to path-loss variability. As the path loss on a link becomes low, i.e., the received signal level becomes high, the thermal noise in a voice channel is relatively quite low. As received signal level decreases toward FM threshold, the thermal noise becomes higher. Signal-to-thermal noise ratio, S/N_t, in a voice channel is proportional to received signal level, P_r, or carrier-to-noise ratio, C/N. In the region above FM threshold, S/N_t may be expressed in several forms (Dept. of Defense, 1977b, p. 4-334):

$$S/N_t = P_r + 20 \log \frac{\delta f}{f_m} - 10 \log (kTb_c \times 10^3) - F + I_E \qquad \text{(J-1)}$$

$$S/N_t = P_r + 20 \log \frac{\Delta F}{f_m} - PF - LF + 10 \log (kTb_c \times 10^3) - F + I_E \qquad \text{(J-2)}$$

$$S/N_t = C/N + 20 \log \frac{\Delta F}{f_m} - PF - LF + 10 \log \frac{B_{IF}}{b_c} + I_E \qquad \text{(J-3)}$$

$$S/N_t = C/N + 20 \log \frac{\delta f}{f_m} + 10 \log \frac{B_{IF}}{b_c} + I_E \qquad \text{(J-4)}$$

$$B_{IF} = 2\ (\Delta F + f_m) \qquad \text{(J-5)}$$

$$\Delta F = (\delta f)\ (\text{antilog} \frac{PF}{20})\ (\text{antilog} \frac{LF}{20}) \text{ in kHz} \qquad \text{(J-6)}$$

$$LF = -10 + 10 \log n, \text{ in dB} \qquad \text{(J-7)}$$

ΔF is the peak carrier deviation in kHz

δf is the rms per channel deviation in kHz

S/N_t is the voice-channel-signal-to-thermal-noise ratio in dB

P_r is the received carrier level in dBm

C/N is the predetection carrier-to-noise ratio in dB and N is the receiver front-end thermal noise power in the same units as P_r

PF is the baseband signal peak factor (13.5 dB)

LF is the RMS noise load factor in dB

b_c is the usable voice channel bandwidth taken to be 3.100 kHz

B_{IF} is the receiver IF bandwidth in kHz

f_m is the highest modulating frequency in the baseband in kHz

F is the receiver noise figure in dB

k is Boltzman's constant, 1.3804×10^{-20} milliJoules/degree K

T is the antenna temperature taken to be 290 K

n is the number of voice channels in the baseband

I_E is the emphasis improvement (4 dB with emphasis and 0 without).

The value of P_r at which thermal noise threshold, $P_r(TH)$, occurs is given by the equation:

$$P_r(TH) = 10 \log (kTB_{IF} \times 10^3) + F \qquad (J\text{-}8)$$

The value of P_r at which FM threshold occurs, $P_r(FMTH)$ is:

$$P_r(FMTH) = K_T + P_r(TH) \qquad (J\text{-}9)$$

where K_T = 10 without threshold and K_T = 3 with threshold extension. The terms of the right-hand side of (J-1) and (J-2), with the exception of P_r, may be calculated for a given set of equipment parameters. This, then, becomes a constant (a figure of merit) and as P_r is allowed to vary, the voice channel signal-to-thermal-noise ratio varies in proportion. Using this information, a receiver thermal noise transfer characteristic or "quieting curve" may be constructed, where its slope is uniquely determined by any of the above equations for conditions above FM threshold.

11.3 Equipment Intermodulation Noise Calculation

For the purpose of system noise calculations, equipment intermodulation noise is defined as the total noise from all sources produced as a result of the presence of a modulated signal except feeder echo noise. Intermodulation noise is measured in a channel with all modulation removed from the channel being measured, and with all remaining channels loaded with actual traffic or with an equivalent amount of white (randomly distributed) noise over a specific bandwidth. The intermodulation noise power in the channel is then equal to the measured total noise with modulation present, less the measured thermal noise with no modulation present.

Values of noise-power ratio (NPR) in the channel having the worst signal-to-noise ratio must be obtained from either equipment performance specifications or carefully controlled tests. The specific loading conditions, and received signal level (RSL) must be known for each NPR value. Of particular importance is the NPR value corresponding to the optimum RSL for a particular microwave radio. If information is not available, an NPR value of 55 dB (obtainable using new, quality equipment) is probably the highest value that can be assumed for the initial estimate. A pre-emphasis improvement of 4 dB in the worst channel is usually assumed to be included in this NPR value.

The noise-power ratio can now be converted to an equivalent noise channel signal-to-equipment intermodulation noise ratio, S/N_e, and additionally to equipment intermodulation noise, N_e:

$$S/N_e = NPR + 10 \log (B_b/b_c) - LF \quad dB \tag{J-10}$$

$$N_e = \text{antilog} \frac{90 - S/N_e}{10} \quad pWO \tag{J-11}$$

$$B_b = f_m - f_l \tag{J-12}$$

where f_m = the upper baseband frequency (kHz)
f_l = the lower baseband frequency (kHz)
b_c = the nominal voice channel bandwidth, 3.100 kHz
LF = the RMS load factor in dB (see Eq. J-7).

In these noise calculations, flat-weighted noise will be used for ease in handling. If the designer desires to use other noise weightings, appropriate factors may be included at the conclusion of the design procedure.

11.4 Feeder Intermodulation Noise Calculation

If a transmission line many wavelengths long is mismatched at both the generator and load ends, its frequency-phase response is linear with a small sinusoidal ripple, and this leads to reflected waves in the line that cause distortion of an FM signal. This type of distortion is more conveniently considered as being caused by an echo signal generated in a mismatched line, which results in intermodulation distortion. Significant levels of this type of intermodulation noise are reached when the waveguide lengths exceed approximately 20 meters per individual antenna, or 30 meters total per hop (Dept. of Defense, 1977b, p. 4-284).

The feeder intermodulation noise is also considered to be independent of path loss or signal level variations and is therefore another component of the time-invariant nonlinear noise power.

Feeder intermodulation noise, N_f, may be approximated given transmission line lengths, velocity of propagation in the lines, transmission system component VSWR's or return losses, transmission line losses, and directional losses. The calculations are performed separately for each end of a link; i.e., transmitter and receiver, and the results are summed to determine the total hop contribution.

To calculate N_f in the worst channel, the echo delay time is first calculated. Determine echo delay time, τ, from the transmission line length, L, and the percent velocity of propagation, (% v), obtained from Figure 23 using:

$$\tau = 2L/V \text{ s}, \quad \text{where } V = (3 \times 10^8)(\% \text{ v} \times 10^{-2}) \text{ m/s} \qquad \text{(J-13)}$$

Reasonable default values for V are:

$V = 0.65\ (3 \times 10^8)$ for elliptical waveguide and

$V = 0.75\ (3 \times 10^8)$ for rectangular waveguide.

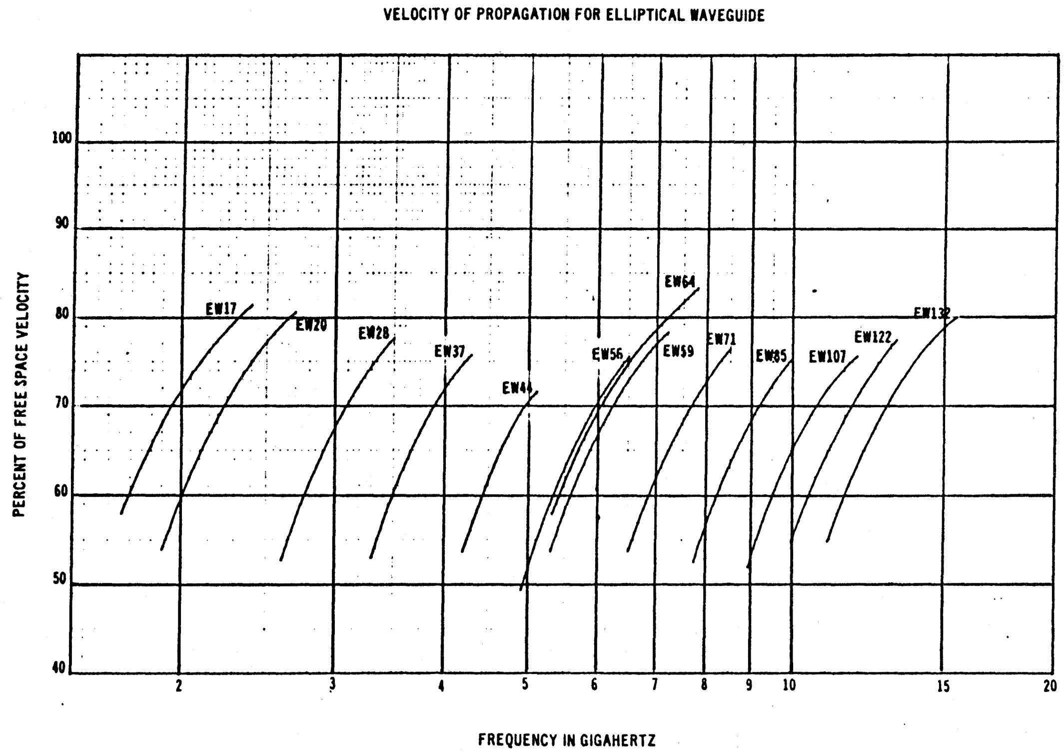
The echo delay time is then converted to radian delay, θ_o:

$$\theta_o = 2\pi f_m \tau \times 10^3 \qquad \text{(J-14)}$$

where f_m is the highest modulating frequency in the baseband. The echo power, r, relative to the signal power causing it is given by the expression:

$$r = RL_e + RL_a + 2A_{tl} \quad \text{(Dept. of Defense, 1977a, pp. 4-286, 4-389)} \qquad \text{(J-15)}$$

Courtesy of Dr. John Osepchuk (MIL-HDBK-416, 1977).



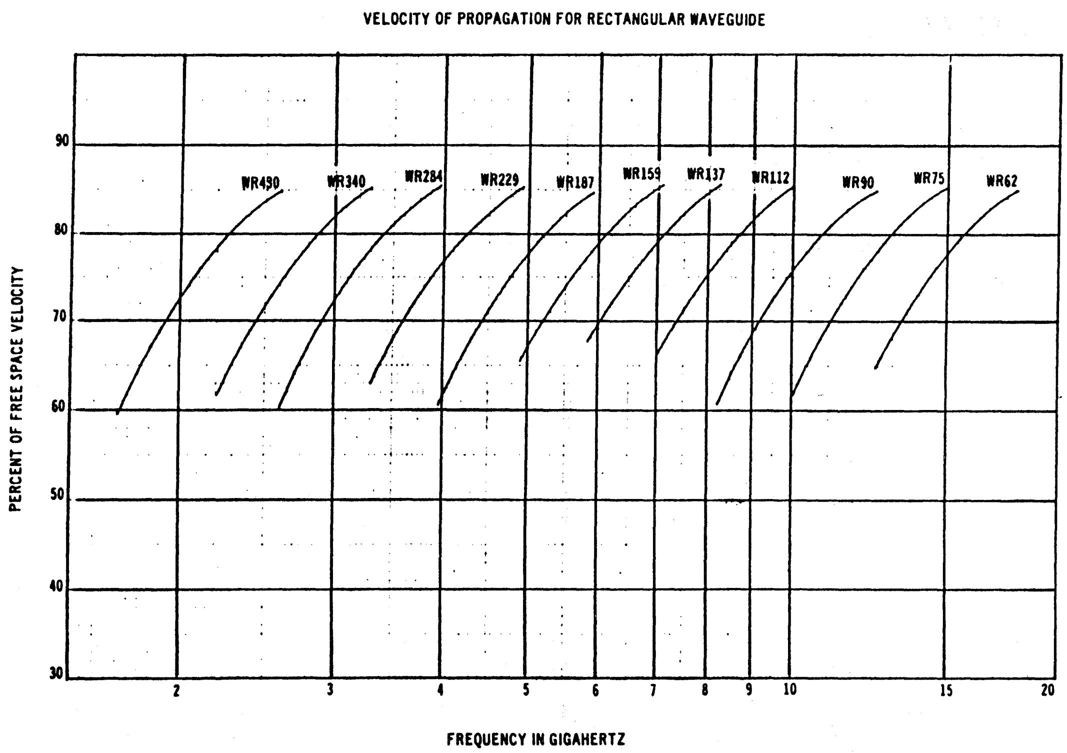


Figure 23. Waveguide velocity curves.

where r = the number of dB that the echo is down from the signal power

A_{tl} = the transmission line loss in dB

RL_e = the return loss (dB) at the interface between the transmission line and either the transmitter or receiver (whichever case is applicable)

RL_a = the return loss (dB) at the interface between the transmission line and the antenna.

This model assumes that all discontinuities are negligible with respect to the ones at these interfaces in the intermediate section of the transmission line between the transmitter or receiver and the antenna.

If parameters other than return loss are provided, such as the VSWR or the voltage reflection coefficient, ρ, they can be converted to return loss, RL, using the following expressions:

$$\rho = \frac{VSWR - 1}{VSWR + 1} \qquad \text{(J-16)}$$

$$RL = 20 \log (1/\rho) \qquad \text{(J-17)}$$

The power in the echo cannot totally be considered as distortion power, D, unless the echo delay is large. To obtain the value of S/D, a "Parameter A" must be determined:

$$A = \frac{\delta F}{f_m} \times 10^{(LF/20)} \qquad \text{(J-18)}$$

or alternatively,

$$A = \frac{\delta f}{f_m} (0.1\ n)^{1/2} \qquad \text{(J-19)}$$

The variables in the equations for A have been defined earlier in this section. See (J-7) to calculate LF.

Using parameter A and θ_o, (S/D - r) can now be obtained from Figure 24. A good approximation (Hause and Wortendyke, 1979, p. 68) for (S/D - r) can be obtained from the equations:

$$F_1(A,\theta_o) = 7.17 - 8.23 \ln A + 40 \log (1/\theta_o) \quad \text{(J-20)}$$

$$F_2(A) = 9.421 - 54.84A + 113.2A^2 - 88.5A^3 + 31.52A^4 - 4.239A^5 \quad \text{(J-21)}$$

where (S/D - r) equals the greater of F_1 and F_2.

The calculation of echo attenuation (separately for transmitter and receiver) outlined above can now be converted to voice channel noise. To do this, the total echo attenuation, r, is added to the (S/D - r) value obtained from Figure 24. This addition results in the signal-to-distortion ratio, S/D, which must be corrected for the ratio of baseband to voice channel bandwidth and for the RMS load factor. In equation form, the voice channel signal to feeder echo noise ratio becomes:

$$S/N_f = S/D + 10 \log (B_b/b_c) - LF + I_E. \quad \text{(J-22)}$$

The conversion to flat-weighted noise is as follows:

$$N_f = \text{antilog} \frac{90 - S/N_f}{10} \quad \text{pWO.} \quad \text{(J-23)}$$

The foregoing feeder echo noise calculations are performed separately for each end of a hop by arbitrarily designating one end the transmitter and the other end the receiver. At the conclusion, these two noise results are summed together to give a total link feeder echo noise contribution.

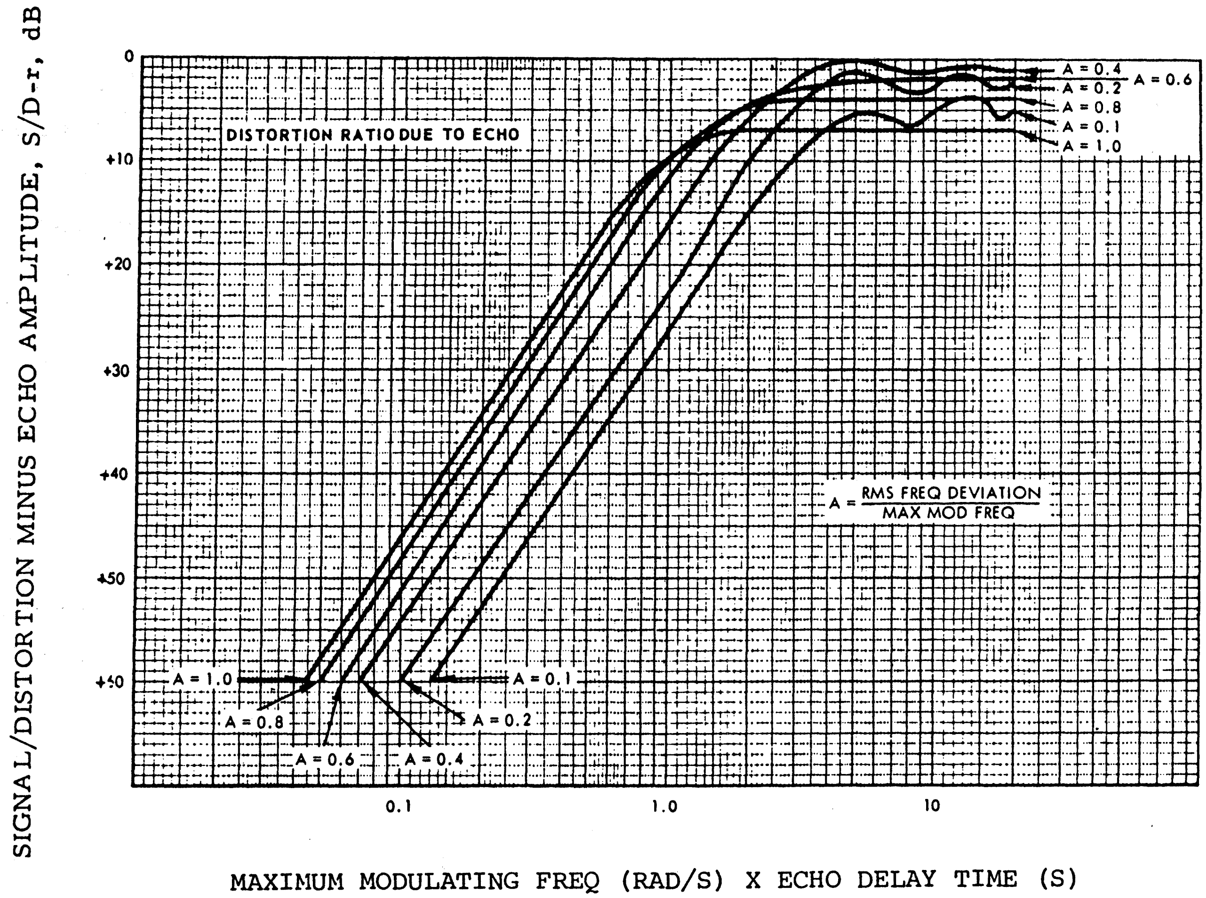


Figure 24. Maximum distortion-to-signal ratio due to echo.

The sum of the total feeder echo noise and equipment intermodulation noise in this design will be called the time-invariant nonlinear noise, since these noise components do not depend upon path loss variablility. This total noise component is normally the dominant contribution for relatively high signal levels near the long-term median.

11.5 Radio System Transfer Characteristic for FM/FDM Links

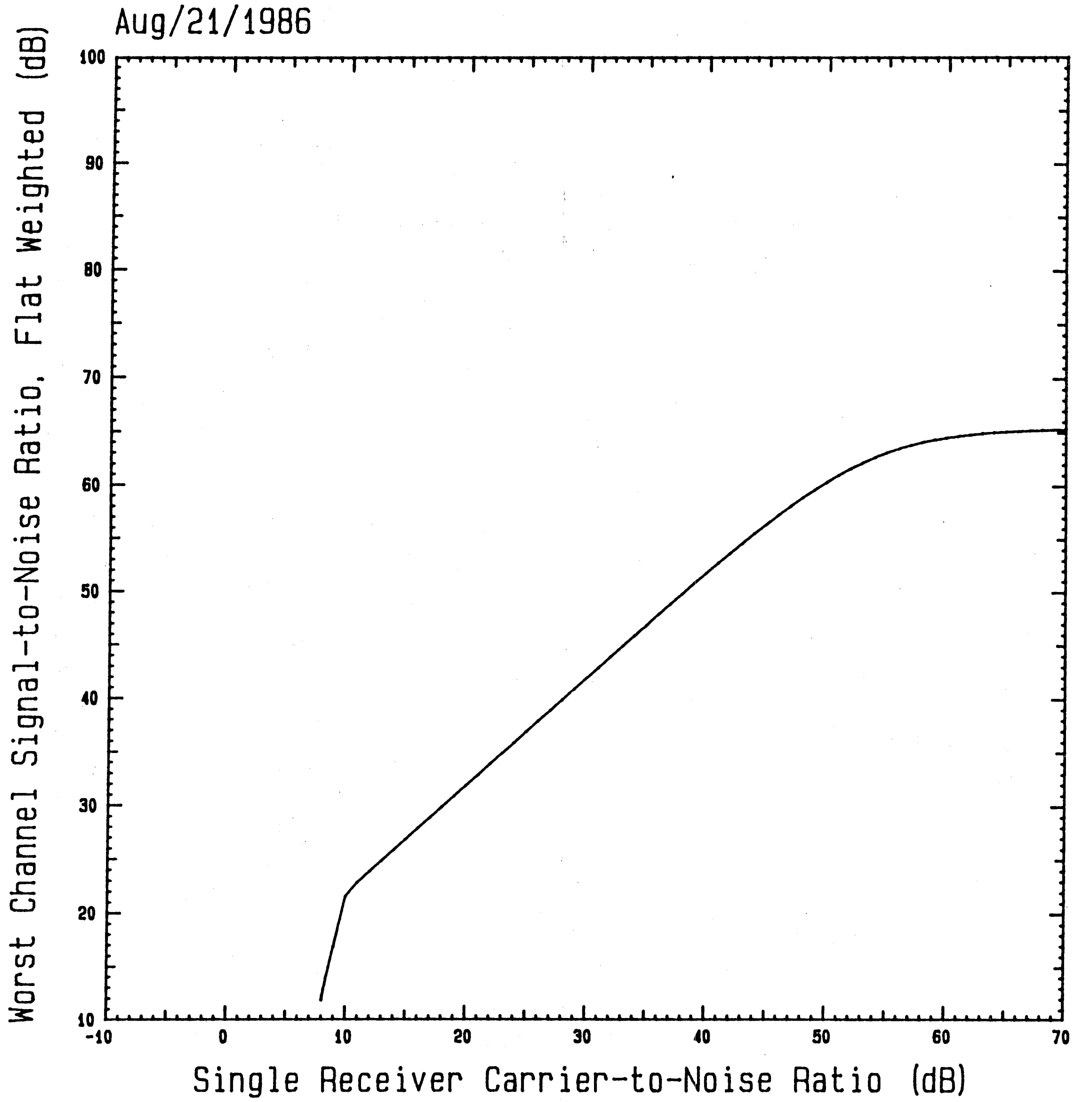
The transfer characteristic is a function showing how the total noise or signal-to-noise ratio (in the highest baseband frequency voice channel) varies with receiver C/N in decibels. The transfer function may also be written in terms of received signal level, P_r, since P_r in dBm is given by the expression:

$$P_r = C/N - 114 + 10 \log B_{IF} + F \qquad \text{(J-24)}$$

where B_{IF} is in MHz. The three types of noise previously described (thermal, feeder echo, and equipment) are added to obtain the total noise at each C/N value down to FM threshold. Performance below the FM improvement threshold can be approximated by a line with a slope of 4 (4 dB decrease in signal-to-noise ratio for each dB decrease in received signal level). These considerations result in the following expression for the transfer characteristic:

$$S/N_{TOT} = -10 \log [10^{-0.1S/N_t} + 10^{-0.1S/N_e} + 10^{-0.1S/N_f}] - \log [10^{4(-C/N + K_T)} + 1] \qquad \text{(J-25)}$$

A sample output of this algorithm is plotted on Figure 25. By finding appropriate intersections of this equation and the C/N distributions, quantitative values of performance are obtained in Algorithm K. Table 14 is an example output tabulation of parameter values used to calculate the transfer function.



Carrier Frequency	GHz	7.40
Per Channel Deviation	kHz	140.00
Median Carrier-to-Noise	dB	53.42
Equipment NPR	dB	55.00
Transmitter Feeder Echo S/N	dB	77.32
Receiver Feeder Echo S/N	dB	76.32
Receiver Noise Figure	dB	3.00
Number of Voice Channels		600
Highest Modulation Frequency	kHz	2460.00
IF Bandwidth	kHz	15182.04

FM/FDM Equipment Transfer Characteristic
Shanzerkopf to Heidelberg Link

Figure 25. Example FM/FDM single receiver transfer characteristic.

Table 14. Example FM/FDM Single Receiver Transfer Characteristic Data

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FM/FDM Single Receiver Transfer Characteristic Parameters
Shanzerkopf to Heidelberg

		Transmitter	Receiver
Transmission Line Length	(Meters)	20.0	15.0
Total Line Loss	(dB)	2.0	1.5
Feeder Velocity Ratio	(Percent)	65.00	65.00
VSWR at Antenna		1.06	1.06
VSWR at Radio		1.06	1.06
Return Loss at Antenna	(dB)	30.71	30.71
Return Loss at Radio	(dB)	30.71	30.71
Echo Delay Time (tau)	(micro s)	0.21	0.15
Echo Velocity (V)	(m/mic s)	195.00	195.00
Angle Delay	(Radians)	3.17	2.38
Signal-to-Echo Ratio (r)	(dB)	65.43	64.43
Parameter A		0.44	0.44
(S/D)-r	(dB)	0.78	0.78
S/D	(dB)	66.21	65.21
Feeder Echo Signal-to-Noise	(dB)	77.32	76.32

Long-Term Median Carrier-to-Noise	(dB)	53.42
Receiver Noise Figure	(dB)	3.0
Receiver IF Bandwidth	(kHz)	15182.0
Emphasis Improvement	(dB)	4.0
Number of Voice Channels		600.0
Voice Channel Bandwidth	(kHz)	3.1
Equipment NPR	(dB)	55.0
Peak Carrier Deviation	(kHz)	5131.0
RMS Per Channel Deviation	(kHz)	140.0
Threshold Extention		No
FM Threshold [P(FMTH)]	(dBm)	-89.0
P(FMTH)-P(TH)	(dBm)	10.0
Thermal Noise Threshold [P(TH)]	(dBm)	-99.0
Baseband Signal Peak Factor		13.5
RMS Noise Loading Factor		17.8
Equipment Noise S/N	(dB)	66.1
Highest Modulating Frequency in BB	(kHz)	2460.0
Lowest Modulating Frequency in BB	(kHz)	60.0
Baseband Bandwidth	(kHz)	2400.0
Thermal S/N-C/N	(dB)	12.0

12. ALGORITHM K: FM/FDM LINK PERFORMANCE

The purpose of the analog link performance algorithm is to calculate the reliability and quality of a line-of-sight repeater link. Performance must be evaluated for both long-term and short-term services. For analog systems, long-term service quality is primarily a function of equipment quality and median signal level.

Noise calculations for analog systems have not changed significantly in the past several years, and the model presented here is much the same as the one used in MIL-HDBK-416 (Dept. of Defense, 1977a).

To obtain an overall summary tabulation having link performance compared to applicable standards, the following steps are necessary:

1) Calculate standards requirements for FM/FDM links.
2) Calculate the FM/FDM link, worst-channel receiver transfer characteristic (signal-to-noise ratio, S/N, as a function of received carrier-to-noise ratio, C/N). Thermal noise, equipment intermodulation distortion and feeder echo distortion must be calculated first to obtain the receiver transfer characteristic.
3) Calculate the outage time at the minimum allowable, short-term, signal quality values from the receiver transfer characteristic (calculated in Algorithm J) with fraction of time values from the C/N time distribution (calculated in Algorithm I) using C/N as the comparison parameter.
4) Tabulate input variables, results from Steps 1, 2 and 3, and other important information about the link.

Each of these steps will be discussed in the order shown above.

12.1 Noise Limit Requirements for FM/FDM Links

Defense Communication System (DCS) standards for the design of FM/FDM links are provided in MIL-STD-188-313, 19 December 1973. Excerpts from MIL-STD-188-313 are as follows:

4.1.2 <u>Subsystem Design and Engineering Standards.</u> The following standards are applicable to subsystem design, equipment performance, and subsystem performance of LOS Radio Transmission Subsystems of the

Defense Communications System. These apportioned performance parameters meet the minimum requirements for the Reference Section described in 4.1.1 and in MIL-STD-188-100; 333 nmi (nominal 600 km) Reference Transmission Line Section.

4.1.2.1 Subsystem Design Considerations. Overall subsystem design standards are not to be confused with equipment standards or specifications, or system performance standards. Some of the parameters used by the system designer cannot be conveniently tested in actual practice but are generally accepted parts of a model and necessary for determining the system configuration. Overall subsystem design includes consideration of the FM modulating-demodulating equipment, the radio equipment, antennas and the transmission media and required subsystem availability.

4.1.2.1.1 Total Channel Noise. Tradeoffs in noise allocation from all sources may be made, provided the total noise of the worst real channel in each single hop being designed meets the worst hour median requirements over the reference section as stated in 4.1.1.2.6.

Diversity improvement, while not a noise source, must be considered in the time distribution of system noise performance and time duration that the system noise objectives are met or exceeded.

4.1.2.1.1.1 Long-term Median Noise. The total long-term median noise from all sources in any nominal 4 kHz channel shall not exceed 1110 pWpO over the reference circuit.

The noise allowed in real sections shall be based upon the actual length (L) in nautical miles as follows:

Section Length (L)	Allowable Noise
L < 27 nmi	150 pWpO
27 < L > 151 nmi	2.76 L pWpO + 85.5 pWpO
L > 151 nmi	3.33 L pWpO

4.1.2.1.1.2 Short-term Mean Noise. The short-term mean noise power, with an integration time of 5 ms, occurring on any referenced 4 kHz channel, shall not exceed 316,000 pWpO for more than an accumulated 2 minutes in any month or more than 1 minute in any hour over any hop in a real section. Short-term noise due to propagation characteristics shall be determined on the basis of measured or statistical data appropriate to the geographical region under consideration. (End of excerpts)

12.2 Long-Term Performance

Section 4.1.2.1.1.1 allocates approximately 3.33 pWpO/km of long-term median noise (in the worst channel) caused by interference, radio equipment and propagation. This value translates to approximately 3.2 pWO/km (flat weighting). To provide a design objective, this value was selected as a parameter for analog link quality comparison. The 3.2 pWO/km value seems to be consistent with CCIR and industry standards for high-performance links. Most of this noise allocation is assigned to equipment noise since thermal noise is a small component at the median signal level. Median path length in terrestrial LOS microwave systems is approximately 35 km. Because of equipment noise predominance and the 35 km average distance, we can allocate 112 pWO of noise in the worst channel, for links less than 35 km long. For a specific combination of paths, a link noise allowance may be calculated as follows:

$$P_{NA} = 3.2\ (d_1 + d_2 + \cdots + d_i + \cdots d_n) \qquad \text{(K-1)}$$

where P_{NA} is the noise allowance per link in pWO

d_i is a path length in km

n is the number of paths

$P_{NA} = 112$ pWO is the default value of noise allowance per link.

Noise values that we have been considering are the amounts of noise that would be measured at a terminal where the reference signal level is 1 mW. This consideration permits us to calculate the signal-to-noise (S/N) using the following expression:

$$S/N = 90 - 10 \log P_{NA} \qquad (K-2)$$

12.3 DCS Short-Term FM/FDM Noise Limits

Section 4.1.2.1.1.2 of MIL-STD-188-313 provides the limits on short-term mean noise which permits more than 316,000 pWpO in the worst channel for no more than an accumulated 2 minutes in any month. To use available propagation outage prediction algorithms, the limitation is interpreted to mean that more than 500,000 pWO (flat weighted) is permitted no more than an accumulated 10 minutes per year.

The 500,000 pWO is equivalent to a worst channel signal-to-noise ratio of 33 dB. An outage time of 10 minutes per year is equivalent to an average yearly availability of 0.99998 of the year. This availability is applicable to an average 35-km link and prorated in proportion to the length of the link.

12.4 Calculating Link Performance and Link Performance Allocation

Parameters for calculating the C/N time distribution function from Algorithm I are called into this algorithm. Parameters from Algorithm J for the single receiver, C/N transfer characteristic function are also called into the calculation. Using these two functions and the threshold S/N, 33 dB, we calculate the annual link availability. Using the long-term median C/N ratio, we calculate the median S/N in the worst channel.

From the total of path lengths in the link, the prorated values of allocated allowable worst channel noise and the allocated link availability are calculated.

12.5 FM/FDM Link Performance Output Format

The output of algorithm K lists the amounts of noise from various sources as well as the calculated and allocated link performance (Table 15).

Table 15. Example FM/FDM Link Performance Data

Aug/21/1986

FM/FDM Link Performance
Shanzerkopf to Heidelberg

Total Number of Paths in the Link		4
Total Length of the Link	(km)	179.9350
Heidelberg Median Received C/N	(dB)	-24.95
Threshold Carrier-to-Noise Ratio	(dB)	21.00
Feeder Echo Noise	(pWO)	41.889
Equipment Noise	(pWO)	245.077
Median Thermal Noise	(pWO)	287.163
Allocated Median Noise	(pWO)	575.792
Calculated Median Noise	(pWO)	574.128
Fade Margin	(dB)	32.42
Allocated Link Availability		0.999897
Calculated Link Availability		0.999922
Is the Performance Satisfactory?		Yes

13. ALGORITHM L: PCM/TDM LINK PERFORMANCE

The purpose of the digital link performance algorithm is to calculate the availability of a line-of-sight repeater link for a particular quality level. Performance must be evaluated for short-term services. For digital systems, long-term service quality is primarily a function of equipment quality. Received bit-error-rate is impractical to measure at the usual median signal levels. Two alternative methods are provided for predicting digital link performance. The first one is based on the requirements of draft MIL-STD 188-323 dated November 14, 1984. The second method is based on requirements described by Kirk and Osterholz (1976). Some of the analysis is common to both methods and this part of the analysis is described next.

The algorithms used for calculating availability use a single receiver transfer function, which is the bit-error-ratio (BER) as a function of received carrier-to-noise ratio, which is accurately represented by the complementary error function. This transfer characteristic is valid for conditions where the received signal is not significantly distorted by multipath fading. Such an assumption is not good for data rates greater than 25 Mbps and may not be adequate for lesser rates for certain modulation schemes.

To obtain an overall summary tabulation having link performance compared to applicable standards, the following steps are necessary:

1. Calculate standards requirements for PCM/TDM links.

2. Calculate the PCM/TDM single receiver transfer characteristic bit-error-ratio as a function of received carrier-to-noise ratio, C/N.

3. Calculate the outage time at the minimum allowable, short-term, BER value using the receiver transfer characteristic (calculated using Equation L-1) and the fraction of time values from the C/N time distribution (calculated in Algorithm I) using C/N as the comparison parameter.

4. Tabulate input variables, results from Steps 1, 2 and 3, and other important information about the link.

13.1 Single Receiver Transfer Characteristic for Digital Systems

For the purpose of link design, the receiver transfer characteristic does not include effects of error control coding on the user's BER. The function that serves as the transfer characteristic for low data rate (25 Mb/s and less) systems is the complementary error function. To select the proper curve, one point on the function is required. This value is usually given in the radio manufacturer's specification and it is called the bit-error-ratio, BER, threshold. Although the BER threshold will change for various types of digital receivers, the shape of the transfer characteristic will generally remain the same in the presence of Gaussian noise (Bell Telephone Laboratories,1970, p. 629). The equation (in terms of C/N in dB) for the receiver transfer characteristic is:

$$\mathrm{BER} = 0.5 \ \mathrm{erfc}\ (k \times 10^{0.05C/N}) \qquad \text{(L-1)}$$

where k is determined from the BER threshold using a successive approximation method. Figure 26 is an example of a digital receiver transfer characteristic. An approximation of the complementery error function is given in Abramowitz and Stegun (1964, p. 299) as follows:

$$\mathrm{erfc}\ x = 1 - \mathrm{erf}\ x \qquad \text{(L-2)}$$

$$\mathrm{erf}\ x = 1 - (a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4 + a_5 t^5) e^{-x^2} + e(x),$$

$$t = 1/(1 + px)$$

$$|e(x)| <= 1.5 \times 10^{-7}$$

where $p = .3275911$

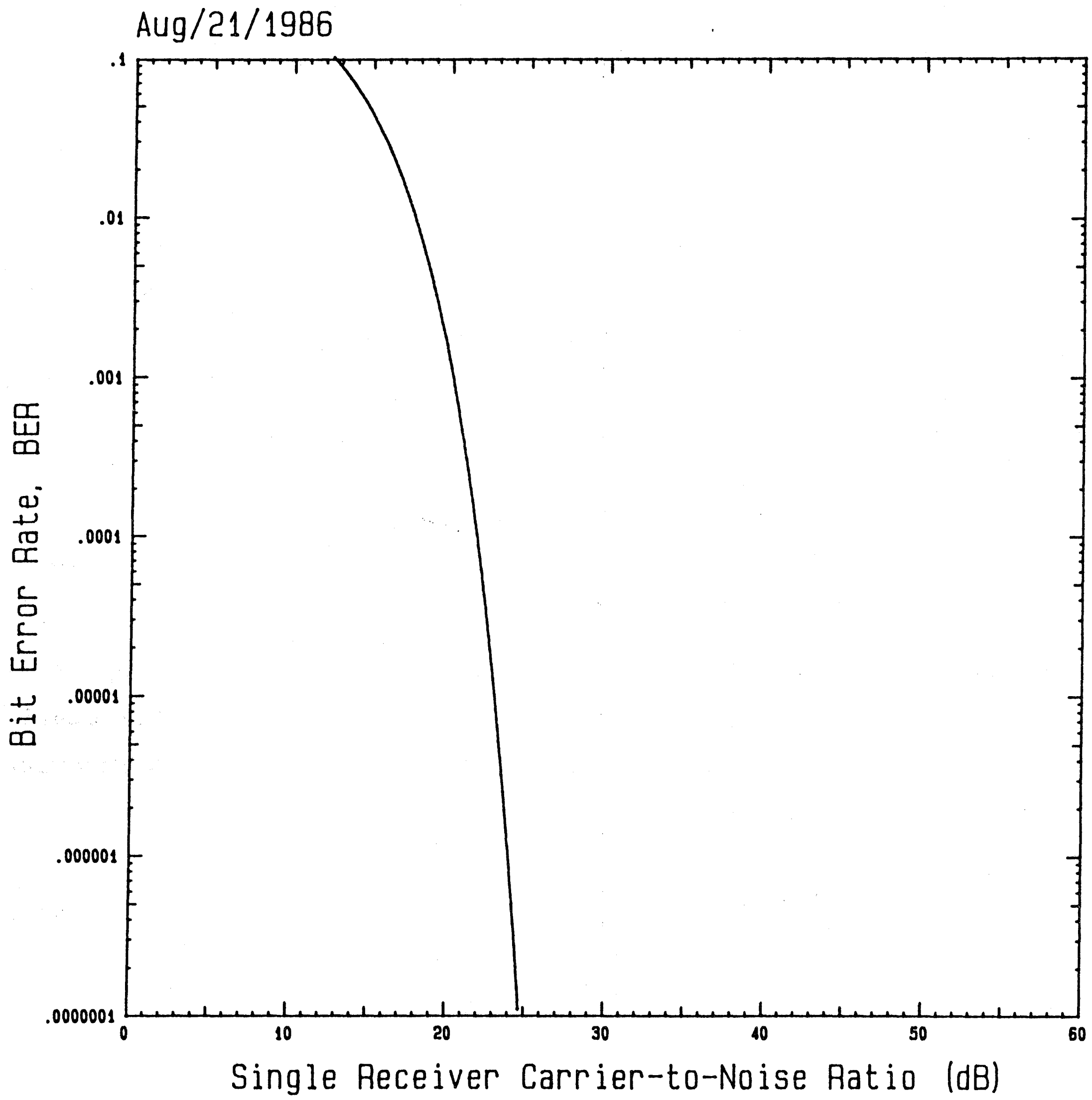
$a_1 = .254829592$

$a_2 = -.284496736$

$a_3 = 1.421413741$

$a_4 = -1.453152027$

$a_5 = 1.061405429.$



Data Transmission Rate	Mb/s	12.50
Modulation Type		Yes

PCM-TDM Single Receiver
Transfer Characteristic for the Link
Shanzerkopf to Heidelberg

Figure 26. Example of a digital link single-receiver transfer characteristic.

13.2 Requirements for PCM/TDM Line-of-Sight Links from Draft MIL-STD-188-323

Defense Communication System (DCS) standards for the design of PCM/TDM are provided in MIL-STD-188-323, 12 November 1984 (Draft). An exerpt from draft MIL-STD-188-323 is as follows:

> 5.5.2.1 <u>LOS link error free second allocation.</u> The 40 km LOS link in the Global, Overseas and Intracontinental HRC's shall be designed to provide 0.9999975 error free second (EFS) performance, during periods of link availability and due to propagation effects only, at the 64 kb/s voice and data user port of the first level (PCM) multiplexer. This level of performance shall be achieved over any continuous 30-day interval during the worst propagation period of the year for the geographic location of the link. The following relationship gives the minimum EFS and maximum errored second (ES) performance criteria for a LOS link as a function of path length, D(km):
>
> $$EFS = 1 - 6.250 \times 10^{-8}/km \times D(km) \qquad (L\text{-}3)$$
>
> and $ES = 6.25 \times 10^{-8}/km \times D(km)$.
>
> 5.5.2.2 <u>LOS link availability.</u> The availability of the line-of-sight (LOS) link for voice and data users at the 64 kb/s interface point shall be at least 0.99965 (Algorithm D, para. 3.3). This availability is based on equipment failures only. [End of excerpt.]

We have assumed that the availability value, 0.99965, is allocated wholly to equipment failures and that the 0.9999975 probability applies wholly to propagation outage. For links in climates characterized by frequent thunderstorms where carrier frequencies greater than 5 GHz are used, most links will not meet the error-free-second, 0.9999975 probability criterion. In terms of the total length of the link, D_t, the allocated availability expression for a link is:

$$P_A = 1 - 6.250 \times 10^{-8} D_t. \quad \text{(L-4)}$$

13.3 Calculating Predicted Outage Time in Terms of Error-Free Seconds

For a 64,000 bps channel, the probability that an error will occur in each second is 0.5 if the rf channel BER is 1/64,000 or 1.56×10^{-5}. Because the errors in a radio channel tend to occur in bursts, we will assume that a period of errored seconds starts when the BER increases above 10^{-6} and stops when BER decreases below 10^{-6}. The C/N value that corresponds to this BER is found using the receiver transfer characteristic function. The C/N value is then applied to the C/N probability density function obtained in Algorithm I to find the fraction of error-free seconds expected in the average year if all errors were due to propagation effects. The year is used instead of the worst month, since rain attenuation data is based on the year.

13.4 Alternative Kirk and Osterholz Digital Link Performance Calculations

This algorithm is based on concepts presented in two Defense Communication Engineering Center reports (Kirk and Osterholz, 1976; Osterholz and Cybrowski, 1980). Link performance characteristics are outage oriented. Outage time may be estimated based on channel statistics such as carrier-to-noise ratio, order of diversity and satisfactory link performance thresholds. Performance characterization is related to the voice user through the concept of outage probability and for the data user through the concept of the probability of receiving error-free data blocks.

13.5 LOS Link Probability of Fade Outage and Unavailability Allocations

For the voice channel, the fundamental DCS LOS link performance measure is the probability of fade outage per call minute for particular ranges of fade outage durations. A radio link is in the fade outage condition when the RSL falls below 10^{-4} bit-error probability threshold. From the ranges defined (Kirk and Osterholz, 1976, p. 20), only Range II and Range III are applicable to the voice channel for LOS digital systems. The maximum allowable probability of fade outage (50-km paths) for Range II is 1.25×10^{-4}, and for Range III it is 1.25×10^{-5}. Of the two conditions, the one requiring the largest fade margin will govern.

The performance of the data channel is stated in terms of the probability of receiving an error-free data block (the fraction of transmitted data blocks that are received error free). Since the data blocks are very short with respect to any given fade duration, the fraction of total fade outage time caused by propagation is very nearly equal the fraction of non-error-free data blocks. Total LOS link allocation of error-free data blocks (considering both equipment and radio propagation) is 0.99997 (Kirk and Osterholz, 1976, p. 18) for a 50-km LOS link.

Each desired performance value is prorated in accordance to path length (Parker, 1977) so that the performance of two short paths combine to equal the performance of a longer path whose length is the sum of the short path lengths.

13.6 Calculating LOS Link Probability of Fade Outage

The calculation method described here is taken from Kirk and Osterholz (1976, pages 30-35). For an LOS link, we calculate the mean-time-between-fade outages, MTBFO (t_1, t_2), in seconds for a particular range of fade durations (from t_1 to t_2). Also, we calculate the number of fade outages, n_f, for that range of fade durations occurring during a call duration of one minute. For small values of n_f, n_f is approximately equal to to the probability of fade outage per call minute since MTBFO (t_1, t_2) will be much longer than 60 seconds (Kirk and Osterholz, 1976, p. 35).

$$n_f = \frac{60}{\text{MTBFO } (t_1, t_2)} \qquad \text{(L-5)}$$

To calculate MTBFO (t_1, t_2) and n_f, use the procedure as follows:

1. Calculate the fade margin, M_T in dB. M_T is the difference between the median C/N level and the C/N level where the BER equals 1 in 10^4.

2. Calculate the fraction of the year, P_o, during which the fade margin M_T is equalled or exceeded as a result of multipath. The loglinear equation for P_o is obtained from two points on the multipath C/N probability distribution (not including rain attenuation) from Algorithm I.

3. Calculate the mean value of the diversity combined signal fade duration, t_o, in seconds. Note that t_o is independent of the rf carrier frequency.

$$t_o = 225 \times 10^{-(M_T/20)}, \quad M_T > 20 \qquad \text{(L-6)}$$

4. Estimate the distribution of fade durations, P(t), about t_o. This estimate is provided by a fit to empirical data given by:

$$P(t) = e^{-1.15(t/t_o)^{2/3}} \qquad \text{(L-7)}$$

5. Calculate the mean-time-between-fade outages, MTBFO, in seconds.

$$\text{MTBFO} = t_o/P_o, \quad M_T > 20 \qquad \text{(L-8)}$$

6. The value of MTBFO (t_1, t_2) in seconds for any particular range of fade duration is:

$$\text{MTBFO}\ (t_1, t_2) = \frac{\text{MTBFO}}{P(t_1) - P(t_2)} \qquad \text{(L-9)}$$

7. Combining these five equations we have:

$$n_f = 0.2667\ P_o \times 10^{M_T/20}\ [e^{-1.15(t_1/t_o)^{2/3}} - e^{-1.15(t_2/t_o)^{2/3}}] \qquad \text{(L-10)}$$

8. Equation L-10 is evaluated for the duration range from 0.2 s to 5 s (Range II) and for the range from 5 s to 60 s (Range III).

13.7 Calculating Probability of Error-Free Data Block and Link Availability

The fraction of total fade outage time resulting from both long-term and short-term fade outages is approximately equal to the fraction of non-error-free data blocks. Total fade outage time, then, is approximately equal to the sum of the diversity combined multipath outage time, the rain attenuation outage time, and outage time during diffraction fading periods. The fractions of time, q, below a particular threshold carrier-to-noise ratio may be obtained from the C/N probability distribution (I-17).

13.8 PCM/TDM Link Performance Output Format

Input parameters required to calculate the link performance are tabulated together with fade margin, allocated link availability, and calculated link availability (Tables 16 and 17). In Table 17, the last item in the table, "Calculated Link Availability," is defined as the probability of receiving error-free seconds. An example of the single receiver transfer characteristic is plotted in Figure 26.

Table 16. Example of Draft MIL-STD-188-323 Digital Link Performance Analysis

Aug/21/1986

PCM-TDM Performance Parameters
Shanzerkopf to Heidelberg

Total Length of the Link	(km)	179.9350
Data Transmission Rate	(Mb/s)	12.500
Modulation Type		QPSK
Mfg Bit-Error-Rate Threshold	(dBm)	-70.00
Mfg Bit-Error-Rate at Threshold		0.0000010
Median Received C/N	(dB)	53.415
Median Received Signal Level	(dBm)	-40.536
Outage Bit-Error-Rate		0.00001000
Threshold Received C/N	(dB)	23.009
Fade Margin	(dB)	30.406
Desired Error-Free-Second Availability		0.99998875
Calculated Error-Free-Second Availability		0.99991401
Is Performance Satisfactory?		No

Note: These values cover propagation effects, not equipment outages.

Table 17. Example of the Kirk and Osterholz (1976) Digital Link Performance Analysis

Aug/21/1986

PCM-TDM Performance Parameters
Shanzerkopf to Heidelberg

Data Transmission Rate	(Mb/s)	12.500
Mfg RSL at Bit-Error-Rate Threshold	(dBm)	-70.00
Mfg Bit-Error-Rate at Bit-Error-Rate Threshold		0.0000010
Multipath Outage Probability, BER = .0001		0.000006
Fade Margin	(dB)	31.596
Minimum Range II Allowable Availibility		0.99955016
Calculated Range II Availibility		0.99996681
Minimum Range III Allowable Availibility		0.99995502
Calculated Range III Availibility		0.99997782
Minimum Allowable Prob of Error-Free-Data Blocks		0.99989204
Calculated Probability of Error-Free-Data Blocks		0.99992486
Desired Link Availability		0.99989204
Calculated Link Availability		0.99991401

Note: These values cover propagation effects, not equipment outages.

14. REFERENCES

Abramowitz, M., and I. A. Stegun (1964), Handbook of Mathematical Functions, U.S. Dept. of Commerce, National Bureau of Standards, AMS 55.

Bean, B. R., and E. J. Dutton (1966), Radio Meteorology, National Bureau of Standards Monograph 92, p. 99.

Bell Telephone Laboratories (1970), Transmission Systems for Communications (Western Electric Company, Inc., Winston-Salem, N.C.).

Burrows, C.R. and S.S. Attwood (1949), Radio Wave Propagation, (Academic Press Inc., New York, NY), p. 146.

CCIR (1982a), Broadcasting Service (Television), Vol IX-1, Recommendation 275, Documents of the XV Plenary Assembly (ITU Geneva).

CCIR (1982b), Recommendations and Reports of the CCIR, 1982; Volume V: Propagation in non-ionized media, ITU, Geneva, Switzerland.

Crane, R. K. (1982), A two-component rain model for the prediction of attenuation statistics, Radio Sci. 17, No. 6.

Department of Defense (1977a), MIL-HDBK-416, Design Handbook for Line-of-sight Microwave Communications System.

Department of Defense (1977b), MIL-HDBK-417, Facility Design for Tropospheric Scatter (Transhorizon Microwave System Design).

Department of the Army (1967), Grid and Grid References, Technical Bulletin No. TM5-241-1, Headquarters Department of the Army, Washington, D.C.

Dutton, E. J. (1977), Precipitation variablility in the U.S.A. for microwave terrestrial system design, Office of Telecommunications Report 77-134 (NTIS Order No. AD A049041).

Dutton, E. J. (1978), Earth-space attenuation predictions for geostationary satellite links in the U.S.A., NTIA Report 78-10 (NTIS Order No. PB 289841/AS).

Dutton, E. J. (1984), Microwave terrestrial link rain attenuation prediction parameter analysis, NTIA Report 84-148 (NTIS Order No. PB 84-207984).

Dutton, E. J., H. T. Dougherty, and R. F. Martin, Jr. (1974), Predictions of European rainfall and link performance and coefficients at 8 to 30 GHz, USACC Tech. Report No. ACC-ACO-16-74 (NTIS Order No. A000804).

Dutton, E. J., H. K. Kobayashi, and H. T. Dougherty (1982), An improved model for Earth-space microwave attenuation distribution prediction, Radio Sci. 17, No. 6.

ESSA (1969), Climates of the World, U.S. Dept. of Commerce, ESSA, Environmental Data Service.

Hause, L. G., and D. R. Wortendyke (1979), Automated digital system engineering model, NTIA-Report-79-18 (NTIS Order No. PB 294-960/AS).

Hogg, D. C., A. J. Giger, A. C. Longton, and E. E. Muller (1977), The influence of rain on design of 11-GHz terrestrial radio relay, BSTJ 56, pp. 1575-1579.

Johnson, R. C., and H. Jasik, (1984) Antenna Engineering Handbook, Second Edition, (McGraw-Hill), pp. 17-24 to 17-27.

Kirk, K. W., and J. L. Osterholz (1976), DCS digital transmission system performance, Defense Communications Engineering Center, Tech. Rept. 12-76.

Liebe, H. J., and G. G. Gimmestad (1978), Calculation of clear air EHF refractivity, Radio Sci., 13, No. 2, March-April 1978.

List, R. J. (1951), Smithsonian Meteorological Tables, 6th Ed. (Smithsonian Institution, Washington, D.C.).

Osterholz, J. L., and W. J. Cybrowski (1980), Application of digital troposcatter to the DCS, Defense Communications Engineering Center, Tech. Rept. 10-80.

Parker, D. E. (1977), Design objectives for DCS LOS digital radio links, Defense Communications Engineering Center Engineering Publication No. 27-77.

Rice, P. L., and N. R. Holmberg (1973), Cumulative time statistics of surface point-rainfall rates, IEEE Trans. Commun. COM-21 No. 10.

Rice, P. L., A. G. Longley, K. A. Norton, and A. P. Barsis (1967), Transmission loss predictions for tropospheric communications circuits, NBS Tech. Note 101, I and II (NTIS Order Nos. AD 687 820 and AD 687 821).

Rummler, W. D. (1982), A comparison of calculated and observed performance of digital radio in the presence of interference, IEEE Trans. Commun. 30, No. 7, pp. 1693-1700.

Smith, D. R. (1985), Digital Transmission Systems, (Van Nostrand Reinhold Company, New York, New York 10020), pp. 428-429.

Thomas, P. D. (1970), Spheroidal Geodesics, Reference Systems, and Local Geometry, U.S. Naval Oceanographic Office, Washington, D.C. 20390.

Vigants, A. (1975), Space-diversity engineering, BSTJ 54, No. 1, pp. 103-142.

Yang, R. F. H. (1957), Passive Repeater Using Double Flat Reflectors, I.R.E. National Convention Paper.

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14. SUPPLEMENTARY NOTES

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.)*

This report describes the mathematical models used in the ARROWS programs. These programs, which run on a desktop computer, automate the calculations involved in the design of line-of-sight microwave radio relay links. The programs calculate, tabulate, and plot information about Earth geometry, terrain profiles, ray paths, repeater-reflector geometry, median basic transmission loss, variability of loss, equipment effects, and link performance. Each model is selected on the basis of its acceptance within the communications industry and the size and type of data base supporting the model. The computer hardware and software configurations are designed to be convenient to operate and to give the design engineer immediate access to calculated results corresponding to changes in design parameters. The programs corresponding to these algorithms are designed to be used interactively by persons having no experience in programming. The algorithms are applicable over a wide range of link parameters. The frequency range is from 1 GHz to 20 GHz. Path lengths should be less than 150 km.

Key words: computer software, digital radio microwave radio, passive repeater, radio link performance, radio relay

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