paths, method (c) underestimates θ_e for all antenna height combinations tested, but for the mountain paths it provides a better estimate than method (b), which overestimates the elevation angle by a wide margin, yielding values more than twice as large as the median values from terrain profiles. Since the elevation angle θ_e is probably the single most important terrain parameter for predicting transmission loss, this wide range in estimates introduces considerable prediction error.

2-5 Terrain Parameters for Colorado Plains, Mountains, and Northeastern Ohio

Profiles of the paths in the foothills and plains of Colorado and in northeastern Ohio were used to obtain horizon distances and elevation angles. These are compared with values calculated as previously described in sections 2-3 and 2-4 for the U. S. random, plains, and mountain paths.

These paths represent much smaller samples than those previously discussed, so one would expect the terrain statistics to be less consistent. Table 2.7 shows median values of the horizon distances d_{L1}, d_{L2}, and d_L for the antenna height combinations used in the measurement program, at distances of 20, 30, 50 and 80 km. The total number of paths, N, in each group is also tabulated. The horizon distances do not appear to be independent of path length as they were for the U. S. random, plains, and mountain paths. This may be attributed in part to the small sample size, and in Colorado to the fact that all paths radiate from a single transmitter located in the plains, resulting in median values of d_{L1} much greater than those of d_{L2}, even with comparable antenna

Table 2.7

The Horizon Distances, Colorado Plains, Mountains, and Ohio

Median Values from Profiles

	h_{g1}	4	h_{g2} 0.6		1.7		3		6		9 m	
d_{km}	N	d_{L1}	d_{L2}	d_L	d_{L2}	d_L	d_{L2}	d_L	d_{L2}	d_L	d_{L2}	d_L km
Colorado Plains, Δh = 90 m, N_s = 290, a = 8327 km												
20	14	11.2	2.0	19.1	2.7	18.1	4.7	19.2	7.2	19.4	7.2	19.4
30	33	12.6	2.0	21.6	2.0	21.6	2.0	21.6	2.0	20.4	4.4	23.4
50	43	14.4	5.0	28.9	6.0	29.0	6.0	29.6	9.2	32.3	18.0	33.7
80	52	21.0					4.5	28.5	10.8	33.3	16.5	35.8
Colorado Mountains, Δh = 650 m, N_s = 290, a = 8327 km												
20	10	7.6	1.2	10.5	1.2	10.9	1.2	10.9	2.0	10.9	2.0	10.9
30	14	9.8	1.5	11.5	1.5	11.5	1.5	11.5	1.5	11.5	1.5	11.5
50	16	10.2	2.8	15.0	2.8	15.0	2.8	15.0	4.3	15.3	4.3	15.3
NE Ohio, Δh = 90 m, N_s = 312, a = 8676 km												
20	42	5.0			2.2	14.1	2.8	12.3	3.0	12.6	5.0	15.0
30	62	7.0			2.5	18.0	2.8	18.0	5.5	23.2	6.0	23.5
50	92	8.6			3.8	22.3	4.4	23.1	5.3	25.3	7.9	26.3

heights. The median value of d_L is not always much greater than the sum of the medians of d_{L1} and d_{L2} especially with the higher receiver heights. The paths in Ohio radiate from six different antenna locations and show median values of d_L much greater than the sum of the medians of d_{L1} and d_{L2}.

The smooth-earth distances d_{Ls1} and d_{Ls2} were calculated for each antenna height and used in (5c) to calculate values of d_{L1}, d_{L2}, and d_L:

$$d_{L1,2} = d_{Ls1,2} \exp(-0.07\sqrt{\Delta h/he}) . \qquad (5c)$$

Table 2.8 shows these calculated values compared with median values from the profiles. The calculated values of d_L are consistently less than the median values from terrain profiles, especially in the Colorado plains. The calculated values of d_{L2}, however, correspond quite well with those from the profiles. This better agreement with d_{L2} is to be expected as the receivers are much more randomly located than the transmitters. The calculated values of d_{L1} and d_{L2}, using (5c), never exceed the corresponding smooth-earth values, but for the Colorado plains paths the median d_L is always much greater than the corresponding value of d_{Ls}. This results from the fact that the transmitter is located in a bowl or depression with rising ground in all directions so the horizon is much farther away than it would be due to the normal fall-off of the earth.

For each of the terrain profiles in the Colorado plains and foothills and in northeastern Ohio, the elevation angles θ_{e1}, θ_{e2}, and their sum θ_e were computed using (3.1) from annex 3 of this report. Table 2.9 shows median values at each distance for the antenna heights used in the

Table 2.8

The Horizon Distances, Colorado Plains, Mountains, and Ohio

Median and Calculated Values

h_{g1} =4m, h_{g2}	0.6			1.7		3		6		9 m	
	d_{L1}	d_{L2}	d_L	d_{L2}	d_L	d_{L2}	d_L	d_{L2}	d_L	d_{L2}	d_L km
Colorado Plains, Δh = 90 m, N_s = 290, a = 8327 km											
a)	13.8	3.5	25.7	4.0	25.3	4.0	28.5	5.6	32.3	11.2	33.7
b)	6.1	2.4	8.5	4.0	10.1	5.2	11.3	7.6	13.7	9.8	15.9
c)	8.2	3.2	11.4	5.3	13.5	7.1	15.2	10.0	18.2	12.2	20.4
Colorado Mountains, Δh = 650 m, N_s = 290, a = 8327 km											
a)	9.8	1.5	11.5	1.5	11.5	1.5	11.5	2.0	11.5	2.0	11.5
b)	3.7	1.4	5.1	2.4	6.1	3.2	6.9	5.0	8.7	6.8	10.5
c)	8.2	3.2	11.4	5.3	13.5	7.1	15.2	10.0	18.2	12.2	20.4
NE Ohio, Δh = 90 m, N_s = 312, a = 8676 km											
a)	7.0			2.5	18.0	2.8	18.0	5.3	23.2	6.0	23.5
b)	6.2			3.2	9.4	5.4	11.6	7.8	14.0	10.0	16.2
c)	8.3			4.2	12.5	7.2	15.5	10.2	18.5	12.5	20.8

a) Median values from profiles

b) Calculated values using (5c)

c) Smooth earth values, $d_{Ls1,2}$ and d_{Ls}

Table 2.9

The Elevation Angles, Colorado Plains, Mountains and Ohio

Median Values in Milliradians

	h_{g1} 4	h_{g2} 0.6		1.7		3		6		9 m	
d_{km}	θ_{e1}	θ_{e2}	θ_e	θ_{e2}	θ_e	θ_{e2}	θ_e	θ_{e2}	θ_e	θ_{e2}	θ_e
Colorado Plains, Δh = 90 m, N_s = 290, a = 8327 km											
20	1.3	5.5	10.4	6.5	10.3	6.1	10.1	5.1	9.3	4.3	8.2
30	0.5	16.8	16.9	14.5	14.6	11.9	12.1	8.8	7.4	7.1	6.9
50	0.9	2.5	5.7	2.0	5.6	1.8	5.0	1.0	4.6	0.4	3.4
80	-2.1					1.9	0.8	1.3	-0.9	0.4	-1.4
Colorado Mountains, Δh = 650 m, N_s = 290, a = 8327 km											
20	25.4	77.4	99.8	76.6	98.6	75.7	97.3	73.7	94.2	71.5	91.2
30	33.7	112.9	135.2	111.2	134.3	109.2	133.3	104.7	129.4	100.1	124.9
50	47.2	105.4	158.8	104.2	158.6	102.8	158.5	99.8	158.3	98.6	158.0
NE Ohio, Δh = 90 m, N_s = 312, a= 8676 km											
20	3.5			6.0	11.2	5.6	11.4	4.8	11.0	4.0	9.9
30	1.0			6.1	10.6	4.8	9.6	3.6	9.0	3.0	6.6
50	0.3			5.3	7.6	4.3	7.3	3.1	6.6	2.8	6.0

measurements. These values show no consistent dependence on distance, and θ_e decreases only slightly with increasing height of the receiving antenna. Table 2.10 shows values of θ_{e1}, θ_{e2}, and θ_e calculated using (6a), compared with median values of θ_e for each antenna height.

$$\theta_{e1,2} = \frac{0.0005}{d_{Ls1}} \left[1.3 \left(\frac{d_{Ls1}}{d_{L1}} - 1 \right) \Delta h - 4\, h_{e1} \right] \text{ radians.} \qquad (6a)$$

2-6 Location Variability

The path-to-path variation in available wanted signal power is discussed in annex 1. Such random variations from location to location are assumed to be normally distributed with a standard deviation σ_{La} dB. An estimate of σ_{La} is required to calculate the service probability Q.

Analysis of path-to-path variability of radio transmission loss for a given frequency and terrain variance assumes statistical homogeneity of the terrain. It has been noted that the plains and mountain areas show a predictable change in the variance of terrain from one direction to another, and that in the area studied in NE Ohio the greatest terrain irregularity occurs in the vicinity of the central transmitter.

Transmission loss data from the measurement program reported by Miles and Barsis (1966) were used to obtain an estimate of σ_{La}. The interdecile range, ΔL, of values of transmission loss recorded for each frequency, polarization, antenna height combination, and distance was tabulated for the Colorado plains and mountain areas, and the area studied in NE Ohio. These interdecile ranges, given in table 2.11, show no consistent dependence on antenna height combinations or on path length, but do increase quite consistently with frequency and terrain irregularity. The interdecile ranges of transmission loss ΔL were plotted versus the parameter $\Delta h(d)/\lambda$ and a smooth curve was drawn through overlapping median values, The analytic expression,

Table 2.10

The Elevation Angles, Colorado Plains, Mountains, and Ohio

Median and Calculated Values in Milliradians

h_{g1}	4	h_{g2} 0.6		1.7		3		6		9 m	
	θ_{e1}	θ_{e2}	θ_e	θ_{e2}	θ_e	θ_{e2}	θ_e	θ_{e2}	θ_e	θ_{e2}	θ_e
Colorado Plains											
a)	0.9	5.5	10.4	6.5	10.3	6.1	10.1	5.1	7.4	4.3	6.9
b)	1.5	5.7	7.2	3.0	4.5	2.2	3.7	0.6	2.1	-0.3	1.2
Colorado Mountains											
a)	33.7	105.4	135.2	104.2	134.3	102.8	133.3	99.8	129.4	98.6	124.9
b)	61.7	169.4	231.1	95.7	157.4	71.7	133.4	41.0	102.7	26.0	87.7
NE Ohio											
a)	1.0			6.0	10.6	4.8	9.6	3.6	9.0	3.0	6.6
b)	1.4			3.5	4.9	1.9	3.3	0.6	2.0	-0.3	1.1

a) Median values from profiles

b) Calculated using (6a), with $d_{L1,2}$ calculated using (5e)

Table 2.11

Interdecile Ranges of Transmission Loss ΔL in dB

Frequency	100 MHz						50 MHz		20 MHz
Polarization	Vertical			Horizontal			Vertical		Vertical
hg_1 = 4, hg_2 =	3	6	9	3	6	9	0.6	1.7	1.3 m
Colorado Plains									
d = 10 km.	24.5	21.9	20.9	23.2	25.5	24.7	23.4	22.1	9.4
20	21.2	21.8	26.6	21.8	25.9	26.1	22.6	16.0	9.0
30	32.3	31.3	29.8	31.0	33.3	34.5	17.5	15.8	19.6
50	17.4	22.0	22.0	20.0	20.6	22.5	16.3	17.5	8.6
80	17.0	21.8	21.0	19.7	18.4	17.8			
Colorado Mountains									
d = 10 km.	25.4	31.6	27.0	39.1		67.3	20.0	36.0	38.3
20	26.3	28.3	29.2	40.6	46.9	43.4	27.2	27.3	29.6
30	30.5	26.1	27.3	35.1		36.1	22.3	24.2	21.6
50	19.6	26.6	28.3				18.8	12.7	16.7
NE Ohio									
d = 10 km.	34.6	26.7	27.3	22.5	27.3	27.5	21.2	20.1	19.9
20	25.6	23.4	23.5	24.8	24.6	24.2	16.3	19.4	15.3
30	33.5	27.5	22.0	26.6	21.1	20.3	16.6	23.1	16.7

$$\sigma_{La} = [0.1 + 0.2\ \lambda/\Delta h(d)]^{-1}\ \text{dB}, \qquad (2.2)$$

was then fitted to these values, where $\sigma_{La} = 0.39\ \Delta L$. This function increases rapidly to about 9 dB for $\Delta h(d)/\lambda = 20$ and then slowly increases further to a maximum value of 10 dB.

The presently available data indicate larger values of σ_{La} with horizontal than with vertical polarization at 100 MHz in the mountains, but no significant polarization effect is observed in the Colorado plains or in Ohio. Further studies of location variability should be made, especially at higher frequency ranges and with higher antennas. The estimate of σ_{La} given by (2.2) depends entirely on the examination of data at 20, 50, and 100 MHz in Colorado and Ohio.

2-7 The Terrain Roughness Factor σ_h

The terrain roughness factor, in (3.5) annex 3, for line-of-sight calculations represents the rms deviation of terrain and terrain clutter within the limits of the first Fresnel zone in the dominant reflecting plane. For this report the factor σ_h is defined by (3.6) as

$$\sigma_h(d) = 0.78\ \Delta h(d)\ \exp\{-\ 0.5\ [\Delta h(d)]^{1/4}\}\ \text{m}, \quad \text{for}\ \ \Delta h(d) > 4\ \text{m}, \qquad (3.6a)$$

$$\sigma_h(d) = 0.39\ \Delta h(d)\ \ \text{m}, \quad \text{for}\ \ \Delta h(d) \leq 4\ \text{m}. \qquad (3.6b)$$

These analytic expressions were developed from a study of about 70 line-of-sight radio paths where detailed terrain profiles were available. For each of these paths the interdecile range of terrain heights $\Delta h(d)$ was calculated, and σ_h was computed using the formulas given in section 5, volume 1, and annex III, volume 2, of the report by Rice et al. (1967).

These formulas define the points at which the first Fresnel ellipse cuts the great circle plane. The factor σ_h was then calculated as the rms deviation of modified terrain elevations relative to a smooth curve within these limits.

The computed value of σ_h was plotted versus the corresponding value of $\Delta h(d)$ for each path. Equation (3.6) defines a smooth curve fitted to these computed values.