be exercised to select sites with a clear foreground, and no nearby obstacle in the direction of the other antenna. With low antennas over irregular terrain the improvement resulting from care in site selection may be highly significant, as shown by the differences in measurements over rugged terrain in Washington and Wyoming. In Washington the majority of the sites were unusually well chosen for good propagation conditions, while in Wyoming many paths were partially obstructed by objects in the near foreground.

The prediction method used to calculate median basic transmission loss as a function of distance was originally developed and tested against the measurements at VHF made in Colorado and Ohio. The present comparisons show that this computer method, described by Longley and Rice (1968) applicable throughout the frequency range from 20 to 10,000 MHz over terrain types ranging from smooth plains to rugged mountains and for antennas less than a meter above ground. The maximum antenna heights tested in this series are 15 m, but other tests have shown that the methods may be used up to heights applicable for air-to-ground communication and to distances much greater than any used in the various measurement programs described in this section.

3. POINT-TO-POINT PREDICTIONS COMPARED WITH MEASUREMENTS

For all the measurement paths discussed in section 2 and for a large number of established communication links, detailed terrain profiles were read from topographic maps. For each path the following parameters were calculated using methods described by Longley and Rice (1968) and by Rice et al. (1967):

a — an effective earth's radius in km, calculated as a function of the minimum monthly mean value of the refractive index of the atmosphere at the surface of the earth,

d	the path length in km,
$\theta_{e1}, \theta_{e2}, \theta_e$	the elevation angles θ_{e1} and θ_{e2} from each antenna to its horizon, and their sum θ_e, all expressed in milliradians,
θ	the angular distance between radio horizon rays in the great circle plane defined by the antenna locations, $\theta = 1000\ d/a + \theta_e$ mr,
d_{L1}, d_{L2}, d_L	the distances d_{L1} and d_{L2} from each antenna to its horizon, and their sum d_L, all expressed in km,
h_{e1}, h_{e2}	the effective height in m of each antenna above terrain along the great circle path between the antennas.

These parameters were used to calculate a predicted value of basic transmission loss for each path, using the computer methods described by Longley and Rice (1968), and each predicted value was compared with the corresponding measured value. Calculations were made for more than 1300 individual paths, at several frequencies and antenna heights. Because such a large amount of information is involved, the path parameters and measured and predicted values of transmission loss for individual paths are not tabulated here. Rather, for each group of data, cumulative distributions of selected path parameters are tabulated. Similar distributions of basic transmission loss, predicted and derived from measurements, and of their individual differences ΔL are plotted in a series of figures. The groups of data are discussed in the same order as in section 2 with the additional data from established communication links considered last.

The point-to-point predictions depend upon values of Δh, d, d_{L1}, d_{L2}, θ_e, and estimates of effective antenna heights calculated for each individual path, in contrast to the area predictions, which are based on the median value of the terrain parameter Δh and estimates of median values for each of the other parameters.

3.1 Gunbarrel Hill and Fritz Peak, Colorado (R-1 and R-2)

Paths with common receiver terminals at Gunbarrel Hill and at Fritz Peak are discussed in this section. The Gunbarrel Hill receiving site is in the open plains about 15 km east of the foothills of the Rocky Mountains. The receiver site at the foot of Fritz Peak is located in the mountains and is shielded from the plains to the east. The majority of sites for the mobile transmitters were selected to provide an unobstructed foreground in the direction of the receiver. Transmission was continuous wave at frequencies of 230, 410, 751, 910, 1846, 4595, and 9190 MHz, with antennas fixed at 6.6 and 7.3 m above ground for the three lower and four higher frequencies, respectively. The receiving antennas, mounted on a tower, were raised or lowered from 1 to 13 m above ground.

Table 1 shows cumulative distributions of parameters for 48 "open" paths to Gunbarrel Hill and 43 "open" paths to Fritz Peak. In this and the following tables the distances d, d_{L1}, d_{L2}, and d_L are in km, the terrain parameter Δh, the antenna heights above ground $h_{g1,2}$, and the effective heights $h_{e1,2}$ are in m, and the sum of the elevation angles θ_e is in mr. In both sets of data path lengths range from less than 3 to 120 km, with a wide range in the terrain parameter Δh in both groups. The median Δh for the R-1 data is 92 m while that for the mountain data is 510 m, with an interdecile range of more than 700 m in each area. These wide ranges in Δh show that no clearcut differentiation between plains and mountains was made in these two groups. The tabulated values of d_{L1}, d_{L2}, d_L, and θ_e are for a receiver height of 1 m. Raising the receiver to 10 m makes little difference to the distributions of these parameters, but does result in a slight increase in median values of d_{L2} and d_L. For more than half of the paths large values of effective height are estimated, especially for the R-2 paths. These values in most cases are subjective estimates of the height of the antenna above average terrain in the direction of the horizon object or of the other antenna.

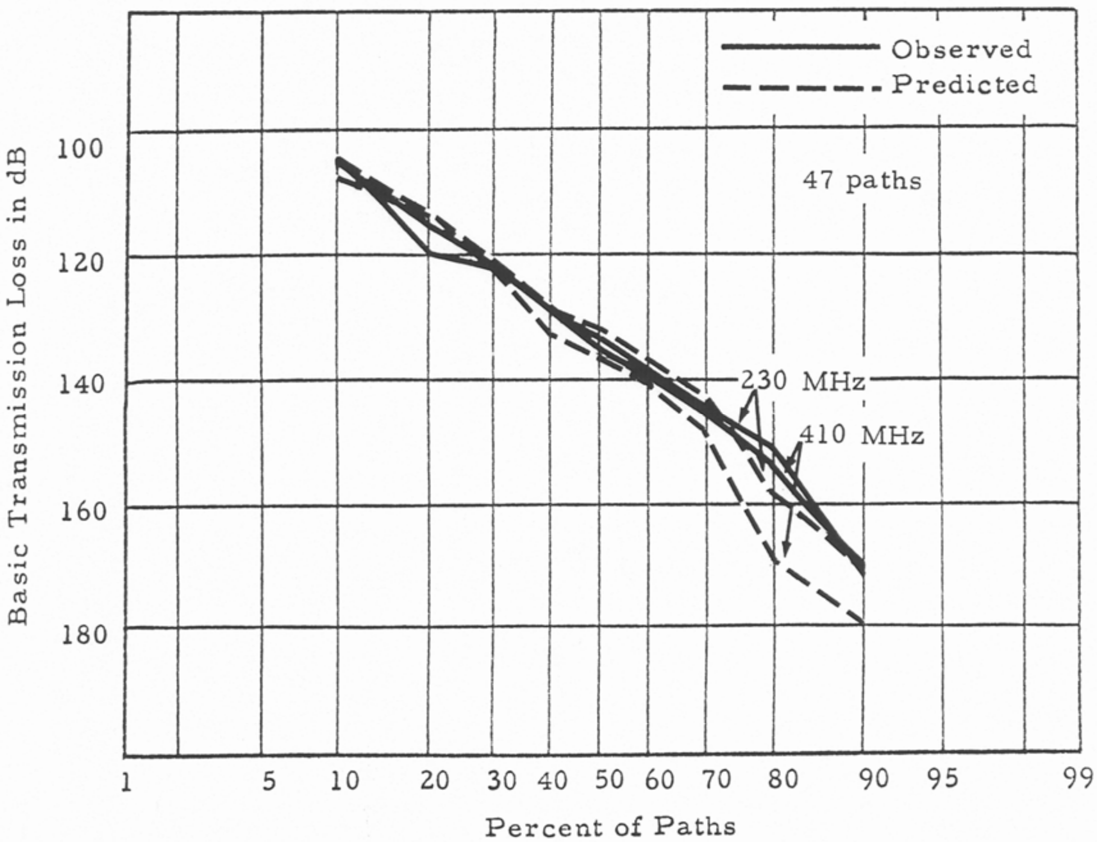
Table 1. Cumulative Distributions of Path Parameters, Colorado Paths

Parameter	Percentage									
	Min	10	20	30	40	50	60	70	80	90
Gunbarrel Hill, (R-1), 48 paths, h_{g1}=6.6 m, h_{g2}=1 m										
d	0.5	3.1	5.0	9.3	10.1	19.8	23.3	49.1	58.7	92.2
Δh	2.2	35.9	60.8	70.1	84.4	91.8	101.9	140.9	187.5	747.2
d_{L1}	0.6	1.1	2.0	3.8	5.7	7.4	9.6	14.3	17.4	27.7
d_{L2}	0.03	0.2	0.3	1.4	11.4	16.3	26.4	31.3	36.1	37.8
d_L	1.3	3.2	5.7	8.5	17.7	20.4	37.6	46.0	50.5	58.7
θ_e	-6.7	-2.8	-0.4	1.0	3.0	7.7	15.1	18.1	40.5	58.9
h_{e1}	6.6	6.6	7.1	16.5	16.6	18.6	26.6	36.6	55.1	150.6
h_{e2} (h_{g2}=10)	10.0	10.0	10.0	15.0	20.0	33.5	35.0	45.0	68.0	210.0
12 line-of-sight, 13 1-horizon paths										
Fritz Peak, (R-2), 43 paths, h_{g1}=6.6 m, h_{g2}=1 m										
d	2.9	3.0	5.0	9.5	10.1	19.6	20.7	50.2	56.5	91.6
Δh	159.9	251.4	289.3	354.8	432.3	511.1	657.0	718.7	914.4	1003.4
d_{L1}	0.1	0.4	1.8	3.3	4.8	5.1	6.2	15.6	37.6	63.9
d_{L2}	0.02	0.02	0.1	0.1	0.1	0.2	2.6	5.2	13.1	18.1
d_L	0.06	2.9	4.5	5.2	5.3	6.3	17.2	28.4	47.2	71.9
θ_e	5.5	57.0	86.9	99.6	132.0	172.9	287.3	336.5	429.0	546.9
h_{e1}	6.6	6.6	36.6	56.6	63.6	106.6	126.6	236.6	306.6	406.6
h_{e2} (h_{g2}=10)	10.0	10.0	10.0	10.0	48.5	60.0	110.0	116.0	205.0	230.0
4 line-of-sight, 11 1-horizon paths										

All measured values of path loss were converted to basic transmission loss and compared with corresponding predicted values. Figures 30, 31, and 32 show cumulative distributions of basic transmission loss, observed L_{bo} and predicted L_{bc}, and of their differences $\Delta L = (L_{bc} - L_{bo})$ in dB, for the Gunbarrel Hill (R-1) receiver site. In each case the values plotted are for a receiver height 2 m above ground. Figure 30 shows good agreement between predicted values and data at 230 and 410 MHz, with a standard deviation of ΔL of about 9 dB. Figure 31 shows similar results at 751 and 910 MHz, while figure 32 shows wider deviations between observed and predicted values at 1846 and 9190 MHz. Referring to the same data plotted in figures 1 through 5 with a receiver height of 1 m we find a range at a single distance of some 80 to 90 dB, even at the lower frequencies. Thus, the point-to-point predictions based upon individual path parameters show considerably better agreement with data than would be possible with an area prediction of basic transmission loss as a function of distance and terrain type alone.

Figures 33 and 34 show cumulative distributions of deviations of predicted from observed values, ΔL in dB, for receiver heights of 1, 3, 7, and 10 m. In all cases the deviations become more positive with increasing antenna height, indicating that the prediction model tends to calculate too much loss at the higher receiver heights. These height differences are more pronounced at the lower than at the higher frequencies.

Figure 35 shows cumulative distributions of L_{bo} and L_{bc} and of their differences ΔL for the Fritz Peak (R-2) receiver site. The predicted losses are greater than those observed at 230 and 410 MHz, with ΔL about 12 dB at the median. Unfortunately, at the higher frequencies more than half of the measurements were "in the noise" so no distributions of differences between observed and predicted values could be prepared. Figure 36 shows cumulative distributions of ΔL for receiver



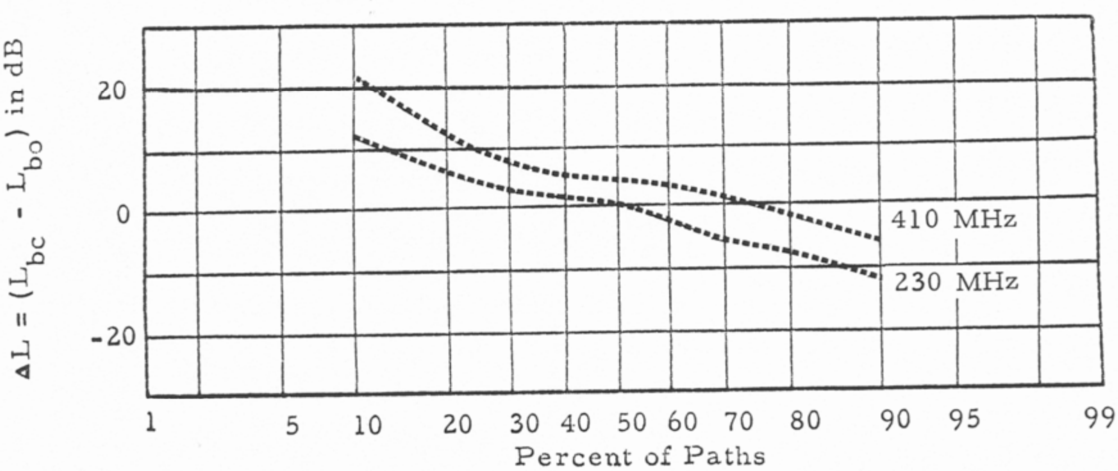


Figure 30. Cumulative distributions of basic transmission loss, observed and predicted, and of ΔL, Gunbarrel Hill, Colorado, R-1, h_{g2}=2 m, f=230 and 410 MHz.

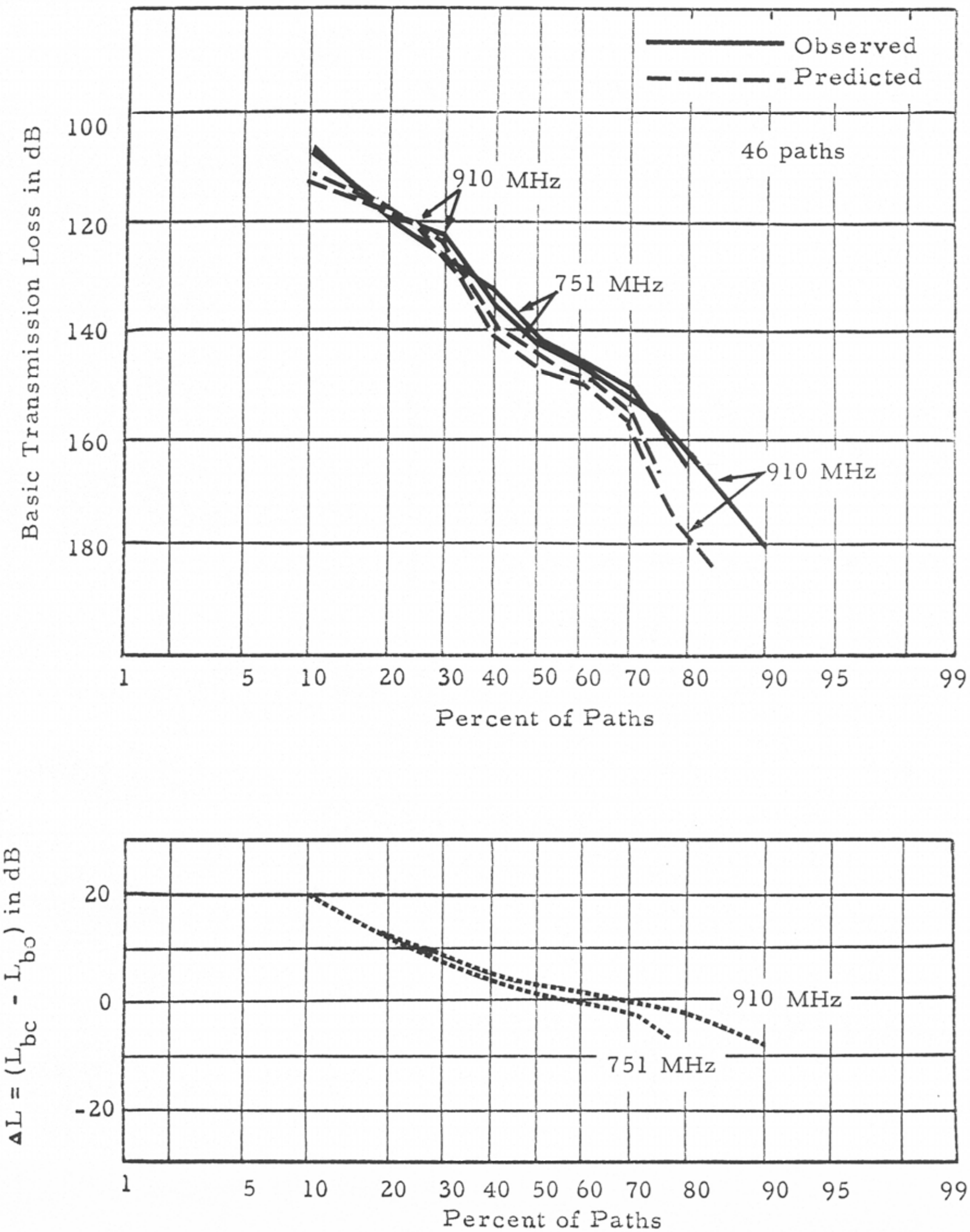


Figure 31. Cumulative distributions of basic transmission loss, observed and predicted, and of ΔL, R-1, h_{g2}=2 m, f=751 and 910 MHz.

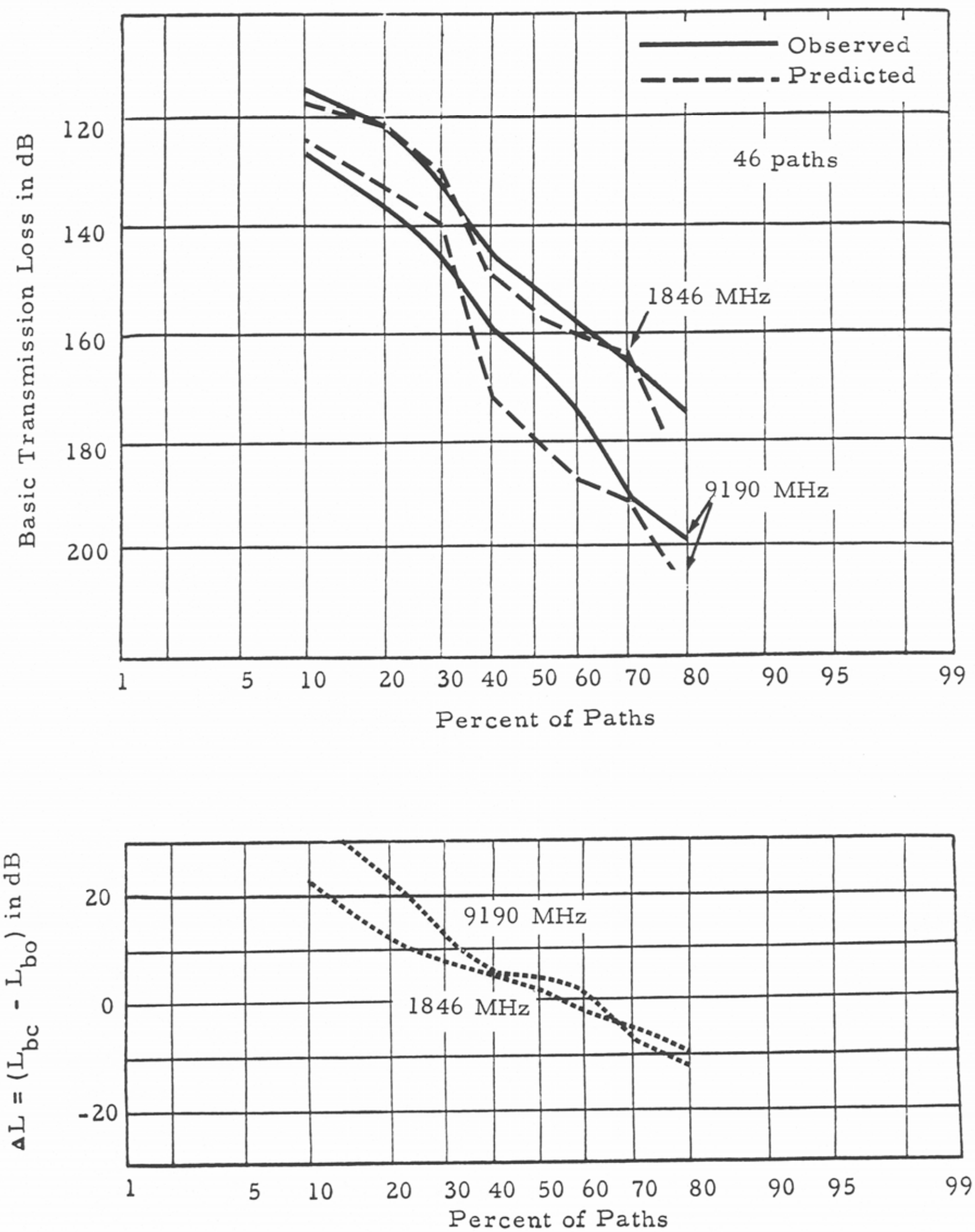


Figure 32. Cumulative distributions of basic transmission loss, observed and predicted, and of ΔL, R-1, h_{g2}=2 m, f=1846 and 9190 MHz.