SAMSO-TR-70-51 VOL. 1

AD703579

A UNITED STATES DEPARTMENT OF COMMERCE PUBLICATION

# ESSA Technical Report ERL 148-ITS 97

# Comparison of Propagation Measurements With Predicted Values in the 20 to 10,000 MHz Range

DDC


A. G. LONGLEY

R. K. REASONER


Final Report Phase D Part 6

In Support of Hard Rock Silo Development

Program 125B

Contract F04701-68-F-0072

Tasks 2.8m, n, and o

essa

BOULDER, COLORADO

January 1970

# ESSA RESEARCH LABORATORIES

The mission of the Research Laboratories is to study the oceans, inland waters, the lower and upper atmosphere, the space environment, and the earth, in search of the understanding needed to provide more useful services in improving man's prospects for survival as influenced by the physical environment. Laboratories contributing to these studies are:

**Earth Sciences Laboratories:** Geomagnetism, seismology, geodesy, and related earth sciences; earthquake processes, internal structure and accurate figure of the Earth, and distribution of the Earth's mass.

**Atlantic Oceanographic and Meteorological Laboratories and Pacific Oceanographic Laboratories:** Oceanography, with emphasis on ocean basins and borders, and oceanic processes; sea-air interactions: and land-sea interactions. (Miami, Florida)

**Atmospheric Physics and Chemistry Laboratory:** Cloud physics and precipitation; chemical composition and nucleating substances in the lower atmosphere; and laboratory and field experiments toward developing feasible methods of weather modification.

**Air Resources Laboratories:** Diffusion, transport, and dissipation of atmospheric contaminants; development of methods for prediction and control of atmospheric pollution. (Silver Spring, Maryland)

**Geophysical Fluid Dynamics Laboratory:** Dynamics and physics of geophysical fluid systems; development of a theoretical basis, through mathematical modeling and computer simulation, for the behavior and properties of the atmosphere and the oceans. (Princeton, New Jersey)

**National Severe Storms Laboratory:** Tornadoes, squall lines, thunderstorms, and other severe local convective phenomena toward achieving improved methods of forecasting, detecting, and providing advance warnings. (Norman, Oklahoma)

**Space Disturbances Laboratory:** Nature, behavior, and mechanisms of space disturbances; development and use of techniques for continuous monitoring and early detection and reporting of important disturbances.

**Aeronomy Laboratory:** Theoretical, laboratory, rocket, and satellite studies of the physical and chemical processes controlling the ionosphere and exosphere of the earth and other planets.

**Wave Propagation Laboratory:** Development of new methods for remote sensing of the geophysical environment; special emphasis on propagation of sound waves, and electromagnetic waves at millimeter, infrared, and optical frequencies.

**Institute for Telecommunication Sciences:** Central federal agency for research and services in propagation of radio waves, radio properties of the earth and its atmosphere, nature of radio noise and interference, information transmission and antennas, and methods for the more effective use of the radio spectrum for telecommunications.

**Research Flight Facility:** Outfits and operates aircraft specially instrumented for research; and meets needs of ESSA and other groups for environmental measurements for aircraft. (Miami, Florida)

Distribution of This Report is Unlimited

ENVIRONMENTAL SCIENCE SERVICES ADMINISTRATION
BOULDER, COLORADO 80302

SAMSO-TR-70-51 VOL. 1

U. S. DEPARTMENT OF COMMERCE
Maurice H. Stans, Secretary
ENVIRONMENTAL SCIENCE SERVICES ADMINISTRATION
Robert M. White, Administrator
RESEARCH LABORATORIES
Wilmot N. Hess, Director

# ESSA TECHNICAL REPORT ERL 148-ITS 97

# Comparison of Propagation Measurements With Predicted Values in the 20 to 10,000 MHz Range

Distribution of This Report is Unlimited

A. G. LONGLEY

R. K. REASONER

INSTITUTE FOR TELECOMMUNICATION SCIENCES
BOULDER, COLORADO

January 1970

For sale by the Superintendent of Documents, U. S. Government Printing Office, Washington, D. C. 20402
Price $1.00

## FOREWORD

This document, the final report covering task 2. 8m, n & o, is submitted by the Institute for Telecommunication Sciences, Boulder, Colorado, in accordance with Contract No. FO4701-68-F-0072. The Air Force Project Officer was Captain M. A. Heimbecker of Headquarters Space and Missile Systems Organization, SMQNL-3, Air Force Systems Command, Norton Air Force Base, California. The study was initiated on 1 July 1969 and completed by 1 February 1970.

Information in this report is embargoed under the Department of State International Traffic in Arms Regulations. This publication does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

## ABSTRACT

Predictions of tropospheric transmission loss over irregular terrain using the computer methods described by Longley and Rice ( 1968 ) are compared with measurements, to determine their limits of applicability and define the boundary conditions for their use. Area predictions for mobile systems where individual path profiles are not available are compared with measurements made with low antennas in Colorado, Ohio, Virginia, Wyoming, Idaho, and Washington. Point-to-point predictions for fixed antenna locations are compared with measurements for each of these paths and for a large number of propagation paths in various parts of the world.

TABLE OF CONTENTS

# COMPARISON OF PROPAGATION MEASUREMENTS WITH PREDICTED VALUES IN THE 20 TO 10,000 MHz RANGE

A. G. Longley and R. K. Reasoner

Predictions of tropospheric transmission loss over irregular terrain using the computer methods described by Longley and Rice (1968) are compared with measurements, to determine their limits of applicability and define the boundary conditions for their use. Area predictions for mobile systems where individual path profiles are not available are compared with measurements made with low antennas in Colorado, Ohio, Virginia, Wyoming, Idaho, and Washington. Point-to-point predictions for fixed antenna locations are compared with measurements for each of these paths and for a large number of propagation paths in various parts of the world.

Key Words: Fixed point systems, irregular terrain, mobile systems, prediction methods, tropospheric propagation.

## 1. INTRODUCTION

Predictions of tropospheric transmission loss over irregular terrain using the computer methods described by Longley and Rice (1968) are compared with a large amount of data to determine their limits of applicability and define the boundary conditions for their use. The computer methods may be used either with detailed terrain profiles to predict the transmission losses expected for specific paths or for "area" predictions where path parameters that are representative of median terrain characteristics for a given area are calculated. These calculations are based on a large number of terrain profiles for widely different types of terrain ranging from smooth plains to rugged mountains.

Median propagation conditions for a specific area are characterized by a terrain parameter $\Delta h$ expressed in meters. To obtain an estimate of $\Delta h$, the interdecile range $\Delta h(d)$ of terrain heights above and below a straight line (fitted by least squares to elevations above sea level) is first calculated at fixed distances for a representative group of terrain profiles. The median values of $\Delta h(d)$ increase with distance, approaching an asymptotic value $\Delta h$ that characterizes the terrain. When an estimate of $\Delta h$ is available, the median value of $\Delta h(d)$ at any desired distance may be obtained from the relationship:

$$\Delta h(d) = \Delta h \left[1 - 0.8 \exp(-0.02d)\right] \text{ m}, \tag{1}$$

where $\Delta h$ and $\Delta h(d)$ are in meters, and the distance $d$ is in kilometers.

When an estimate of the terrain parameter $\Delta h$ has been obtained the other essential parameters are: the radio frequency $f$ in MHz, the path distance $d$ in km, and the transmitting and receiving antenna heights above ground $h_{g1}$ and $h_{g2}$ in meters. From these required parameters the others used to calculate basic transmission loss as a function of distance are derived. Some of the more important additional parameters are the effective heights $h_{e1}$ and $h_{e2}$, the horizon distances $d_{L1}$ and $d_{L2}$, and the horizon elevation angles $\theta_{e1}$ and $\theta_{e2}$.

For area predictions, estimates of the effective heights depend on the procedures followed in choosing antenna sites. When sites are selected randomly with respect to hills or other obstructions, the effective heights are assumed to be equal to the structural heights. If antenna sites are chosen on or near hilltops to improve propagation conditions, the effective heights are larger than the structural heights by an amount that depends upon the terrain irregularity and the structural heights. When antennas are high and the terrain is relatively smooth, the effective and structural heights are almost equal, but with low antennas over irregular terrain the improved propagation conditions that can be achieved by careful site selection may be highly significant.

Because area predictions of basic transmission loss as a function of distance do not depend upon individual path profiles, they are particularly useful for military communication and surveillance, for mobile systems including ground-to-ground and air-to-ground communication, for broadcasting systems, and for calculating preliminary estimates of performance for system design.

When detailed profiles for individual paths are available, the parameters for each separate path are obtained from its profile and used in calculating the basic transmission loss. Such point-to-point predictions are particularly useful in the design and operation of systems with fixed antenna locations.

Both point-to-point and area predictions are compared with data from several measurement programs carried out in the United States. Point-to-point predictions are also compared with measurements recorded over a large number of established communication links in several countries. For convenience in handling, all measured values have been converted to basic transmission loss, defined as the system loss that would occur between loss-free isotropic antennas, free of polarization and multipath coupling losses.

## 2. AREA PREDICTIONS COMPARED WITH MEASUREMENTS

Measurements of transmission loss with low antennas over irregular terrain have been made in several areas in the United States including Colorado, Idaho, Ohio, Virginia, Washington, and Wyoming. These measurements cover a wide range of frequencies, from 20 to 9200 MHz, with structural heights ranging from less than a meter to 15 meters, in areas where the terrain characteristics range from smooth plains to rugged mountains. Some of the geographic areas, frequencies, and the number of paths in each area are described by Barsis, Johnson, and Miles (1969).

Measurements made in Colorado in the frequency range from 230 to 9200 MHz, with support from the U. S. Army Electronics Command and the U. S. Army Security Agency, are divided into four groups, each group having a common receiving location. The Gunbarrel Hill and Fritz Peak data (R-1 and R-2) are compared with predictions in this report. The data recorded near Golden and southeast of Longmont, Colorado, (R-3 and R-4) have not been completely analyzed and are therefore not included. Only a partial analysis of the measurements in Virginia has been made, but currently available data are considered. Comparisons are made with measurements in Wyoming, Idaho, and Washington that were sponsored by the U. S. Air Force Space and Missile Systems Organization and with earlier measurements in Colorado and Ohio sponsored by the U. S. Army Electronics Command.

Within each area median reference values of basic transmission loss were calculated as a function of distance for each radio frequency and antenna height combination, using an estimate of the terrain irregularity. Comparisons of these area predictions with measured values are discussed.

### 2.1 Gunbarrel Hill, Colorado (R-1)

Propagation experiments in the 230 to 9200 MHz range conducted over irregular terrain in Colorado are reported by McQuate, Harman, and Barsis (1968). The data for all frequencies were recorded at a single common receiver site located near the summit of Gunbarrel Hill (R-1) northeast of Boulder, Colorado. The site is in the open plains about 15 km east of the foothills of the Rocky Mountains. All measurements were conducted using mobile transmitters, and the majority of the transmitting sites were selected to provide a clear, unobstructed foreground in the direction of the receiver. The measurement locations were arranged in roughly concentric circles around the receiving site at nominal distances of 0.5, 3, 5, 10, 20, 50, 80, and 120 km from the receiver. Of the 55 transmitter sites selected 10 are located in the mountains, with the others in the somewhat rolling plains. For seven of the transmitting sites a companion "concealed" site was selected, where rows or clusters of trees are located in front of the transmitter. The following discussion is concerned chiefly with the paths where the foreground is clear and unobstructed.

All transmissions were continuous wave at frequencies of 230, 410, 751, 910, 1846, 4595, and 9190 MHz. The transmitting equipment was housed in two mobile units, with the antennas fixed 6.6 and 7.3 m above ground for the three lower and the four higher frequencies, respectively. The receiving antennas were mounted on a tower and could be raised or lowered from 1 to 13 m above ground. A complete description of the equipment, procedures, and experimental results is given by McQuate, Harman, and Barsis (1968).

Path profiles read from detailed topographic maps were obtained for the 47 unobstructed paths, and for each path the terrain parameter $\Delta h$ was calculated. The median value, $\Delta h = 90$ m, was used to characterize the terrain irregularity for these paths. Area predictions were calculated for each frequency, transmitting antenna height, and for integral receiver heights from 1 to 13 m. Figures 1 to 5 show predicted values of basic transmission loss as a function of distance compared with values derived from measurements for receiver heights of 1 and 10 m and for frequencies of 230, 410, 751, 4595, and 9190 MHz. In each case calculations were made assuming both randomly and very carefully

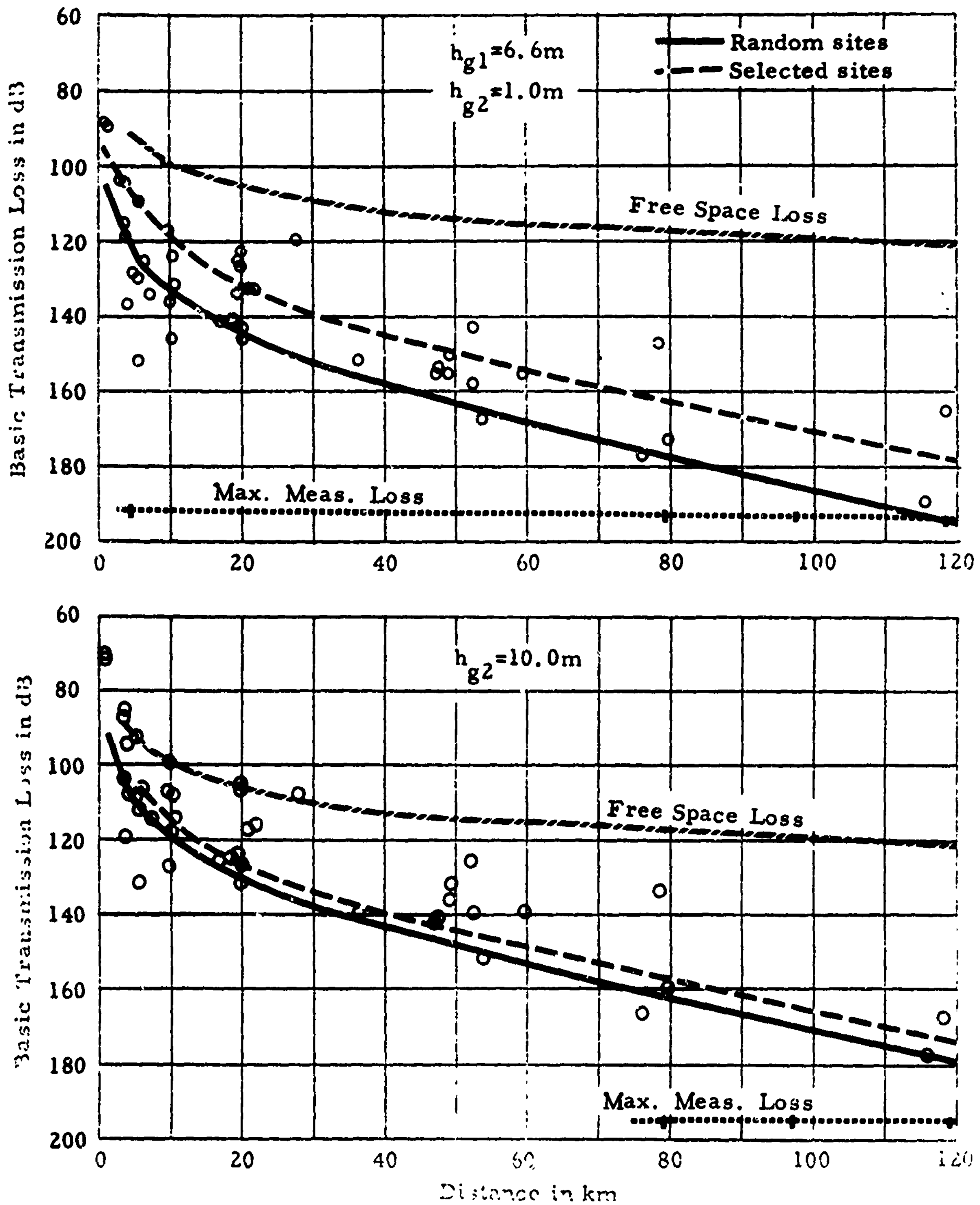



Figure 1. Basic transmission loss, measured and predicted, common receiver site R-1, $\Delta h$=90m, f=230 MHz.

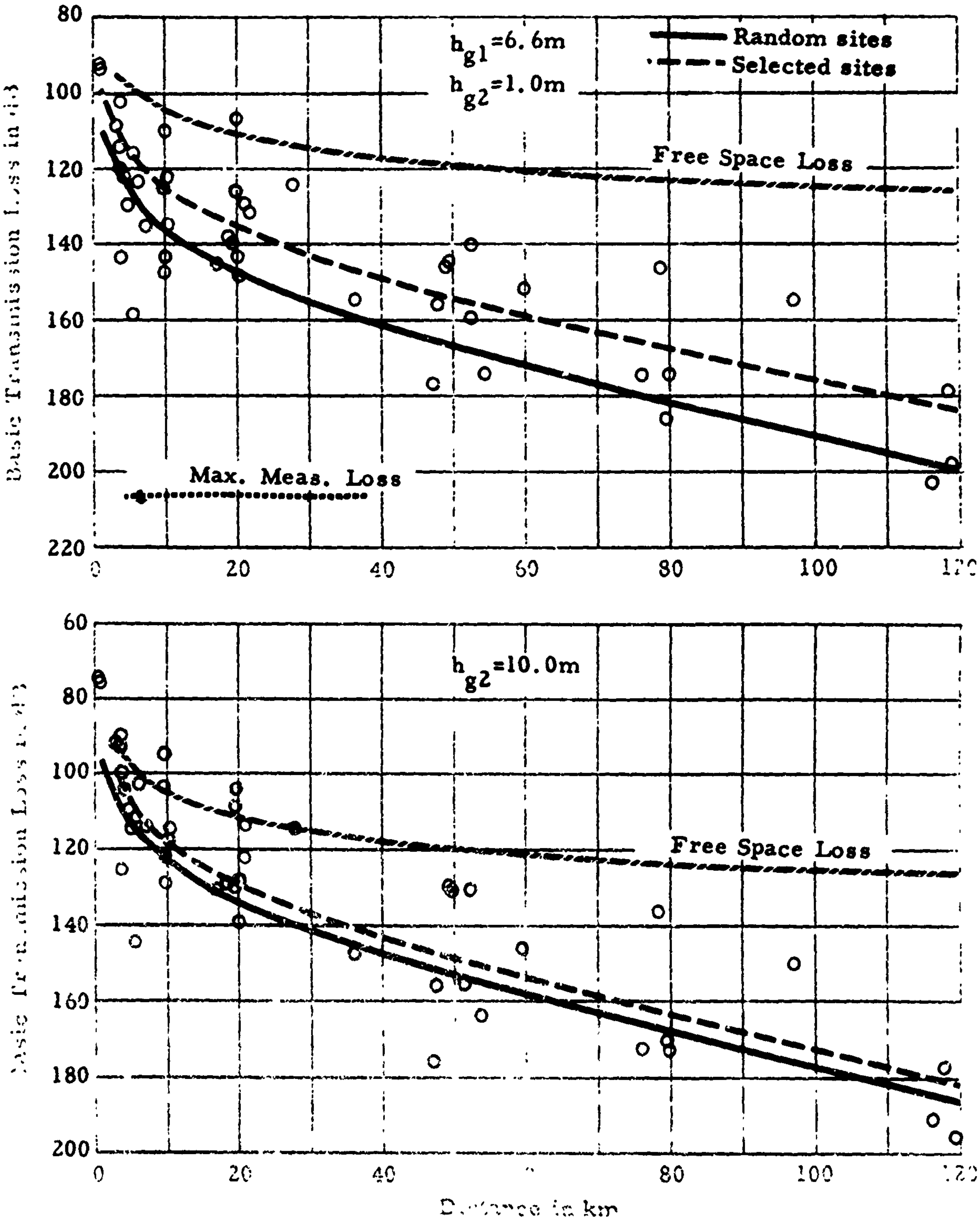
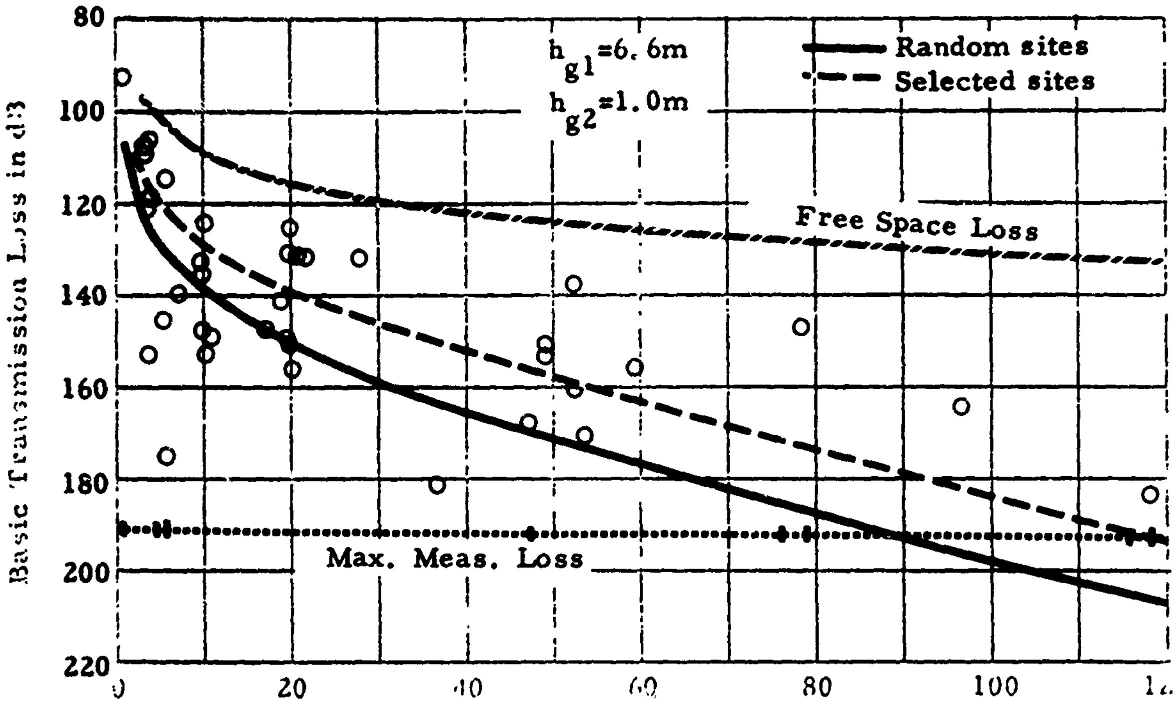



Figure 2. Basic transmission loss, measured and predicted, common receiver site R-1, Δh=90m, f=410MHz.



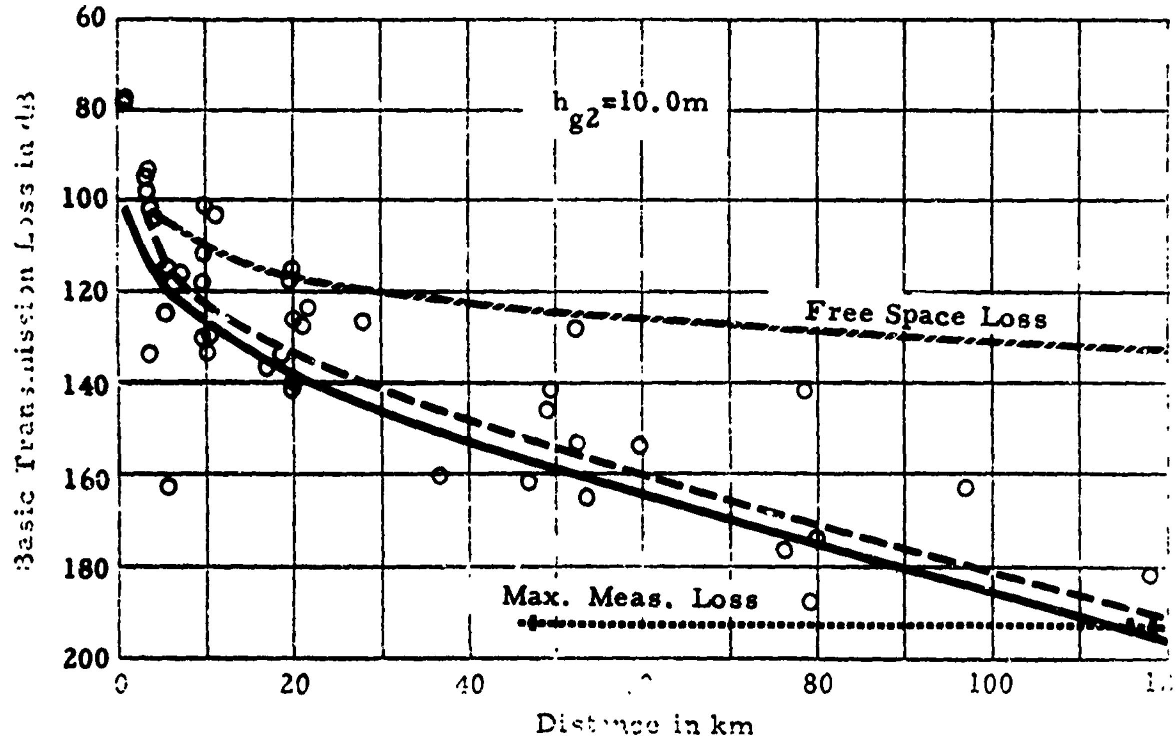




Figure 3. Basic transmission loss, measured and predicted, common receiver site R-1, $\Delta h$=90m, f=751MHz.

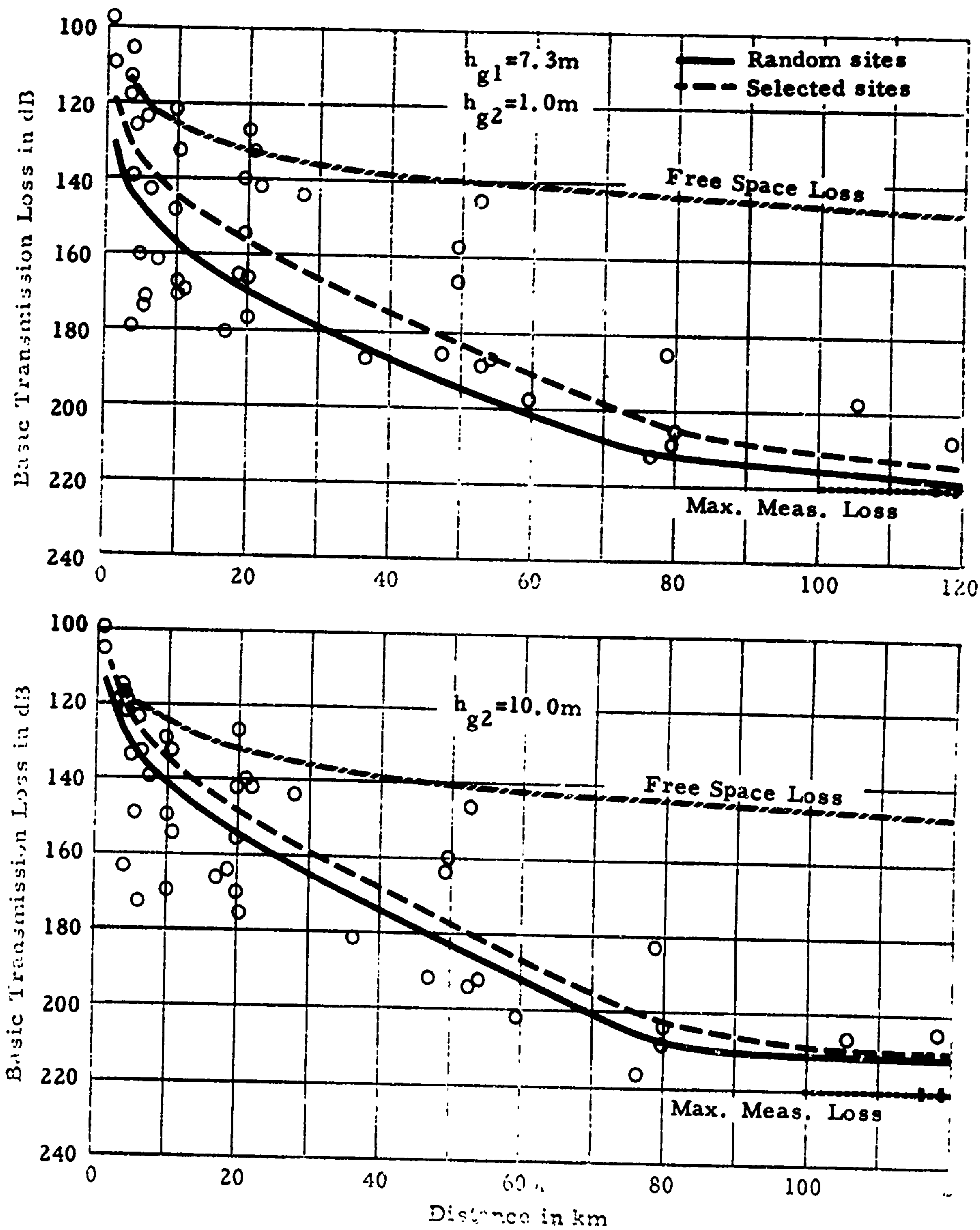



Figure 4. Basic transmission loss, measured and predicted, common receiver site R-1, Δh=90m, f=4595MHz.

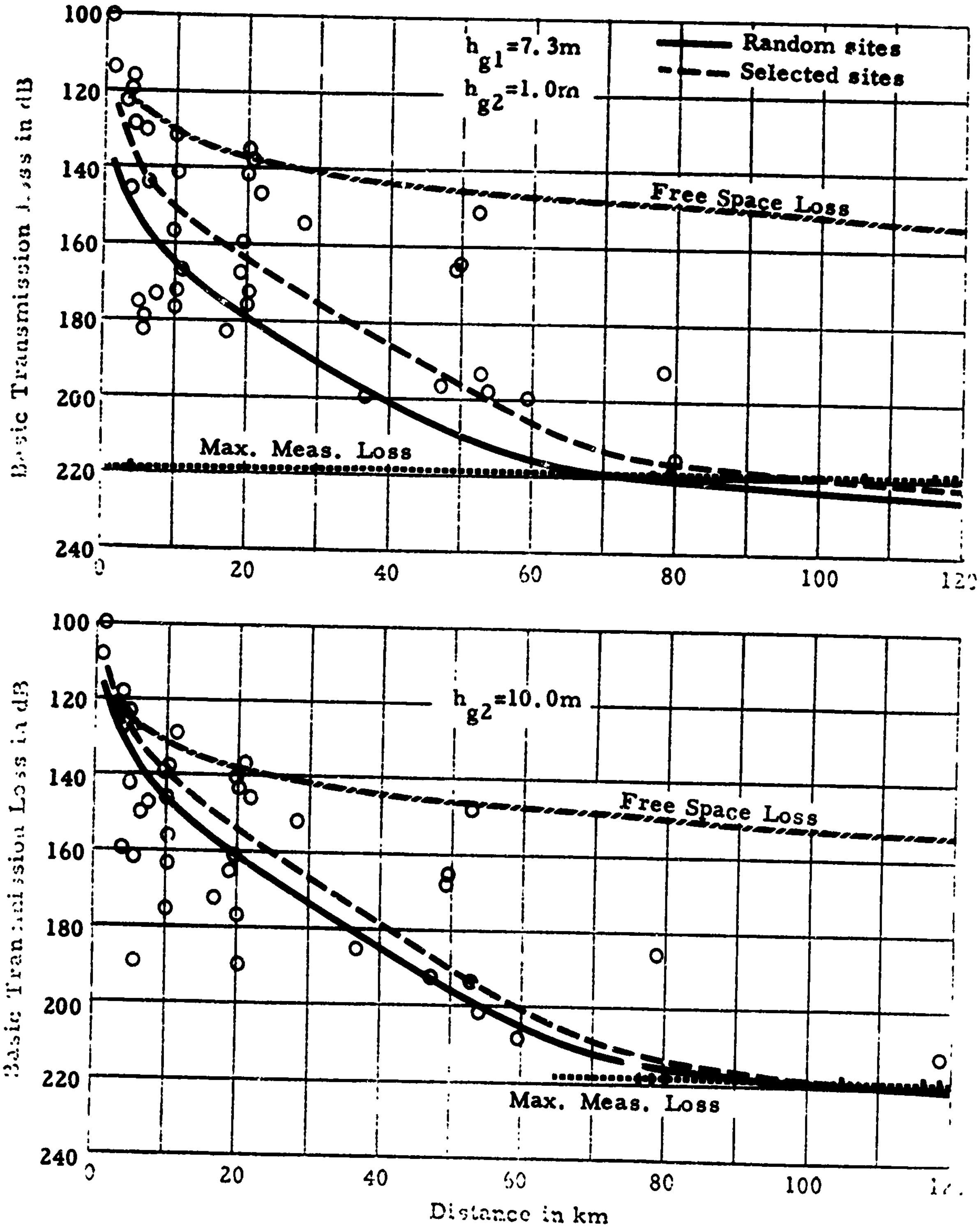



**Figure 5. Basic transmission loss, measured and predicted, common receiver site R-1, $\Delta h$=90m, f=9190MHz.**

selected sites, as described by Longley and Rice (1968). Measurement attempts that failed because the signal was "in the noise" are indicated by a mark located at the level of the maximum measurable loss. In each figure the upper graph shows measured and predicted values with a receiver height of one meter, the lower graph presents the same information with a receiver height of 10 m. A definite improvement in propagation conditions with the increased receiver height is consistently shown, particularly at the lower frequencies.

These five figures all show a wide scatter of the data when plotted as a function of distance. Most of this scatter results from differences in individual path profiles. If low values of transmission loss are observed over a path at one frequency and receiver height, consistently low values are observed at the other frequencies and heights. For example, the low losses (plotted high in the figures) shown for paths at d = 27.5, 52.5, 79, and 119 km appear at all frequencies and receiver heights. An examination of the corresponding profiles shows that these are either clear line-of-sight or isolated knife-edge diffraction paths. On the other hand, the larger than average losses for paths at d = 5, 79.5, and 119 km are all for two-horizon paths with rather large elevation angles.

Such path-to-path differences, caused by differences in individual profiles, are taken into account in the point-to-point predictions for specific paths, as described in section 3 of this report. An area prediction calculates the median transmission loss expected at each distance, with an allowance for path-to-path or location variability.

In figures 1 through 5 with the receiver only one meter above ground, the medians of data lie between the two curves for random and carefully selected sites at the lower frequencies, but at the higher frequencies the prediction curve for selected sites describes the medians of data. With the receiver 10 m above ground the prediction for selected sites agrees with the medians of data at all distances and frequencies shown.

For several paths in this group the measurements were repeated on three or more different days. In some instances two or three measurements were made in the same month, but in others the elapsed time was six months to a year. For some paths the results of the repeated measurements agree closely with each other, but for other paths the results differ by 15 to 20 dB. Some of these differences represent commonly observed seasonal differences in propagation conditions; others may result from local atmospheric changes. In general the values measured during the period April through June show less attenuation than those measured in the period November through February. No detailed analysis of these changes has been made.

The measurements at seven "concealed" transmitter sites were compared with those at corresponding "open" sites. These paths range from 6 to 36 km in length. At all distances and receiver heights the paths with concealed transmitters show larger values of transmission loss than the corresponding open paths. These differences range from about 4 dB for the shortest path at 230 MHz to 35 or 40 dB for the longer paths at 4595 and 9190 MHz. Even a rather thin screen of deciduous trees increases the transmission loss 20 to 25 dB at 9190 MHz, while at the three lower frequencies over the same paths the increased losses are 6 to 10 dB. At present the area predictions make no allowance for such surface "clutter" in a quantitative way. More measurements of this type are needed as a basis for defining a "clutter factor" that would allow for the effects of natural and man-made objects.

## 2.2 Fritz Peak, Colorado, R-2

Measurements in the 230 to 9200 MHz range were continued with a common receiver site located in the mountains west of Boulder at the foot of Fritz Peak. The peak shields the site from the eastern plains, and 36 of the 44 transmitter sites are located in the mountains. These measurements are described in detail in part II of the report by McQuate, Harman, and Barsis (1968). The data represent conditions in rough mountainous terrain, where the ground cover is chiefly coniferous forest.

The immediate foreground at the receiver site is clear to a distance of more than 50 m but is rather heavily forested beyond that distance. The paths range in length from 2.5 to 120 km. The majority of the transmitting sites were selected to provide an unobstructed foreground in the direction of the receiver.

Path profiles were read from detailed topographic maps and the terrain parameter calculated for each path. The median value, $\Delta h = 650$ m, was used to characterize the terrain irregularity for these paths. Unfortunately, even though the common receiver is located in the mountains the paths in this group do not have similar characteristics. The 3 to 10 km paths would be better represented by a much smaller value of $\Delta h$, and several of the longer paths extend well out over the plains, with transmission over relatively smooth terrain for the major part of their lengths.

Figures 6 through 10 show the measured and predicted values of basic transmission loss plotted as a function of distance. The wide scatter of data, some 60 dB for the shorter paths, indicates that the characteristics of these short paths show marked differences from each other. An examination of the terrain profiles for the 3 to 10 km paths shows that the median value of $\Delta h$ is less than 200 m, and that most of these are line-of-sight and knife-edge diffraction paths. In this group only two 3 km paths

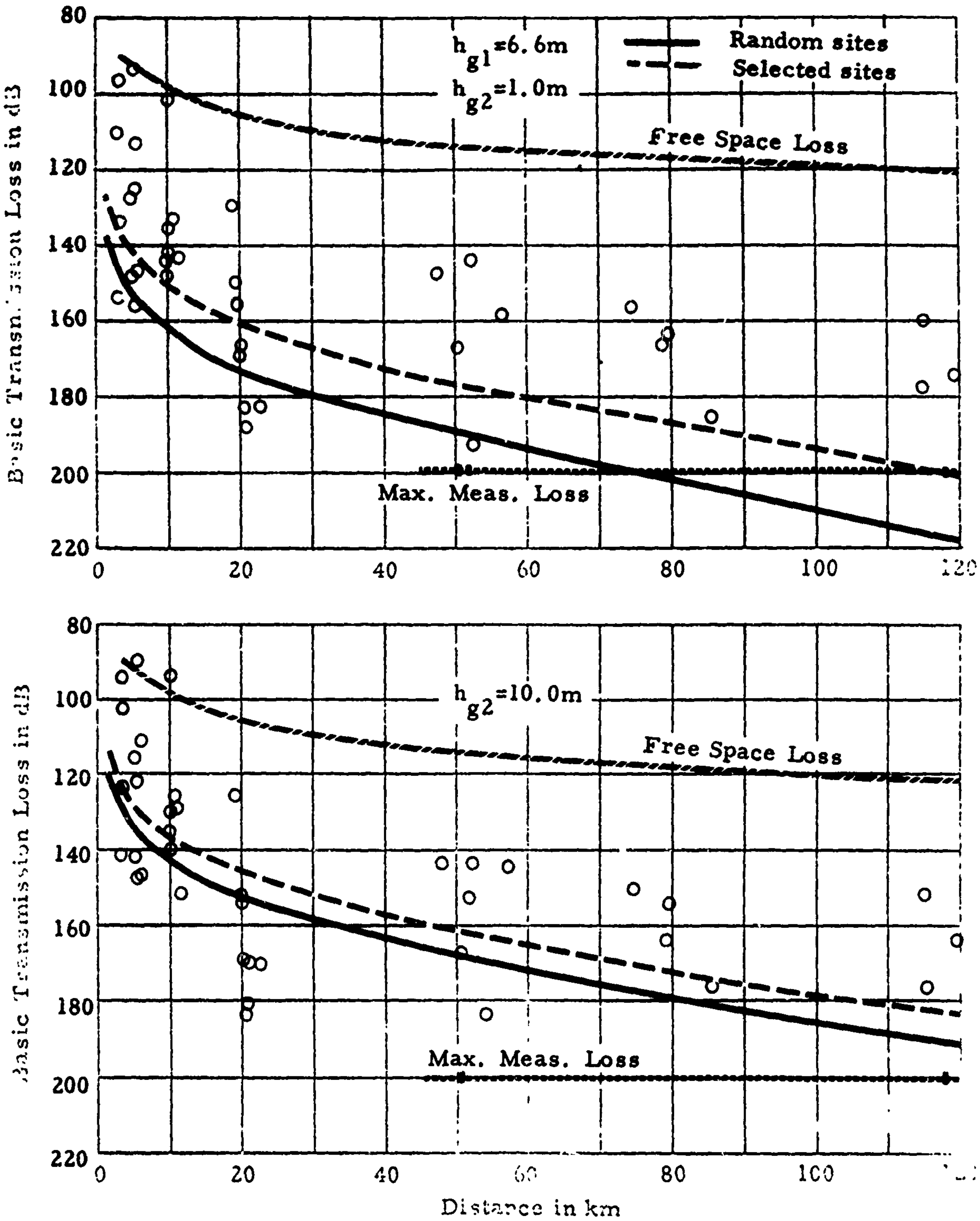



Figure 6. Basic transmission loss, measured and predicted, common receiver site R-2, Δh=650m, f=230MHz.

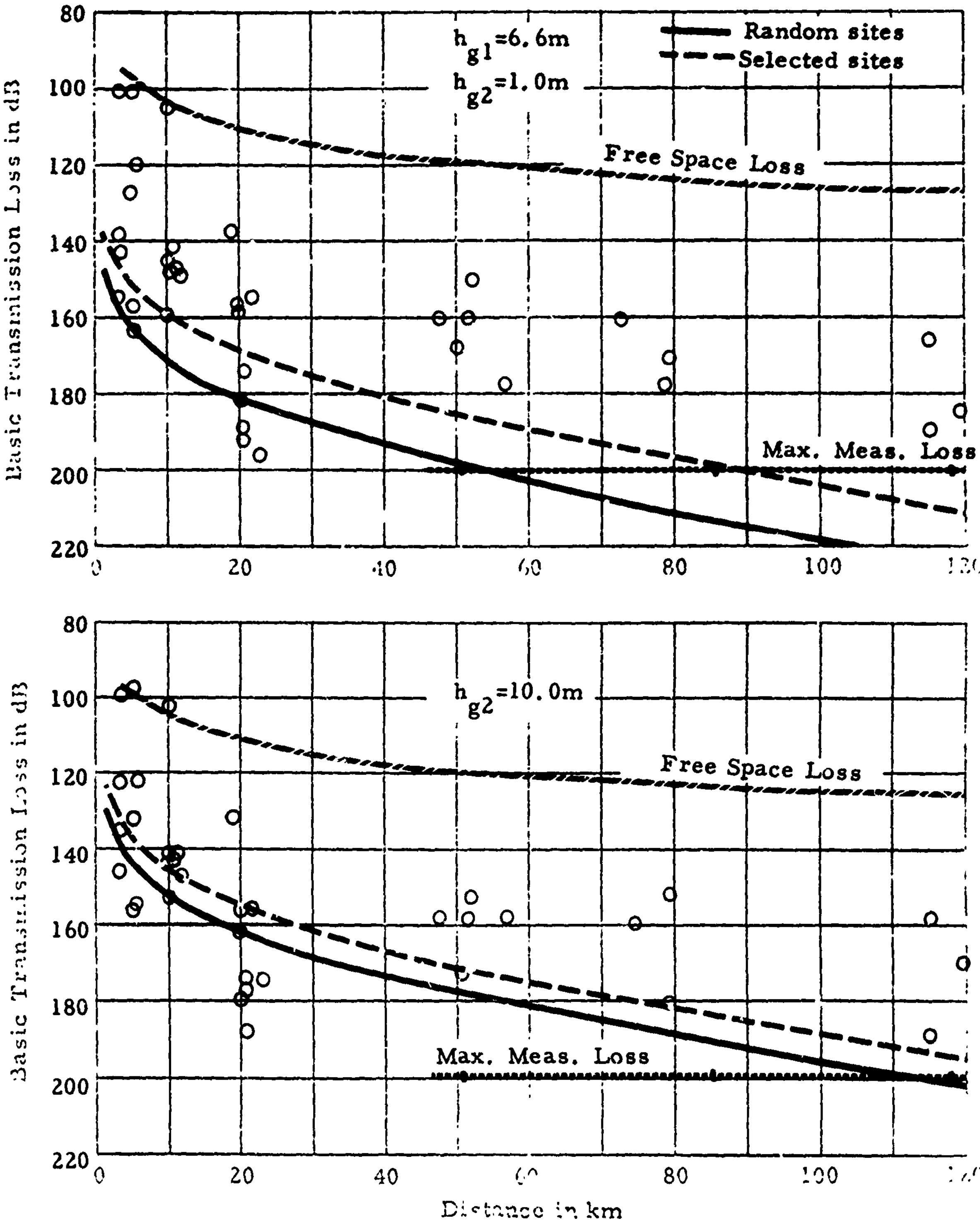



Figure 7. Basic transmission loss, measured and predicted, common receiver site R-2, Δh=650m, f=407MHz.

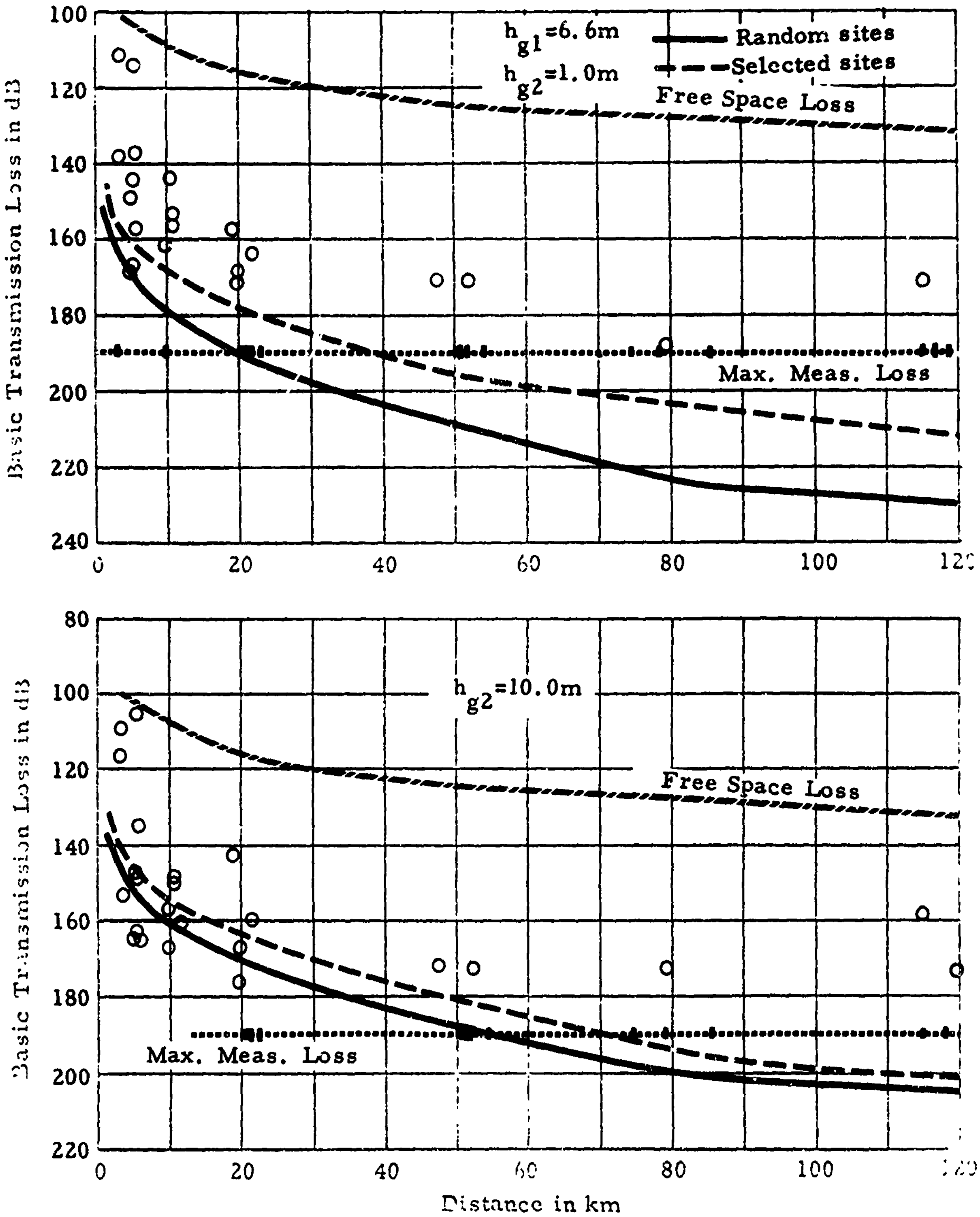



Figure 8. Basic transmission loss, measured and predicted, common receiver site R-2, $\Delta h$=650m, f=751MHz.

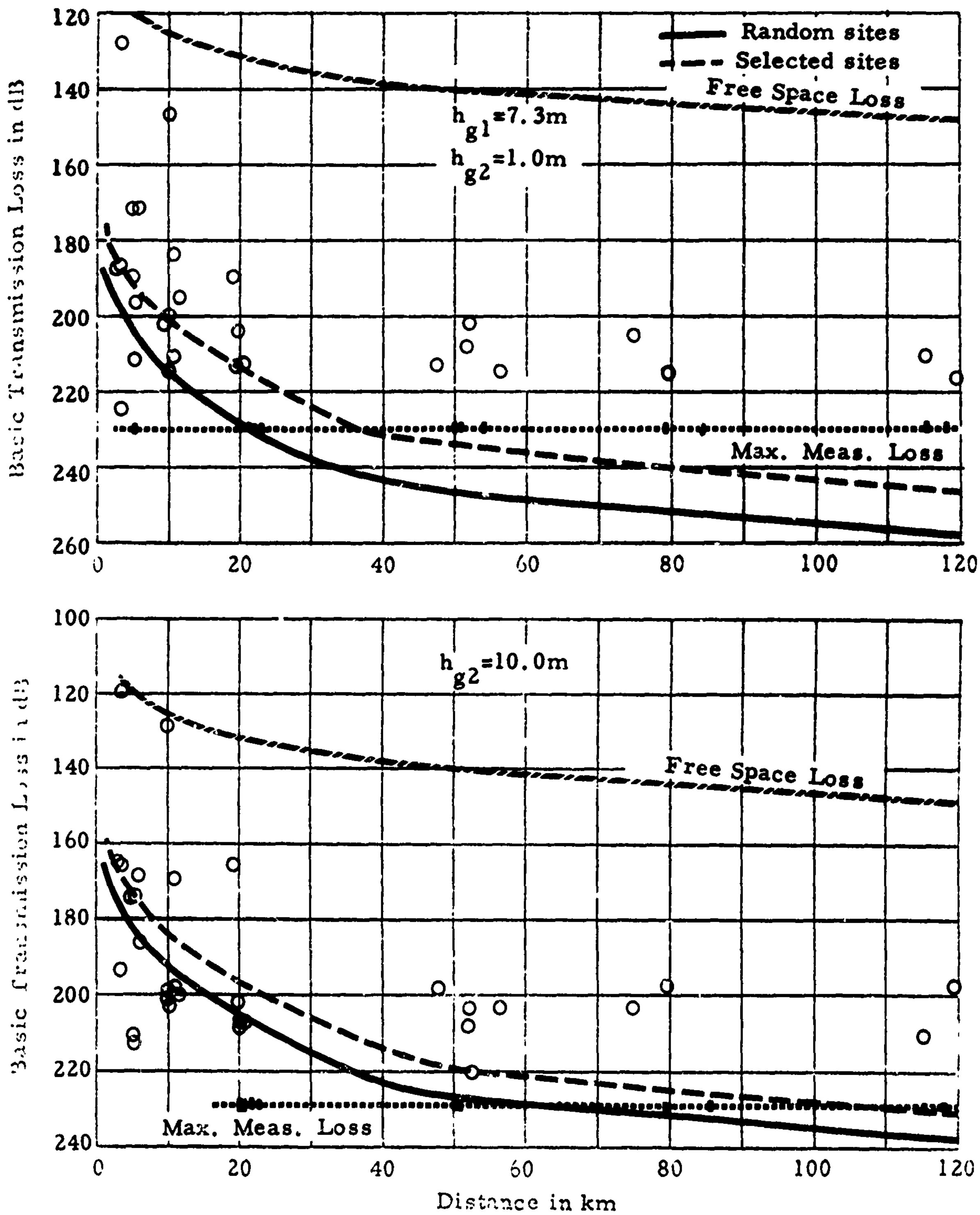



Figure 9. Basic transmission loss, measured and predicted, common receiver site R-2, Δh=650m, f=4595MHz.

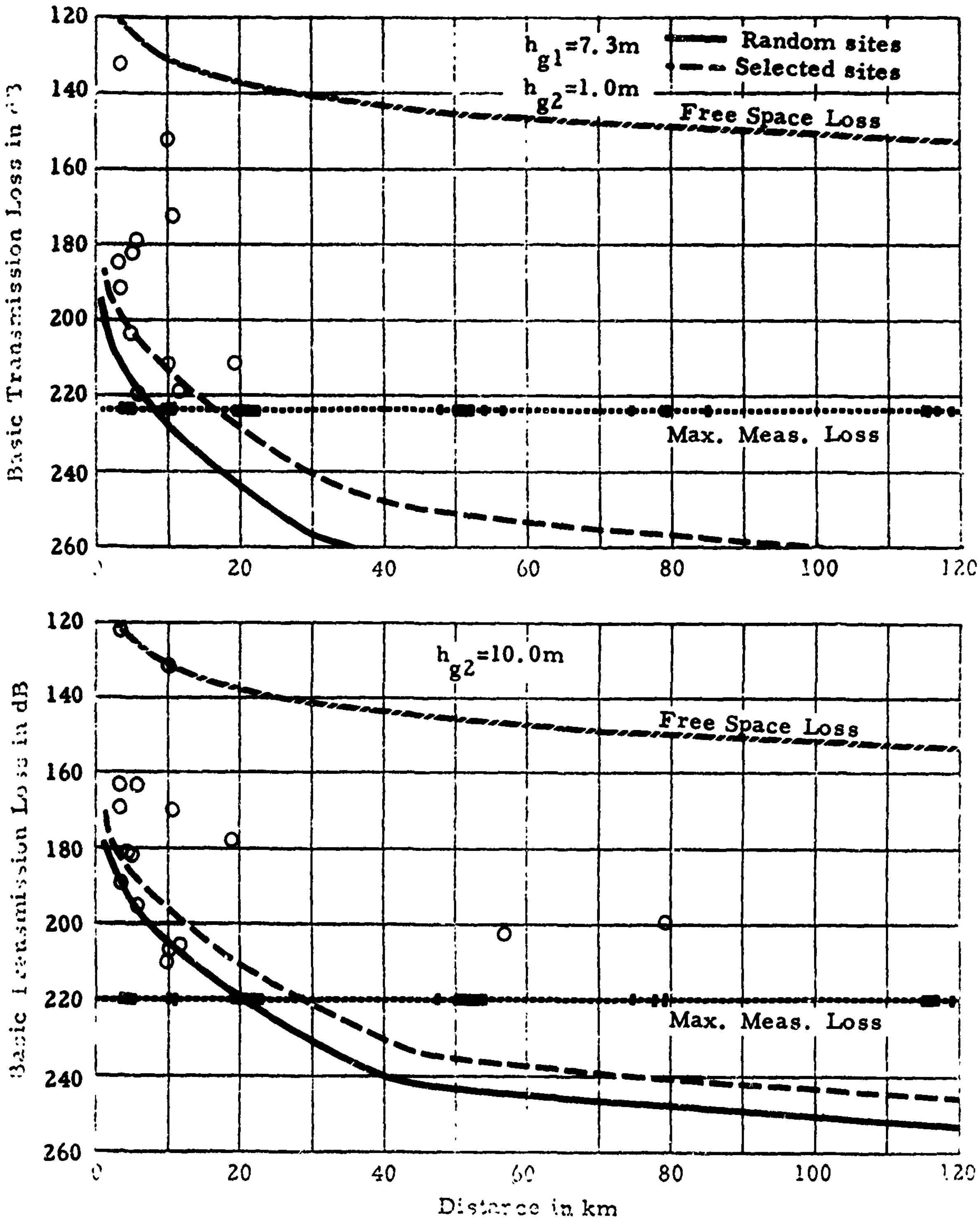



Figure 10. Basic transmission loss, measured and predicted, common receiver site R-2, Δh=650m, f=9190MHz.

and three 5-km paths have more than one horizon. The 20-km paths are over highly irregular terrain, and six of them are transhorizon paths. Ten of the longer paths are typical knife-edge diffraction paths and show the expected low values of transmission loss.

Even though the measurements in this group were not all made over rugged mountainous terrain, they show clearly the improvement in propagation that can be gained by careful site selection. At the higher frequencies measurements at 20 km and beyond were successful only over the line-of-sight and knife-edge diffraction paths, the other values of transmission loss exceeding the maximum measurable value.

Because of the unusually advantageous siting, and the non-homogeneous terrain, the area predictions with $\Delta h = 650$ m tend to overestimate the transmission loss, especially for the lower receiver height. Point-to-point predictions were also calculated for each individual path and are discussed in the next section.

Some measurements at all frequencies were made with the transmitter at "concealed" sites, for paths 2.9, 4.7, 11.2, 20.0, and 52.1 km long. In this small sample the results are not completely consistent, but in general they show increases in transmission loss of 10 to 20 dB for the concealed sites over the shorter paths. The results for the longer paths are inconclusive because in about half the cases the signal was "in the noise".

## 2.3 Virginia Paths

Measurements in Virginia were performed by the General Electric Company under contract to the Institute for Telecommunication Sciences (ITS). The results of these measurements have not yet been completely analyzed, so no detailed descriptive report is available. Some of the data are included in the previously referenced report by

Barsis, Johnson, and Miles (1969). These measurements were made with seven common transmitter sites, and with receiving locations arranged in roughly concentric circles about them at nominal distances of 0.5, 3, 5, 10, 20, 50, 80, and 120 km. In this area the terrain is rolling, hilly, and partly covered by deciduous trees.

Terrain profiles have been read from topographic maps for only about one-sixth of these paths. A median value of the terrain parameter, $\Delta h = 85$ m, was obtained for these 51 paths, most of which are rather short, but a few longer ones are included.

Figures 11, 12, and 13 show predicted values of basic transmission loss as a function of distance compared with measured values for frequencies of 76, 173, 409, 950, 2180, and 8395 MHz. The prediction is for structural heights of 12 m and randomly selected sites. The measurements were made with antenna heights of 11.3 and 15.0 m for the transmitters and 12.1 and 15.0 m for the receivers. These 51 paths include data from four of the seven transmitter sites. The plots indicate that the area prediction, based on randomly selected sites, tends to overestimate the transmission loss at the two lower frequencies, describes the medians of the data at 409 MHz and tends to underestimate the losses at the higher frequencies. This may result from surface clutter in the form of deciduous trees in full leaf that would cause considerably more attenuation at the higher than at the lower frequencies. This possibility will be further investigated when more of the path profiles are available.

Because of current interest in the use of very low antennas, a group of measurements was made with the receiving antenna 2 m above the surface of the ground. For these 95 paths the transmitting antennas were 11.3 and 15.0 m above ground. Figure 14 shows predicted values of basic transmission loss compared with measured

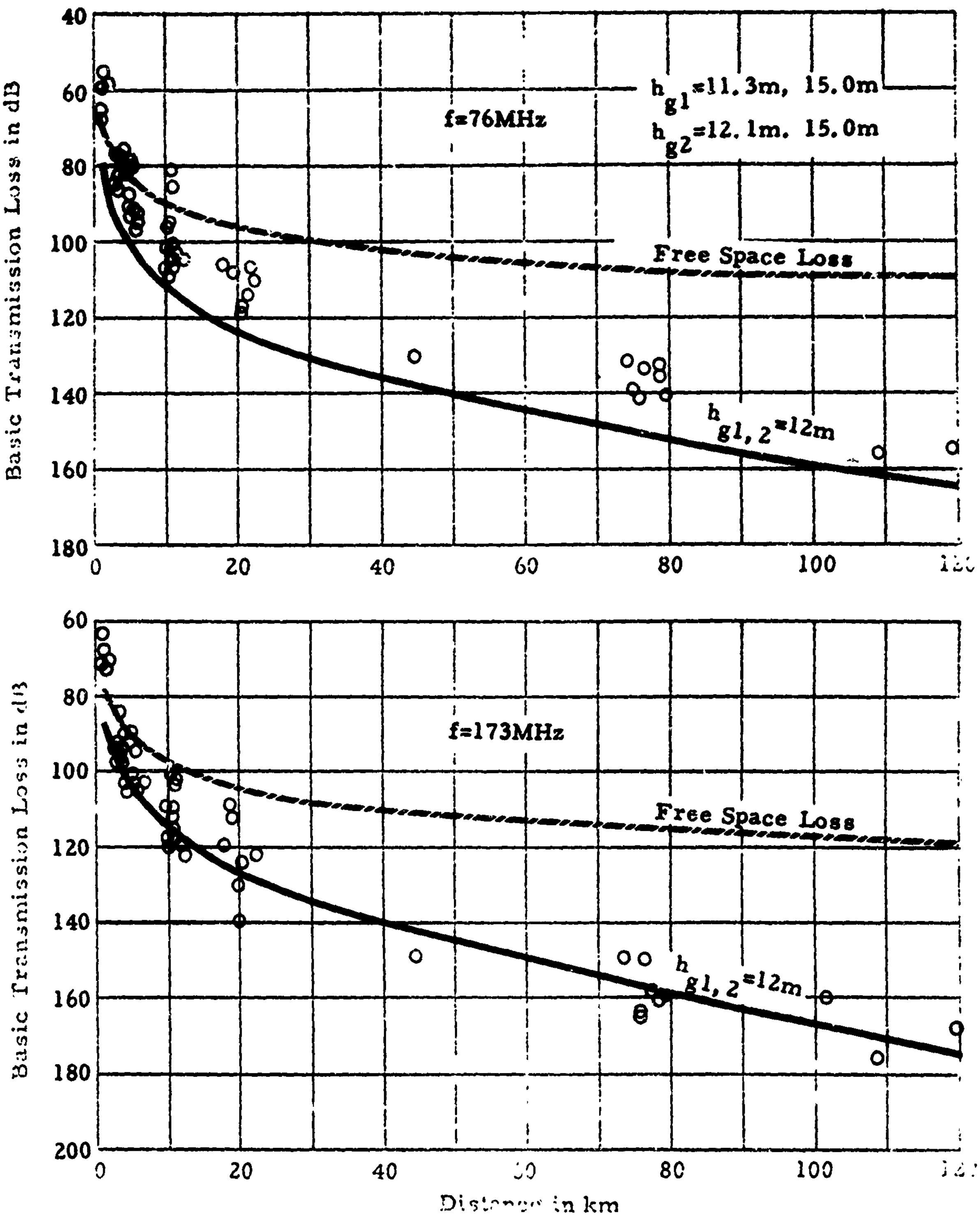



Figure 11. Basic transmission loss, measured and predicted, 51 paths in Virginia, Δh=85m, f=76 and 173MHz.

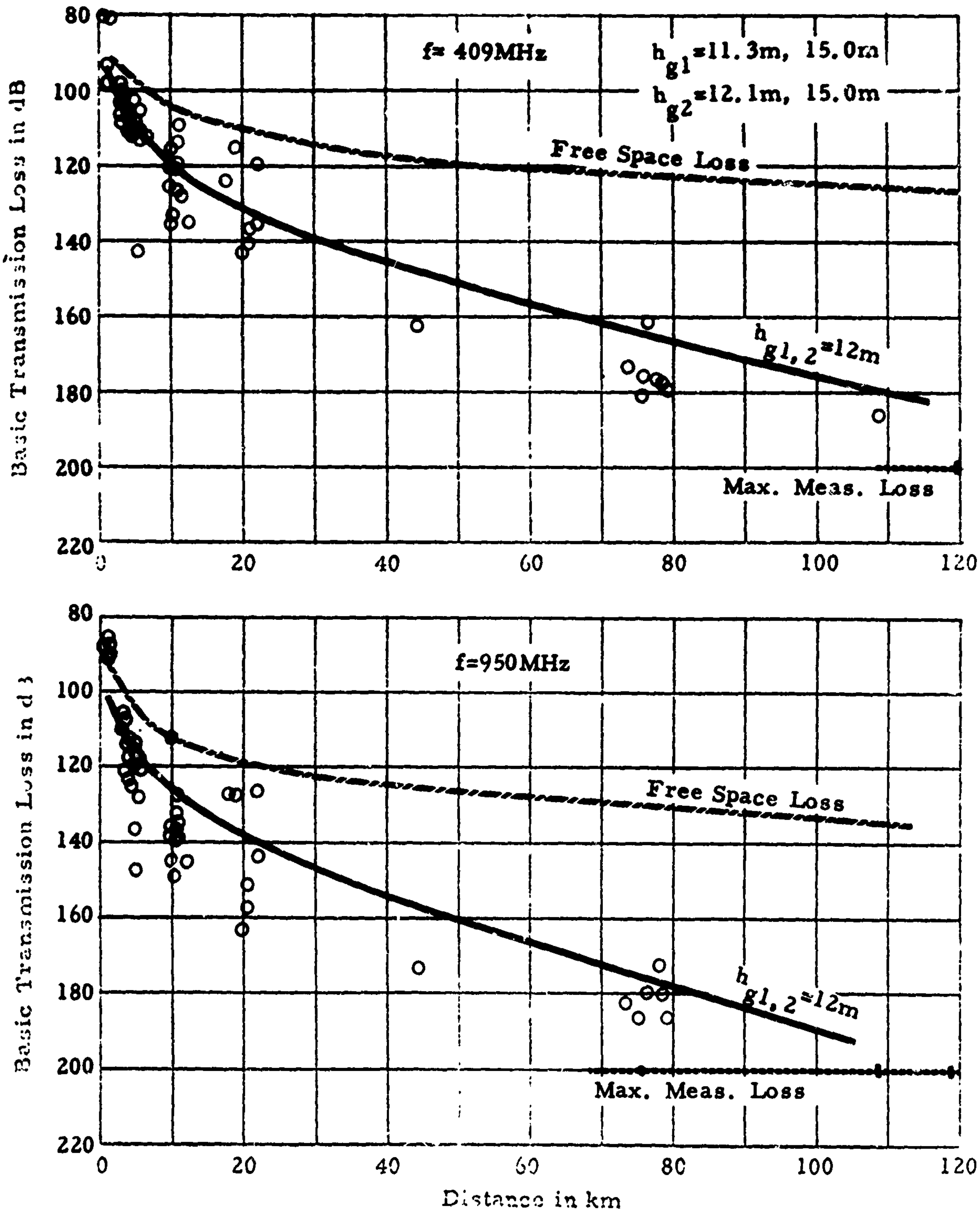



Figure 12. Basic transmission loss, measured and predicted, 51 paths in Virginia, Δh=85m, f=409 and 950MHz.

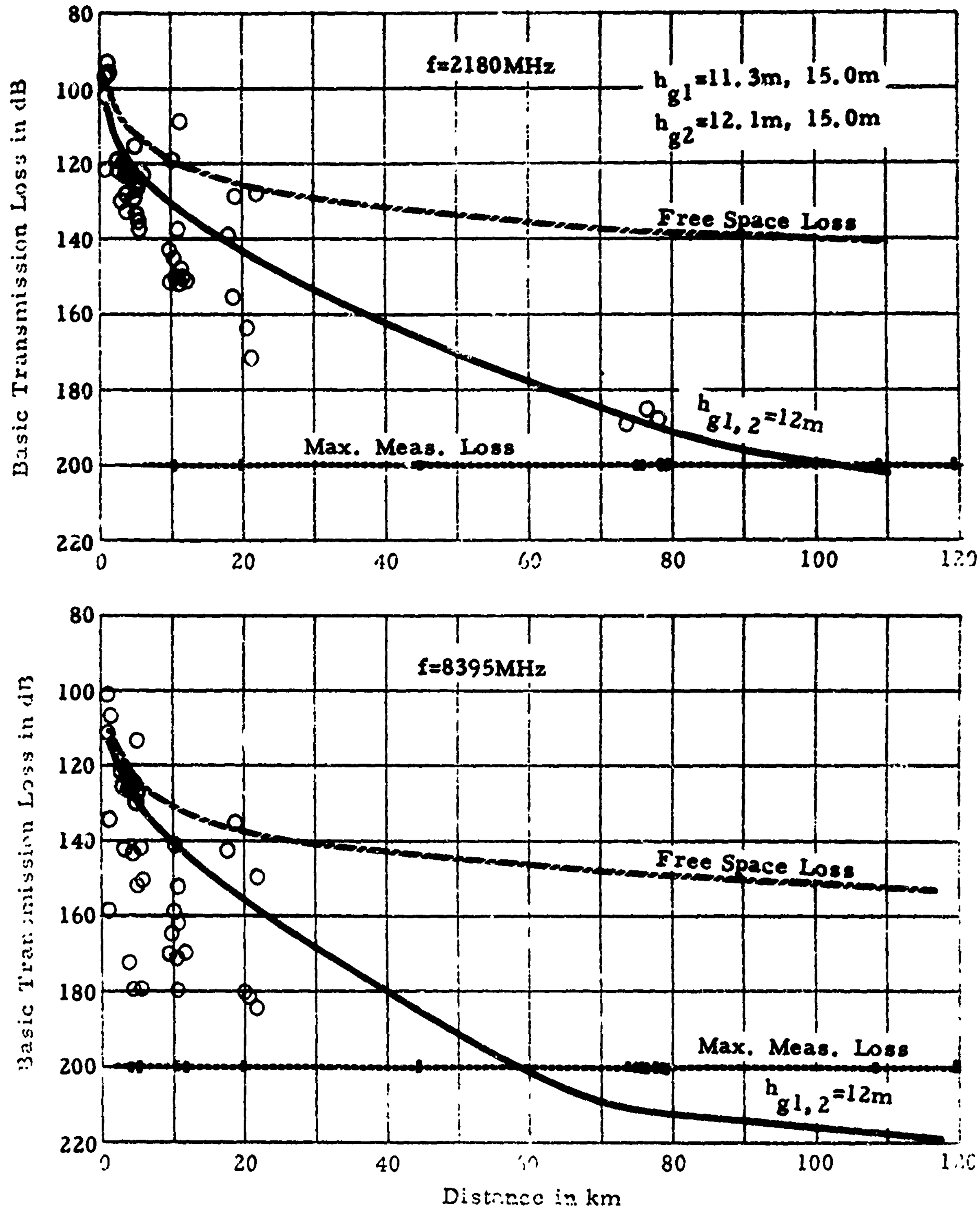



Figure 13. Basic transmission loss, measured and predicted, 51 paths in Virginia, $\Delta h$=85m, f=2180 and 8395MHz.

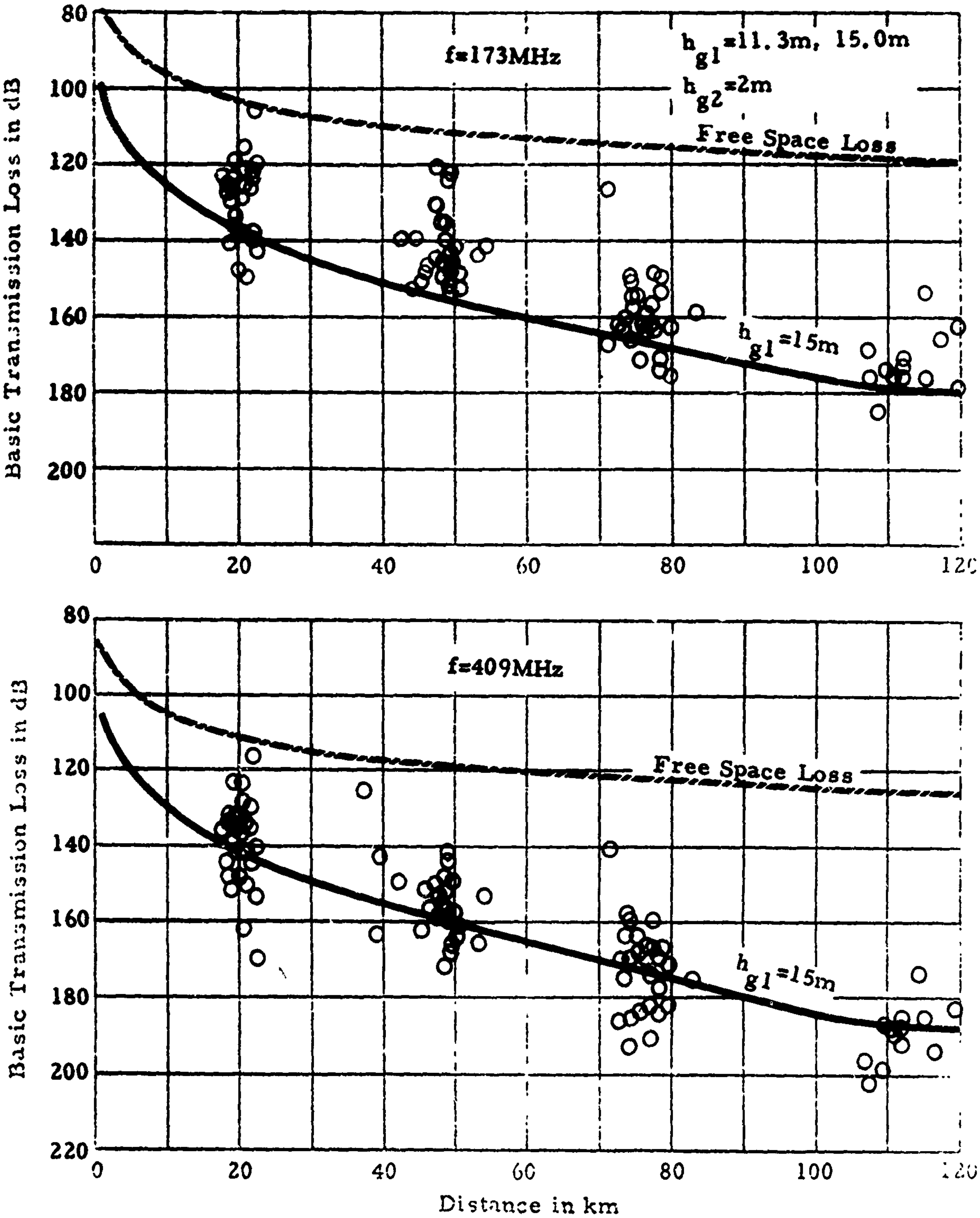



**Figure 14. Basic transmission loss, measured and predicted, Virginia, all paths with $hg_2$=2m, f=173 and 409MHz.**

values at frequencies of 173 and 409 MHz. The predictions were calculated assuming antenna heights of 15 m and 2 m, with randomly selected antenna sites. The data are from all seven transmitting locations. These plots show that the area prediction tends to overestimate the transmission loss at 173 MHz but describes the median loss as a function of distance at 409 MHz. No plots are shown for the higher frequencies with this low receiver height because a large proportion of the attempted measurements were in the noise, showing greater losses than the maximum measurable values. A significant feature in this area is that the path-to-path or location variability is considerably less than that observed in either the R-1 or R-2 data. This probably indicates more homogeneous terrain with fewer unusually good or bad propagation paths.

Point-to-point predictions for the paths where terrain profiles are available are discussed in section 3. Further comparison of these data with predictions will be deferred until path parameters are available for more of these measurements.

### 2.4 Wyoming, Idaho, and Washington Paths

The measurement program conducted in Wyoming, Idaho, and Washington was limited to two frequencies, 230 and 416 MHz, and to very low antenna heights, from 0.75 to 3 m above ground. Both the transmitting and receiving units were mobile. The transmitting antennas for both frequencies were fixed at heights of 0.75 and 3 m above ground, while the receiving antennas were raised continuously from 0.75 to 3 m. Details of these measurements and the equipment used are described by Hause, Kimmett, and Harman (1969).

This series of measurements differs from those previously described in that no attempt was made to choose sites that would provide good propagation conditions. With such low antennas the selection of sites in road cuts or behind large rocks may cause a partial obstruction that is not recorded on detailed topographic maps. In this series few common transmitter or receiver sites were chosen, and those for only a limited number of paths.

Point-to-point predictions were calculated for specific measurement paths in each of the three areas and will be discussed in section 3.

### 2.4.1 Wyoming Paths

Measurements were made over 47 paths between 25 sites in the Laramie range area, Wyoming. The terrain is irregular and barren with low sparse ground cover, mostly prairie grasses. Detailed topographic maps were used to obtain more than 100 path profiles in the measurement area. The statistics from these profiles show a median value, $\Delta h = 120$ m, of the parameter used to characterize terrain irregularity.

Transmission loss values as a function of distance were calculated for equal antenna heights of 0.75 and 3 m at frequencies of 230 and 416 MHz. Figures 15 and 16 show measured and predicted values of basic transmission loss plotted as a function of distance. For each set of data two prediction curves are drawn, one with the effective antenna heights assumed equal to the structural heights, the other with effective antenna heights calculated for selected sites. In all cases the prediction for randomly chosen sites, $h_e = h_g$, describes the medians of the data.

Photographs taken at each site along the path in the direction of the other antenna location show that several paths in this group were partially obstructed by small hills or large rocks that were not shown on the topographic maps. These are coded on the figures and show larger than average losses. An examination of the terrain profiles

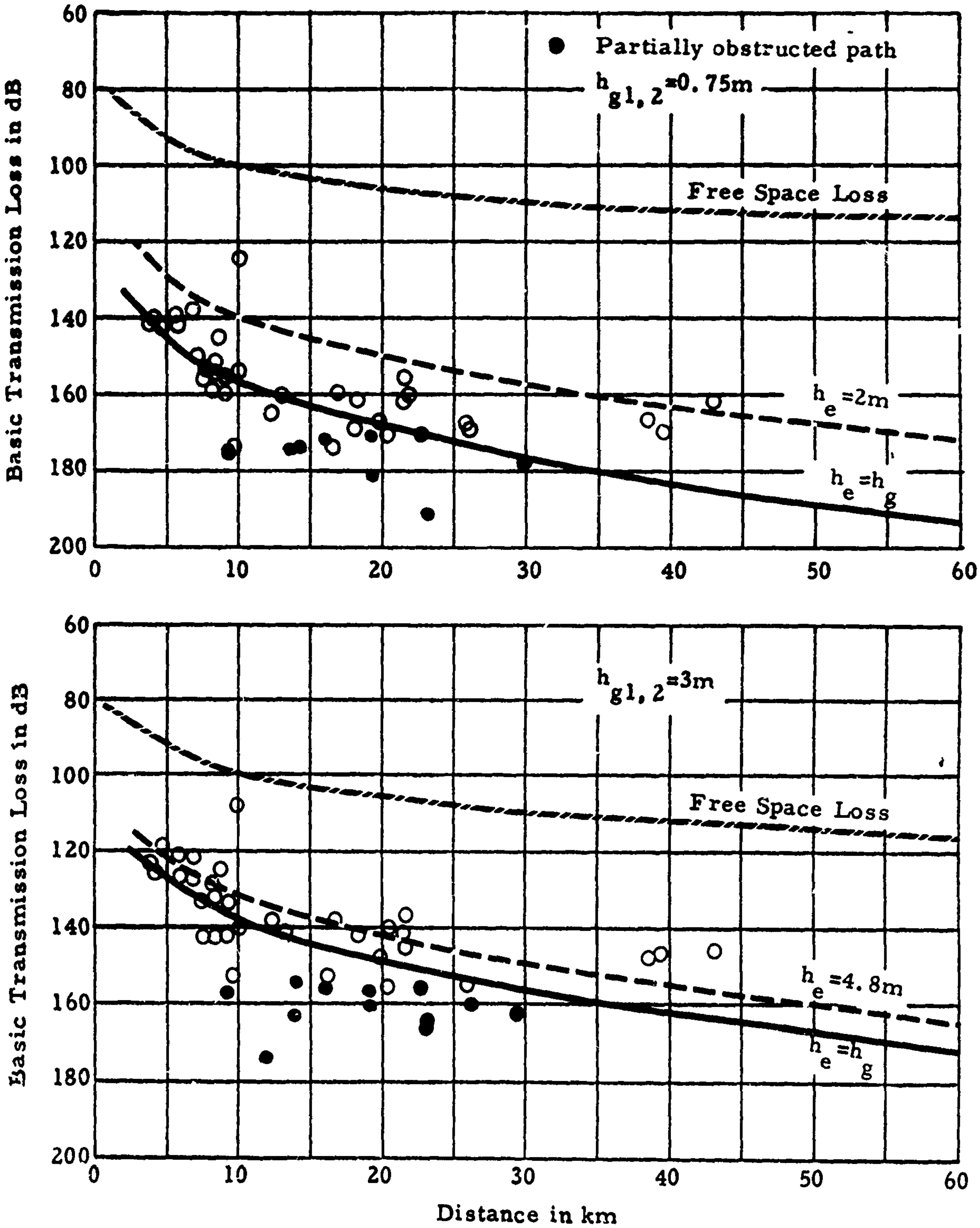



Figure 15. Basic transmission loss, measured and predicted, Laramie range, Wyoming, $\Delta h$=120m, f=230MHz.

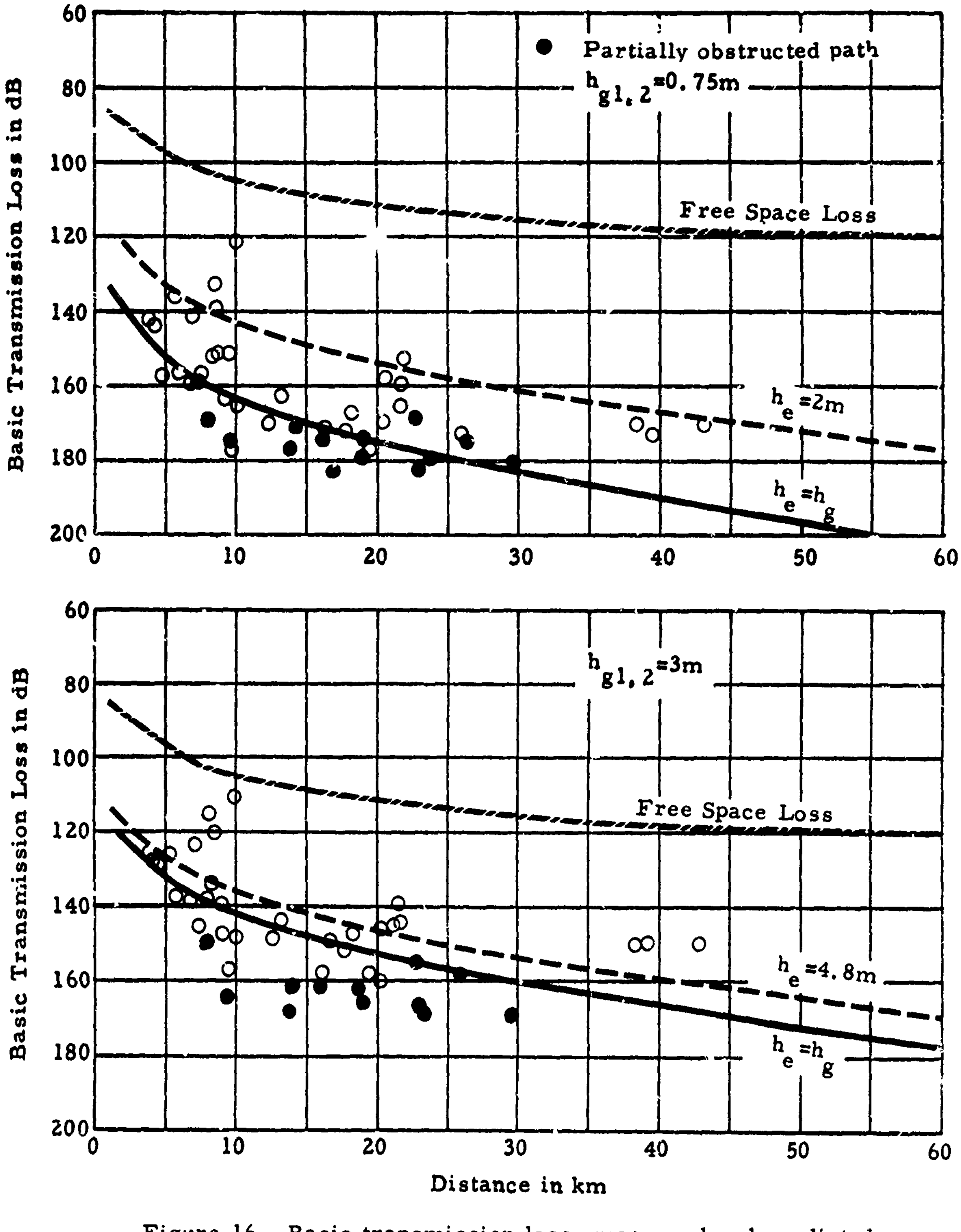



Figure 16. Basic transmission loss, measured and predicted, Laramie range, Wyoming, $\Delta h$=120m, f=416MHz.

shows that the three paths that are more than 38 km long are all single horizon knife-edge diffraction paths, where less than average transmission loss is expected.

The path-to-path or location variability is not very large, with a standard deviation of 9 or 10 dB. If care were exercised to select only antenna sites with clear foreground terrain, the larger values of transmission loss could be avoided, even with these very low antennas, and the path-to-path variability would be considerably reduced. For many applications the variability introduced by low values of transmission loss over unusually favorable line-of-sight or knife-edge diffraction paths is much less important than that resulting from unusually poor propagation conditions.

2.4.2 Idaho Paths

Measurements were made over some 31 paths in the lava flows of Idaho. The area consists of extensive plains cut by stream valleys. In the northeastern part much bare lava is exposed, while to the southwest there is a considerable depth of soil in places with some sagebrush and prairie grass cover. No detailed maps are available for most of the test area and profiles were read from one by two degree maps with a contour interval of 200 ft. Maps on this scale show only the gross features of terrain, so estimates of the terrain parameter, the horizon distances, and the elevation angles are subject to considerable error. For a few paths located in the southwestern part of the area, finer scale maps are available. Information from these was compared with that from the coarse-grained maps and for these few paths no major differences were noted. This is relatively smooth terrain, with a median value $\Delta h = 60$ m and an interdecile range of $\Delta h$ from 25 to 116 m.

Figures 17 and 18 show measured and predicted values of transmission loss plotted as a function of distance for equal antenna

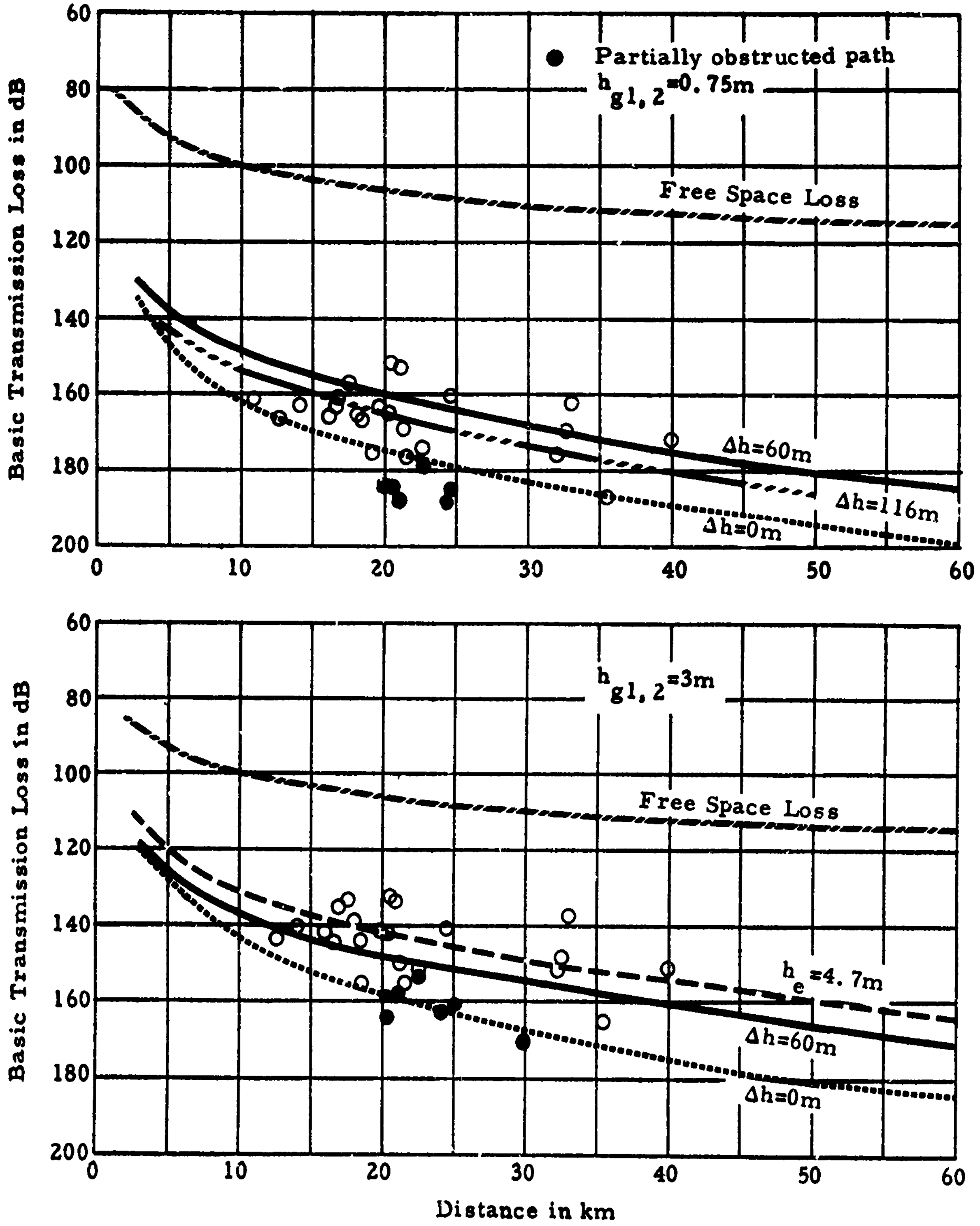



Figure 17. Basic transmission loss, measured and predicted, lava flows, Idaho, median Δh=60m, f=230MHz.

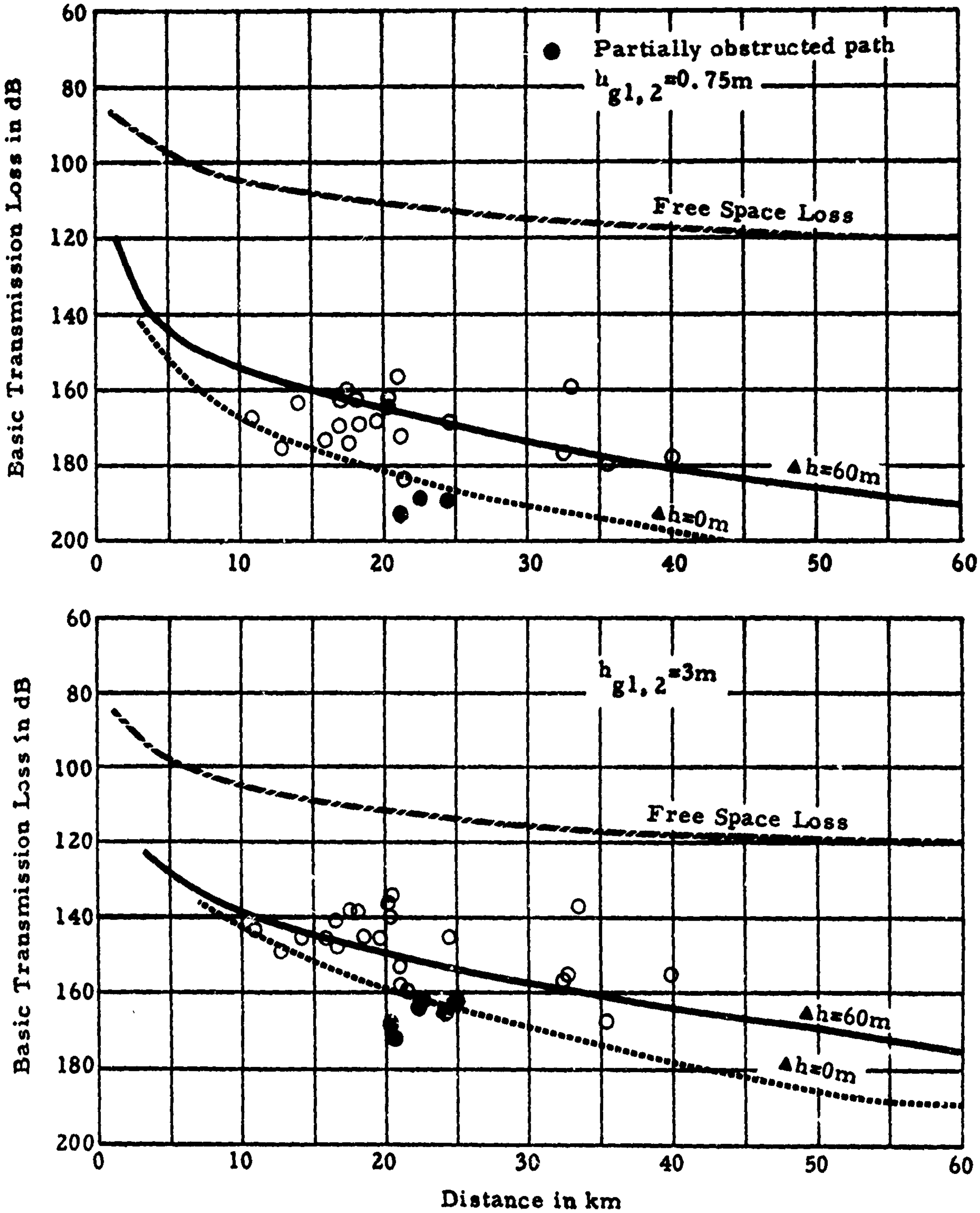



Figure 18. Basic transmission loss, measured and predicted, lava flows, Idaho, median Δh=60m, f=416MHz.

heights of 0.75 and 3 m, at frequencies of 230 and 416 MHz. Three curves of predicted basic transmission loss are shown in the upper half of figure 17 for values of $\Delta h$ = 0, 60, and 116 m, assuming the effective antenna heights equal to the structural heights of 0.75 m. These curves show the minimum, median, and upper decile of the estimates of $\Delta h$ for the 30 measurement paths. Note that as $\Delta h$ increases from zero to 60 m, the predicted values of basic transmission loss decrease, but that a further increase in $\Delta h$ results in an increase in the predicted loss. For the paths in this area the median value $\Delta h$ = 60 m is an optimum value for propagation, so with the lowest height many of the measured values show more loss than predicted, and the medians of data lie about halfway between the curves for $\Delta h = 0$ and $\Delta h$ = 60 m. The lower half of figure 17 shows three prediction curves, two with $h_e = h_g$ = 3 m for $\Delta h$ = 0 and 60 m, and one for $h_e$ = 4.7 m, $\Delta h$ = 60 m. In this figure the curve drawn for effective antenna heights equal to the structural heights with the median value of $\Delta h$ describes the medians of the data. In figure 18, where only the curves for $h_e = h_g$ and for $\Delta h$ = 0 and 60 m are drawn, similar results are observed.

Photographs from each site in the direction of the other antenna show that in some cases the path is partially obstructed by a nearby hill, or the immediate foreground is obscured by sagebrush. These paths are coded in the figures, and show larger than average values of transmission loss. Even in this comparatively smooth terrain care in site selection can avoid unusually poor paths and reduce location variability, but no great advantage can be gained from siting for unusually good propagation conditions because there are few isolated hills or ridges.

### 2.4.3 Washington Paths

Measurements were made in three localities in Washington at frequencies of 230 and 416 MHz. Fifteen paths were located in an area of plains and low hills near Ritzville, where some of the acreage is planted in wheat, and the rest is covered by prairie grasses. This terrain is characterized by a value $\Delta h = 70$ m. A second group of 39 paths were chosen in rugged terrain with steep hills, coulees, and deep canyons with almost vertical walls, where the principal ground cover is sagebrush. The median value of the terrain parameter $\Delta h = 210$ m for these paths is used to characterize the terrain in this area. A third group of 14 paths were selected in the Spokane river valley near Fort Spokane. These are short paths with a common receiver site in the valley and transmitter sites in the surrounding mountains. The terrain is very rugged, characterized by a value $\Delta h = 305$ m, and is largely covered by coniferous forest.

The measurements made near Ritzville and corresponding predicted values are shown in figures 19 and 20. The predictions are for randomly chosen sites, with the effective heights equal to the structural heights. The results in this area are quite comparable to those in Idaho.

Measurements made in the areas of rugged terrain are shown in figures 21 and 22. Data from the few short paths in the Spokane area are included with the larger sample. Although no specific attempt was made to choose sites that would provide good propagation conditions, an examination of the path profiles shows that most of the sites were selected on hilltops and provide an unusually large number of line-of-sight and single horizon paths. The curves showing predicted values are drawn for selected sites with $\Delta h = 210$ m. Using $\Delta h = 305$ m the predicted values are a little larger than those shown by the curve. At both 230 and

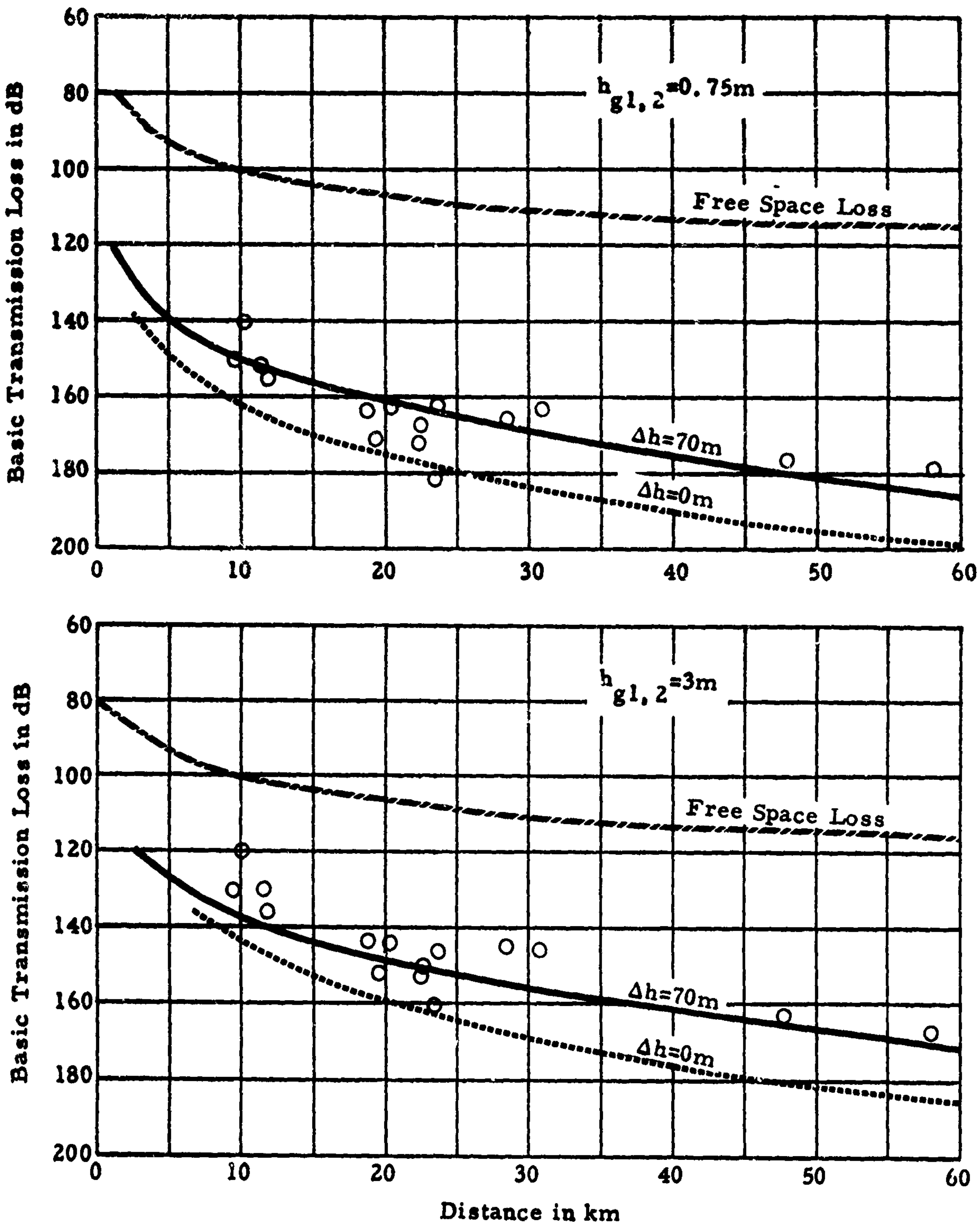



Figure 19. Basic transmission loss, measured and predicted, Ritzville area, Washington, Δh=70m, f=230MHz.

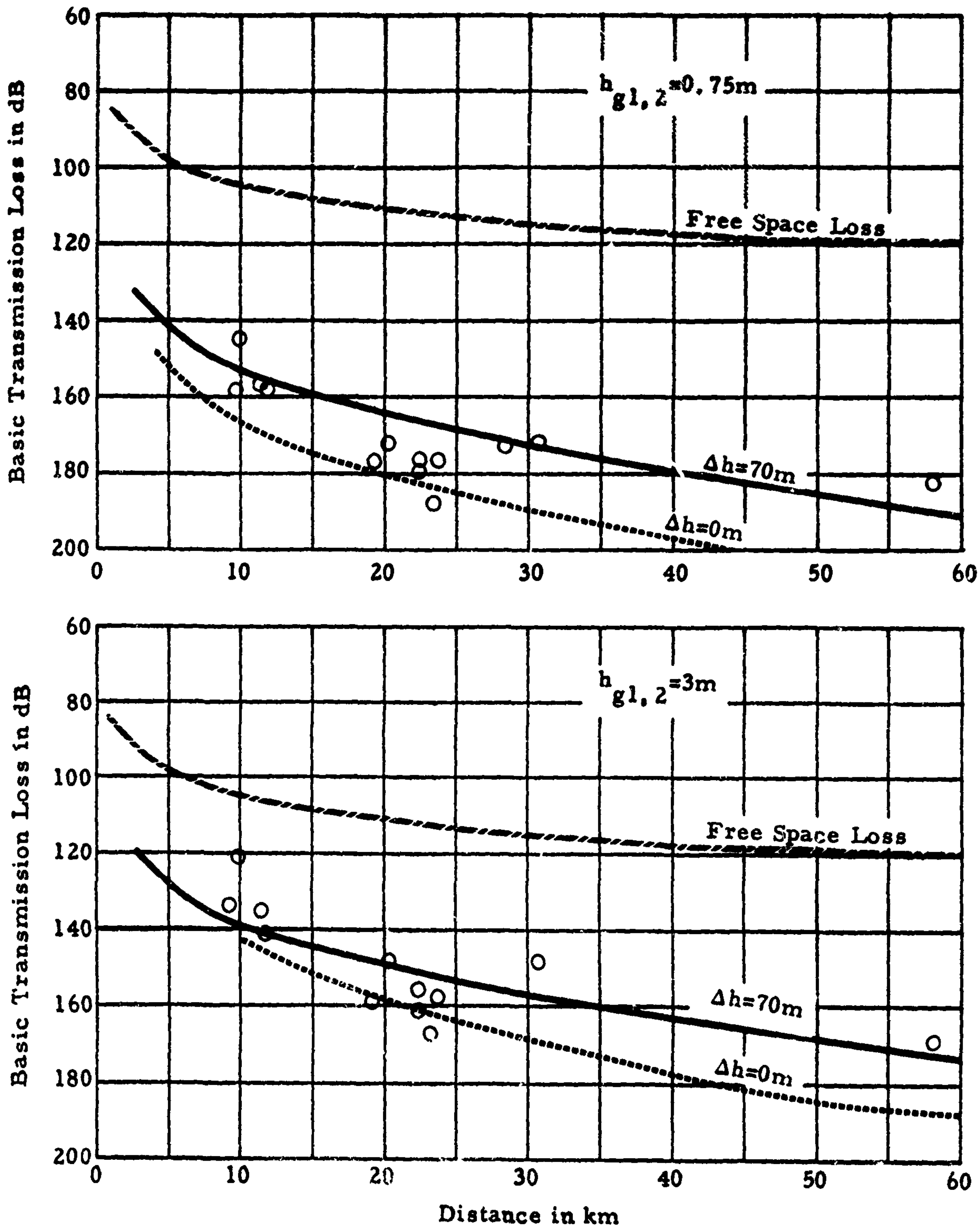



Figure 20. Basic transmission loss, measured and predicted, Ritzville area, Washington, Δh=70m, f=416MHz.

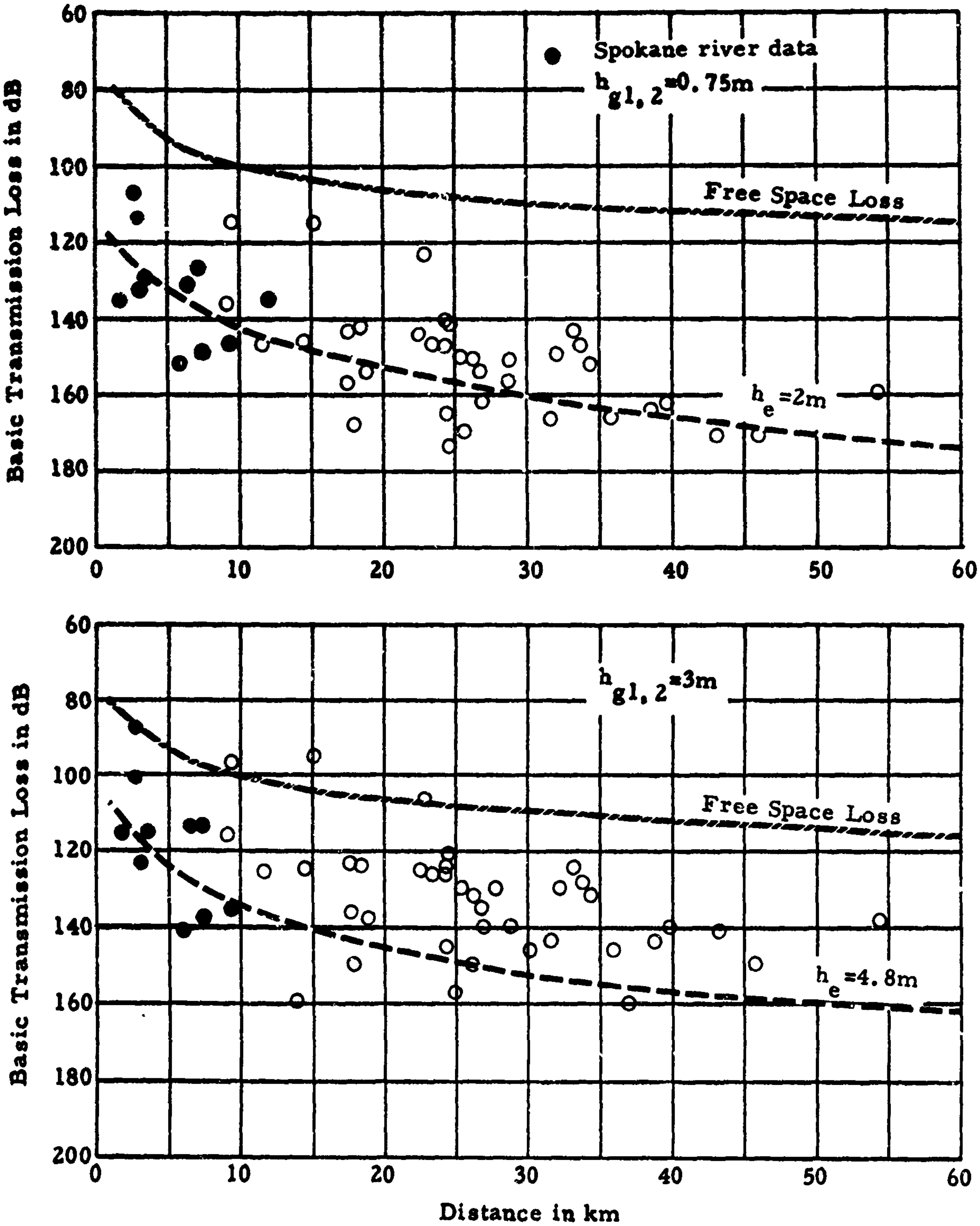



Figure 21. Basic transmission loss, measured and predicted, mountainous terrain, Washington, $\Delta h$=210 and 305m, f=230MHz.

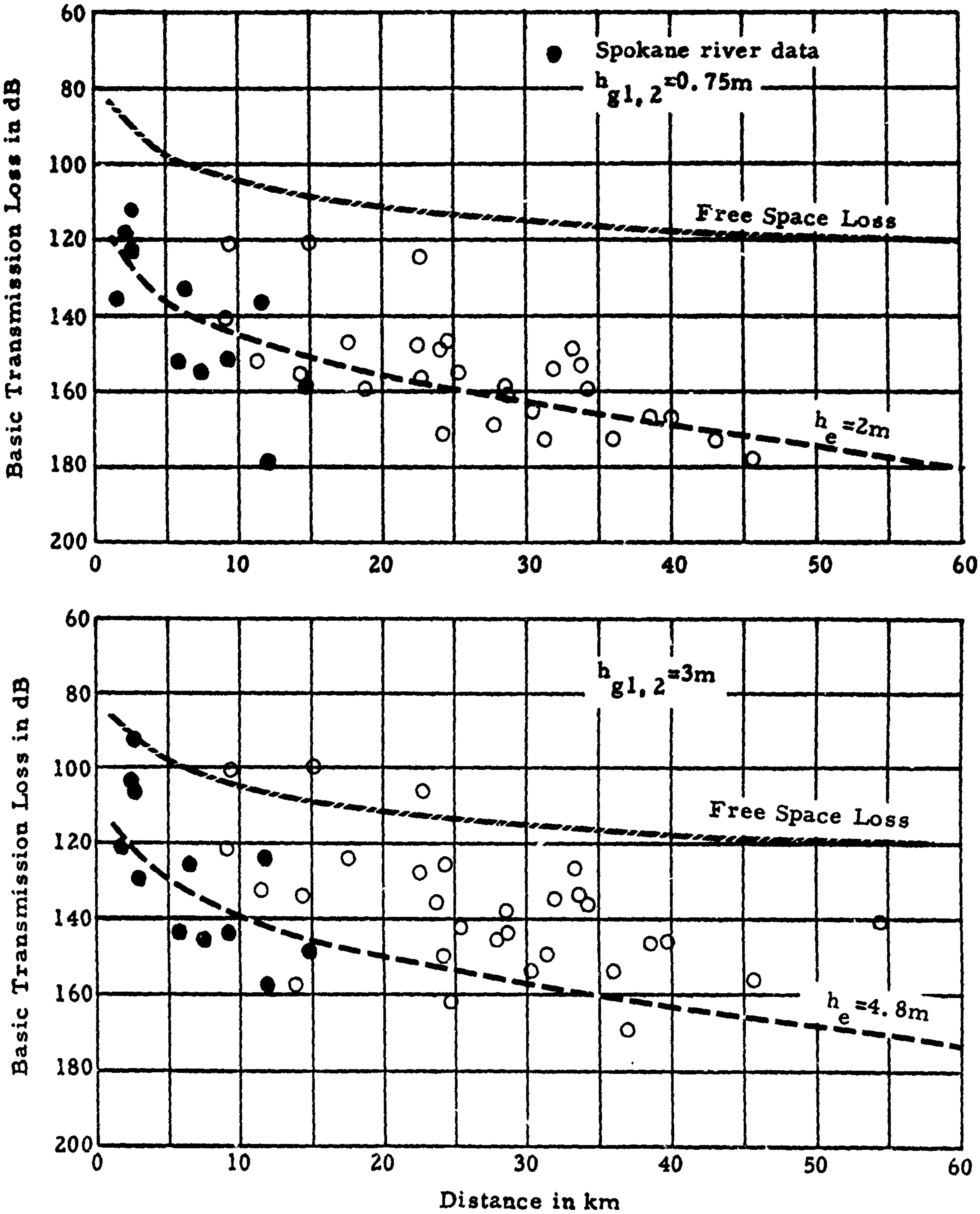



Figure 22. Basic transmission loss, measured and predicted, mountainous terrain, Washington, Δh=210 and 305m, f=416MHz.

416 MHz the predicted values overestimate the transmission loss especially for the higher antennas. Calculations based on very carefully selected sites would describe the medians of these data.

## 2.5 Measurements at VHF

A series of measurements with low antennas at frequencies of 20, 50, and 100 MHz was carried out in the Colorado plains and mountains and in an area in northeastern Ohio. This measurement program was sponsored by the U. S. Army Electronics Command to simulate net-type vehicular operations at frequencies up to 100 MHz and with antenna heights limited to less than 10 m above ground. The measurements in Colorado were made by personnel of the Institute for Telecommunication Sciences (formerly the Central Radio Propagation Laboratory of the National Bureau of Standards) and those in northeastern Ohio by Smith Electronics under contract to CRPL. Details of geographical locations, experimental procedures, and cumulative distributions of the data are reported by Barsis and Miles (1965), while path profiles and a complete tabulation of data are contained in a series of reports by Johnson et al. (1967).

All measurements in the Colorado plains and mountains were made from a common transmitter site northeast of Boulder. Receiving sites were selected from a map study at nominal distances of 5, 10, 20, 30, 50, and 80 km from the transmitter site, which is close to the plains-mountains boundary. All transmissions were continuous wave, using vertical polarization at 20.08 and 49.72 MHz, and both vertical and horizontal polarization at 101.5 MHz.

The measurement program in Ohio was conducted in an area surrounding Cleveland, using one central and five peripheral transmitters. Receiver sites were selected in concentric circles around the central transmitter at distances of 10, 20, 30, and 50 km. All paths were in hilly and partly wooded terrain, with none in urban areas. Transmission was at 19.97, 49.72, and 101.8 MHz with vertical polarization, and at 101.8 MHz with horizontal polarization.

In this report comparisons with predictions are shown for data taken using vertical polarization. Comparisons with data at 100 MHz using horizontal polarization are very similar to those using vertical polarization. Most of the comparisons are with data for the "principal" or randomly selected receiver site. An alternate site is the readily accessible site within a 100 m radius of the principal site at which a maximum value of field strength was recorded. An example of the resultant improvement in propagation conditions in Ohio is included.

The measurements in Colorado were chiefly in the plains but extended into the mountains. The paths were rather arbitrarily divided into two groups, those in the plains and those in the mountains. The separation is not clear-cut, as both groups include some measurements in the foothills, and neither group can be considered as representative of homogeneous terrain.

Point-to-point predictions for all paths in Colorado and Ohio have been compared with measurements and will be discussed in section 3.

### 2.5.1 Colorado Plains

For paths in the Colorado plains the transmitting antenna heights were 3.3 and 4 m for 20.08 and 49.72 MHz, respectively, with receiving antenna heights of 1.3 m at the lower frequency and 0.55 and 1.7 m at the higher one. At 101.5 MHz the transmitting antenna height was 3.15 m, with receiving antennas 3, 6, and 9 m above ground.

The common transmitting site is located in an open area with level terrain and clear foreground. Most of the receiving sites show clear foreground in the direction of the transmitter, but some paths are partially obstructed by buildings or trees. Procedures were planned to simulate completely random choices of sites by selecting readily accessible sites at nominal distances from the transmitter with a separation of at least 1 km between adjacent sites.

Measurements were made over about 190 paths in the plains at nominal distances of 3, 5, 10, 20, 30, 50, and 80 km from the common transmitter. At each of the shorter distances only 13 paths were used, with 18, 35, 43, and 52 measurements at nominal distances of 20, 30, 50, and 80 km, respectively. Values of the terrain parameter calculated from profiles read from topographic maps for all measurement paths have a median value $\Delta h = 90$ m that characterizes terrain for the area. Values of $\Delta h$, ranging from almost zero to 275 m, were obtained showing the wide diversity of terrain in this group of paths.

Figures 23 and 24 show the median and interdecile range of basic transmission loss derived from measurements at nominal distances of 3, 5, 10, 20, 30, and 50 km and a curve of predicted values as a function of distance assuming randomly selected sites. Figure 23 shows the results of measurements at 20 MHz with antenna heights of 3.3 and 1.3 m, and at 50 MHz with a transmitter height of 4 m and receiver heights of 0.55 and 1.7 m, and corresponding predictions of basic transmission loss as a function of distance. Figure 24 shows data at 101.5 MHz with a transmitting antenna height of 4 m and receiving antenna heights of 3, 6, and 9 m, with corresponding predictions. In both figures the interdecile range of data is rather large, often more than 20 dB, but in most cases the medians show good agreement with

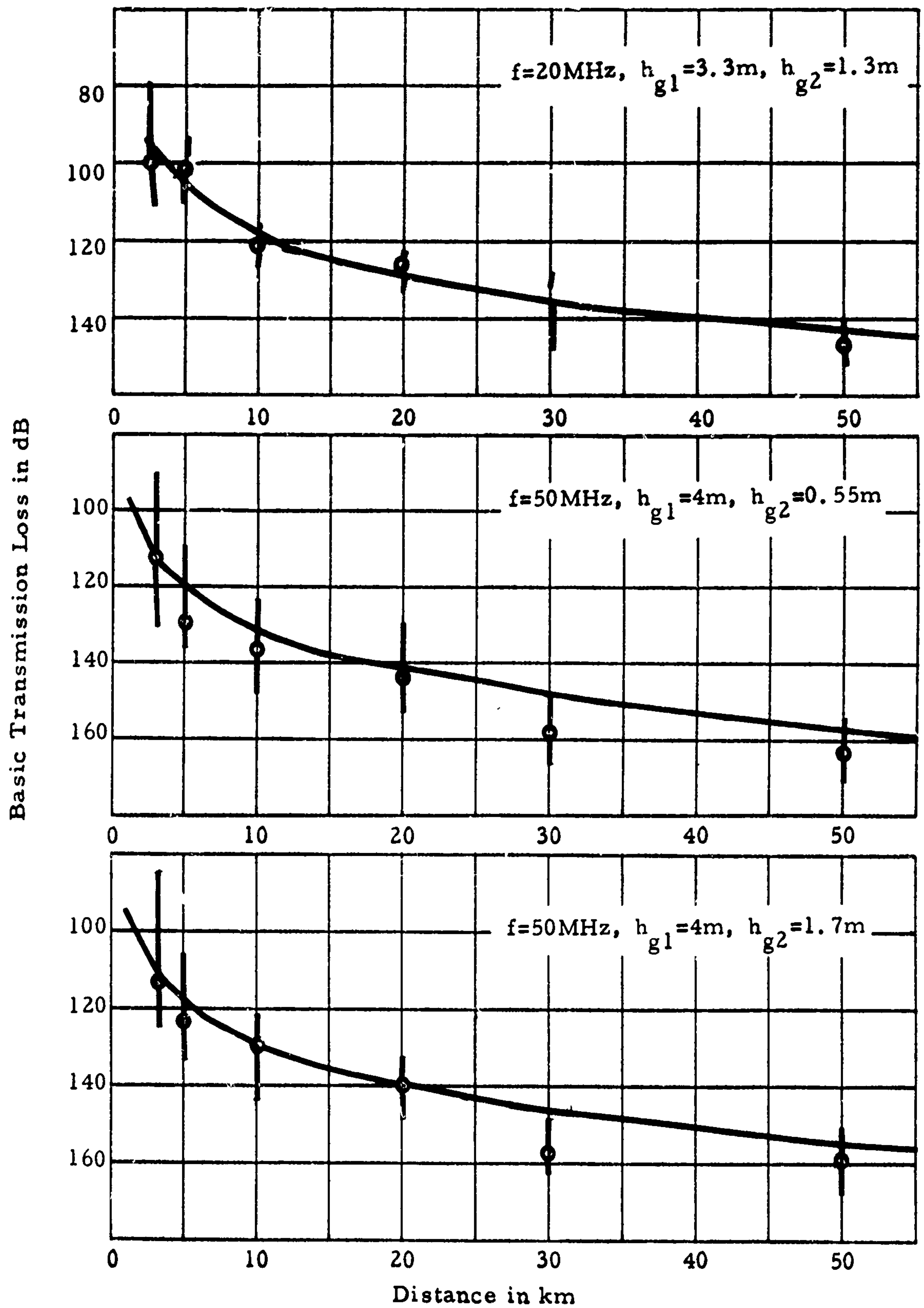



Figure 23. Basic transmission loss, Colorado plains, $\Delta h \approx 90$m, f=20 and 50MHz, showing median and interdecile range of values at each nominal distance.

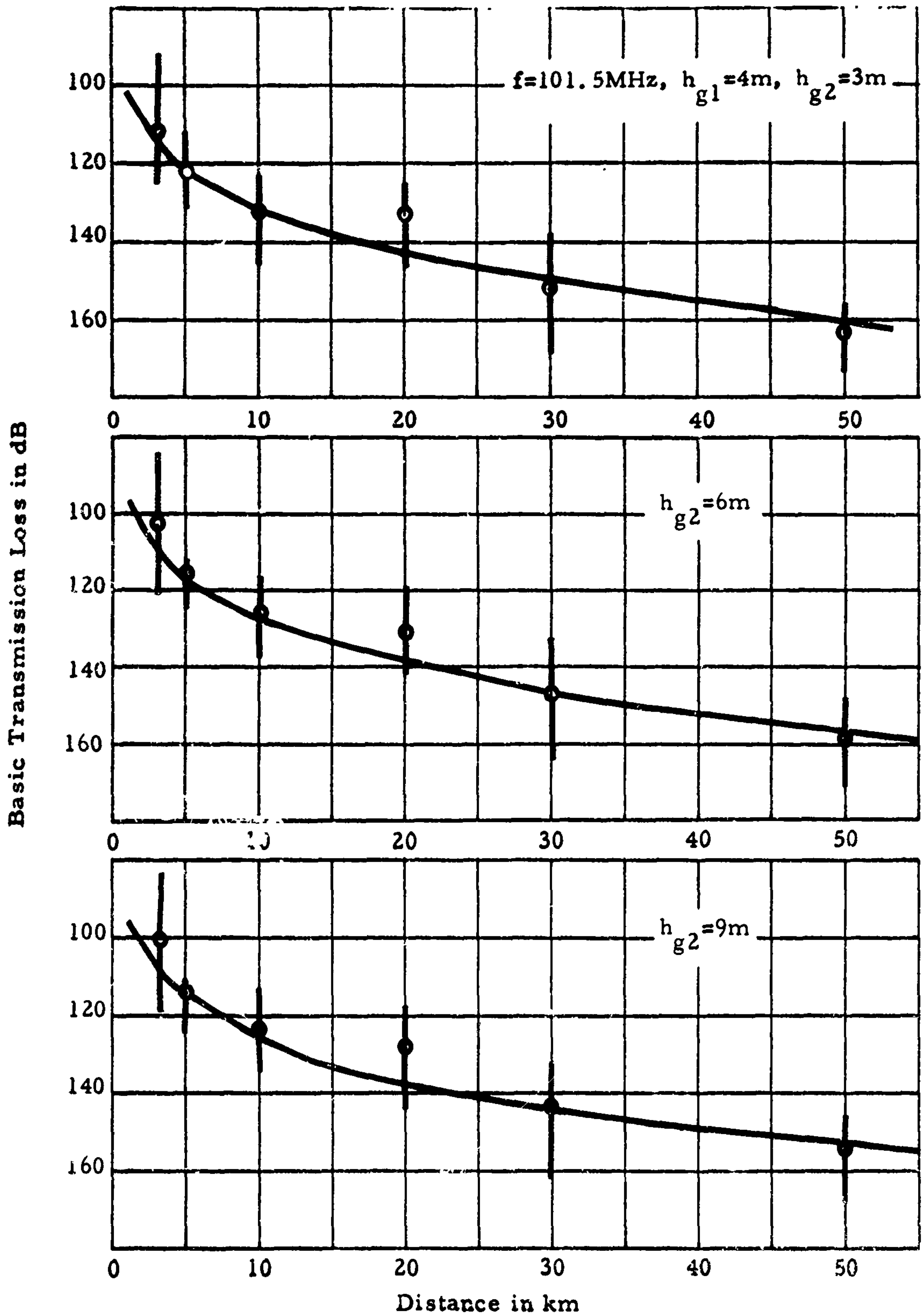



Figure 24. Basic transmission loss, Colorado plains, Δh=90m, f=101.5MHz, showing median and interdecile range of values at each nominal distance.

the predicted values. Measurements at 101.5 MHz and a distance of 80 km are not shown in figure 24 but agree with predictions as well as those shown at 50 km.

### 2.5.2 Colorado Mountains

About 46 of the measurement paths in Colorado extended from the transmitter site on the plains into the mountains and were classed as mountain paths. Of these paths 6, 10, 14, and 16 were at nominal distances of 10, 20, 30, and 50 km, respectively. A median value of the terrain parameter $\Delta h = 650$ m was used to characterize the terrain. Values of $\Delta h$ calculated from profiles of these paths range from 260 to 1750 m. The frequencies and antenna heights are the same as those for the Colorado plains.

Figures 25 and 26 show the median and interdecile range of basic transmission loss derived from measurements at nominal distances of 10, 20, 30, and 50 km, and a curve of predicted values as a function of distance assuming randomly selected sites. Figure 25 shows predicted and measured values at 20 and 50 MHz, while figure 26 shows values at 100 MHz for receiver heights of 3, 6, and 9 m. These two figures show a wide range of measured values at each distance and frequency but a reasonably good agreement of their medians with predicted values. The wide range of measured values probably results in part from the wide range in terrain irregularity, and in part from the fact that sites were randomly selected, without regard for good propagation conditions.

### 2.5.3 Northeastern Ohio

Measurements in northeastern Ohio were made with one central and five peripheral transmitting locations. The receivers were located on concentric rings about the central transmitter at nominal distances

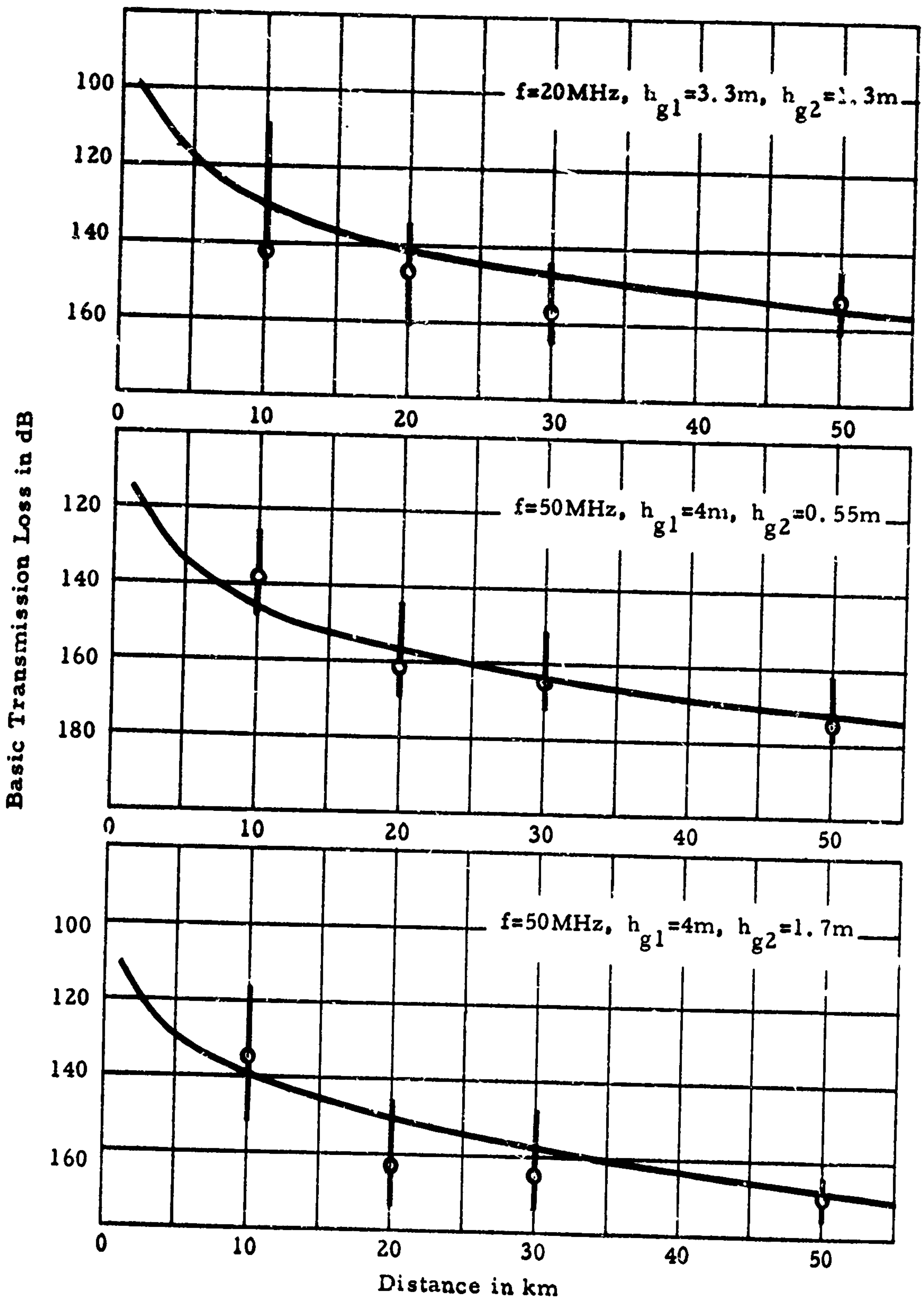



Figure 25. Basic transmission loss, Colorado mountains, $\Delta h$=650m, f=20 and 50MHz, showing median and interdecile range of values at each nominal distance.

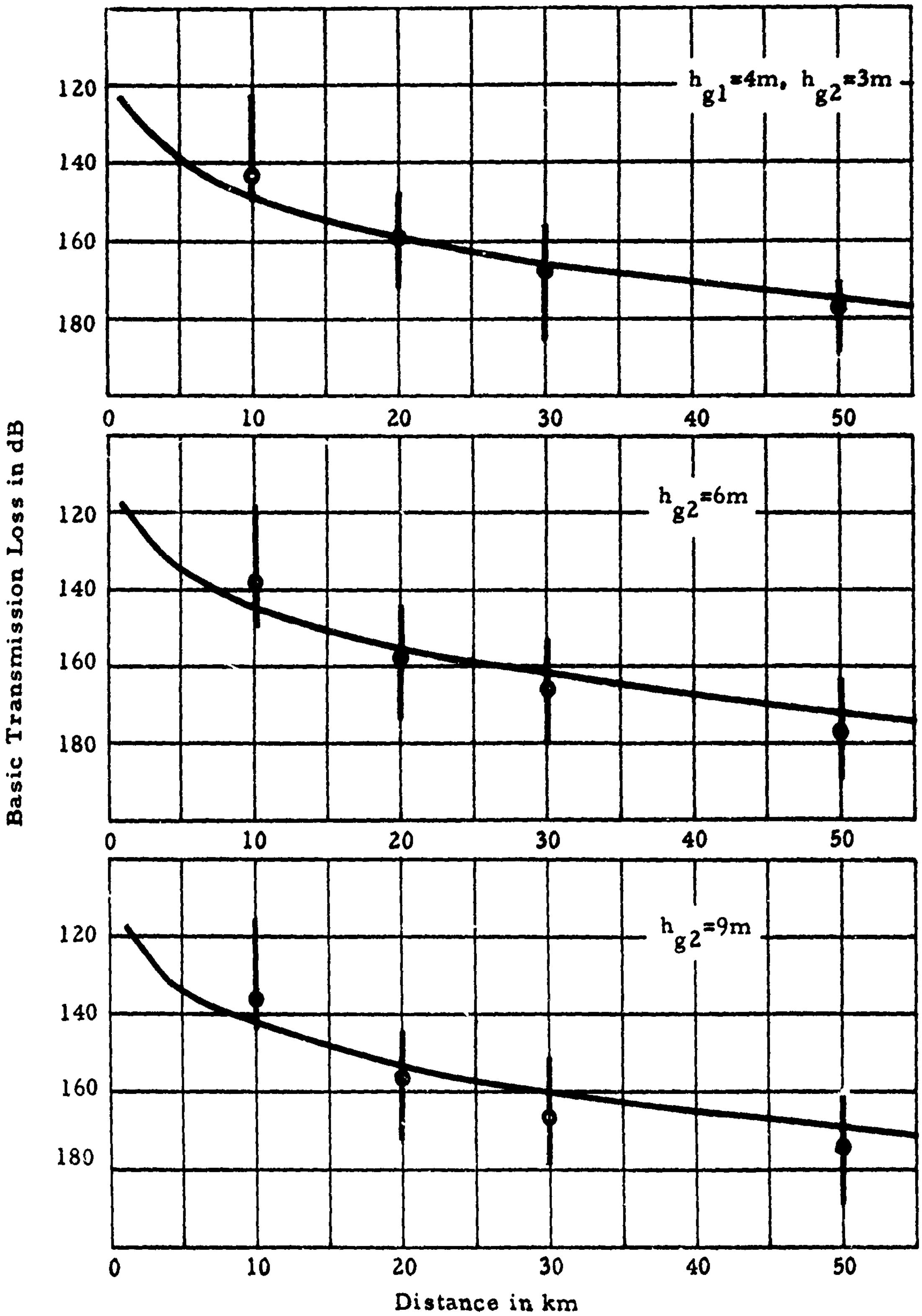



Figure 26. Basic transmission loss, Colorado mountains, $\Delta h$=650m, f=101.5MHz, showing median and interdecile range of values at each nominal distance.

of 3, 5, 10, 20, 30, and 50 km. The transmitting antenna heights were 3.3 m at 20 MHz and 4 m at 40 and 100 MHz. At 20 MHz the receiving antenna height was 1.3 m, at 50 MHz heights of 0.55 and 1.7 m were used, and at 100 MHz heights of 3, 6, and 9 m were used. With six different transmitter locations and a large number of receiving locations at each distance, these measurements should closely simulate a situation with randomly selected sites.

In this report we consider data from all transmitters, providing a total of about 255 paths. Of these, 45, 51, 67, and 92 are at nominal distances of 10, 20, 30, and 50 km, respectively, from the transmitter. Terrain profiles for all measurement paths were used to determine a median value of the terrain parameter $\Delta h = 90$ m. Values from individual paths ranged from 20 to 270 m.

Figures 27 and 28 show the medians and interdecile ranges of measured values at each nominal distance, with curves showing predicted basic transmission loss as a function of distance. In all cases, good agreement with medians of the data is noted with a rather wide range of data at each distance. The downward arrows at the longer distances indicate that several values were in the noise so the 90 percent level could not be determined. The improvement obtained by selecting the best receiving site within a 100 m radius of the principal site is shown in figure 29. The only difference between the data in figures 28 and 29 is the choice of receiving sites. Some improvement is noted at all distances and receiver heights but particularly with the lowest height and at the longer distances. On figure 29 two prediction curves are drawn for each set of data. The lower curve is for randomly selected sites with the effective heights equal to the structural heights $h_{e1,2} = h_{g1,2}$. The upper curve is calculated assuming that the receiving antennas are at carefully selected sites, $h_{e2} = 7$, 10.4, and 13.1 m.

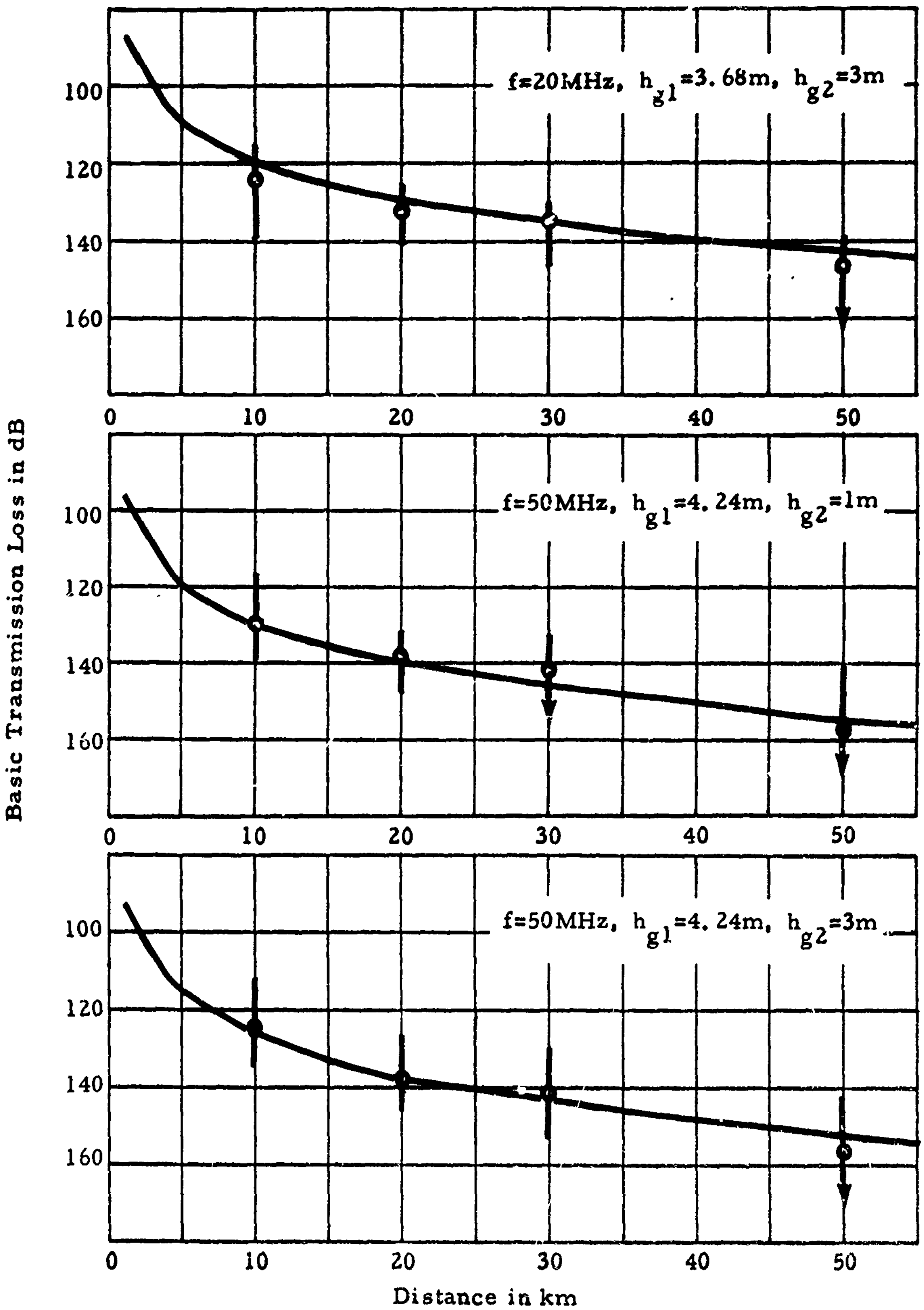



Figure 27. Basic transmission loss, Ohio, $\Delta h$=90m, f=20 and 50MHz, showing median and interdecile range of values at each nominal distance.

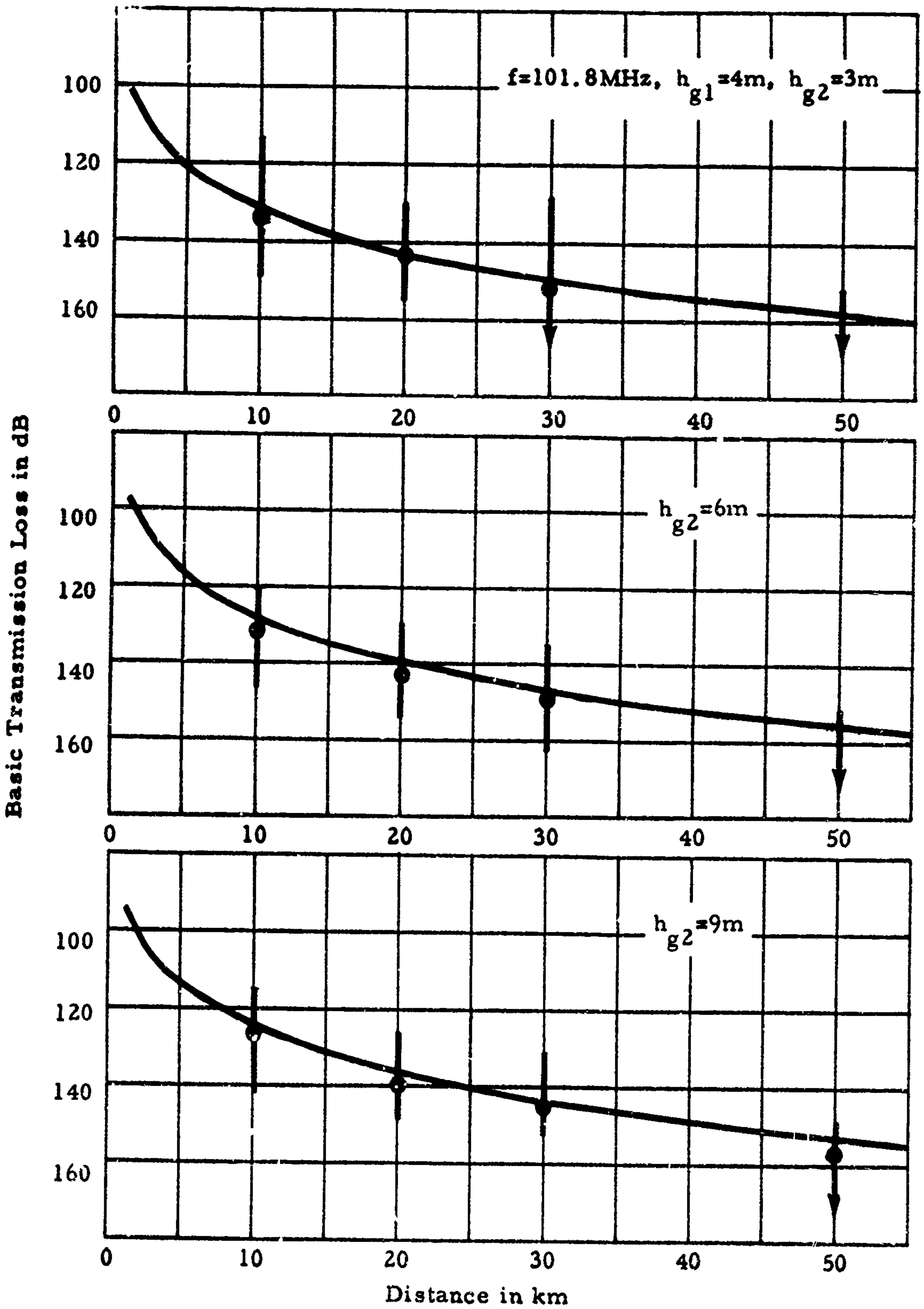



Figure 28. Basic transmission loss, Ohio, $\Delta h$=90m, f=101.8MHz, showing median and interdecile range of values at each nominal distance.

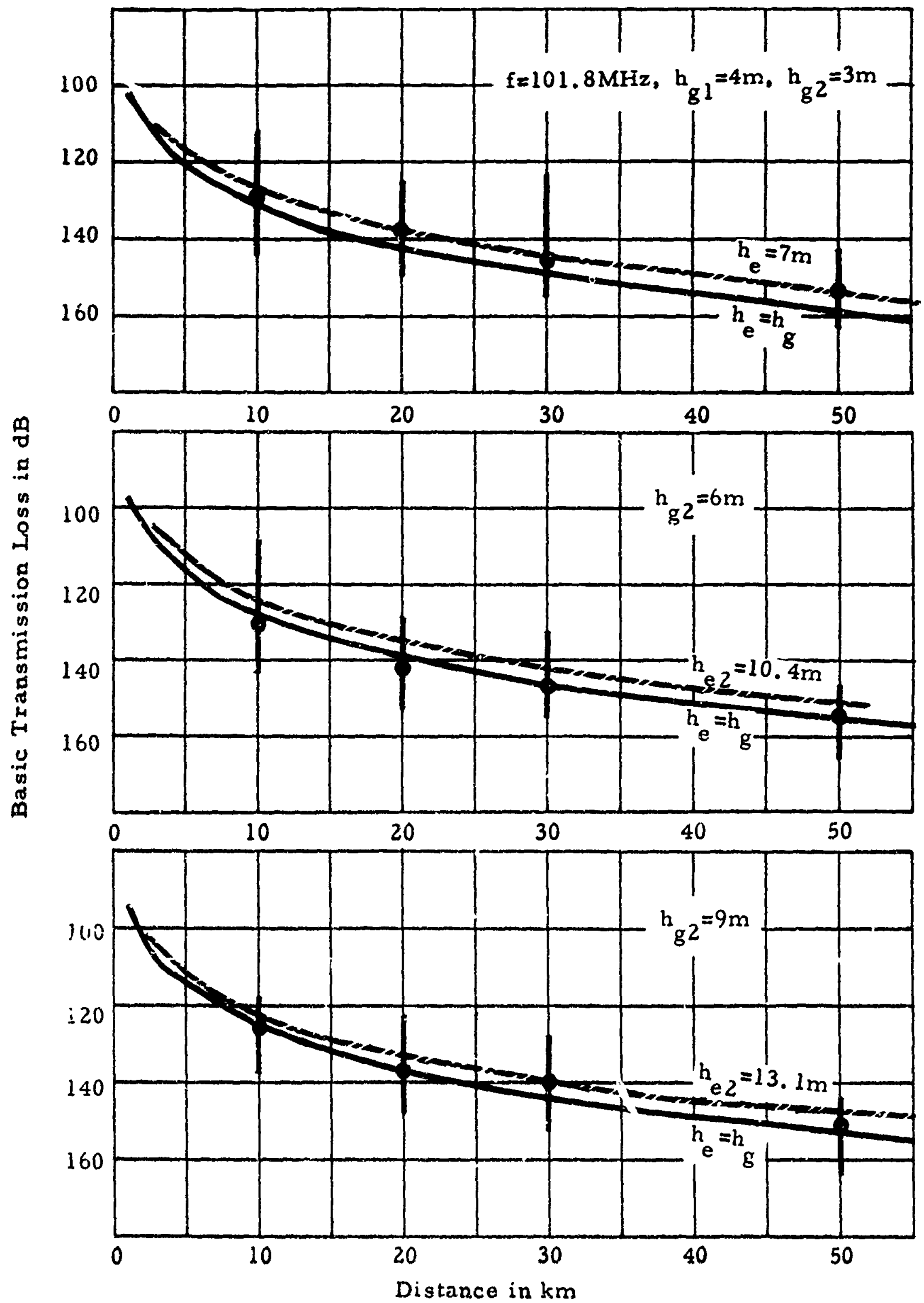



Figure 29. Basic transmission loss, Ohio, $\Delta h$=90m, f=101.8MHz, using alternate receiving locations, vertical polarization.

The observed improvement is slightly less than that predicted for carefully selected sites. This is to be expected as the improvement in each case is only at the receiving site.

### 2.6 Summary of Area Predictions

Area predictions of basic transmission loss as a function of distance are based upon an estimate of terrain irregularity in the area and the way in which antenna sites are selected. Such predictions depend upon median propagation conditions, where path parameters that are representative of median terrain characteristics are calculated from the terrain parameter $\Delta h$ and the structural antenna heights, with estimates of effective antenna heights depending upon the rules followed in site selection. If the terrain in an area is homogeneous so that values of $\Delta h$ calculated for individual paths do not diverge widely from the median value and antennas are all either advantageously or poorly situated, the scatter of data about the median will be minimized. In nonhomogeneous terrain a wide scatter of measured values may occur. In some groups of measurements a range of 60 dB, or more, between the highest and lowest values recorded over paths of the same length is observed. Most of this scatter of data results from differences in individual path profiles and in the way sites are selected. Some of the scatter may also result from the fact that these are single "spot" measurements. For the few paths where measurements were repeated on two or more different days the measured losses differed by as much as 15 to 20 dB over a single path.

Such path-to-path differences may be taken into account by an allowance for path-to-path or location variability. For many applications, the variability introduced by high values of field strength over unusually favorable transmission paths is much less important than that resulting from unusually poor propagation conditions. In such cases, care should 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 $\theta_{e1}$ and $\theta_{e2}$ from each antenna to its horizon, and their sum $\theta_e$, all expressed in milliradians, |
| $\theta$ | 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 $\Delta L$ 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 $\Delta h$, d, $d_{L1}$, $d_{L2}$, $\theta_e$, 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 $\Delta h$ 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 $\Delta h$, 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 $\theta_e$ 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 $\Delta h$ in both groups. The median $\Delta h$ 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 $\Delta h$ 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 $\theta_e$ 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 |
| $\Delta h$ | 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 |
| $\theta_e$ | -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 |
| $\Delta h$ | 159.9 | 251.4 | 289.3 | 354.8 | 432.3 | 511.1 | 657.0 | 718.7 | 914.4 | 1002.4 |
| $d_{L1}$ | 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 |
| $\theta_e$ | 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 $\Delta L$ 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, $\Delta L$ 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 $\Delta L$ for the Fritz Peak (R-2) receiver site. The predicted losses are greater than those observed at 230 and 410 MHz, with $\Delta L$ 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 $\Delta L$ for receiver

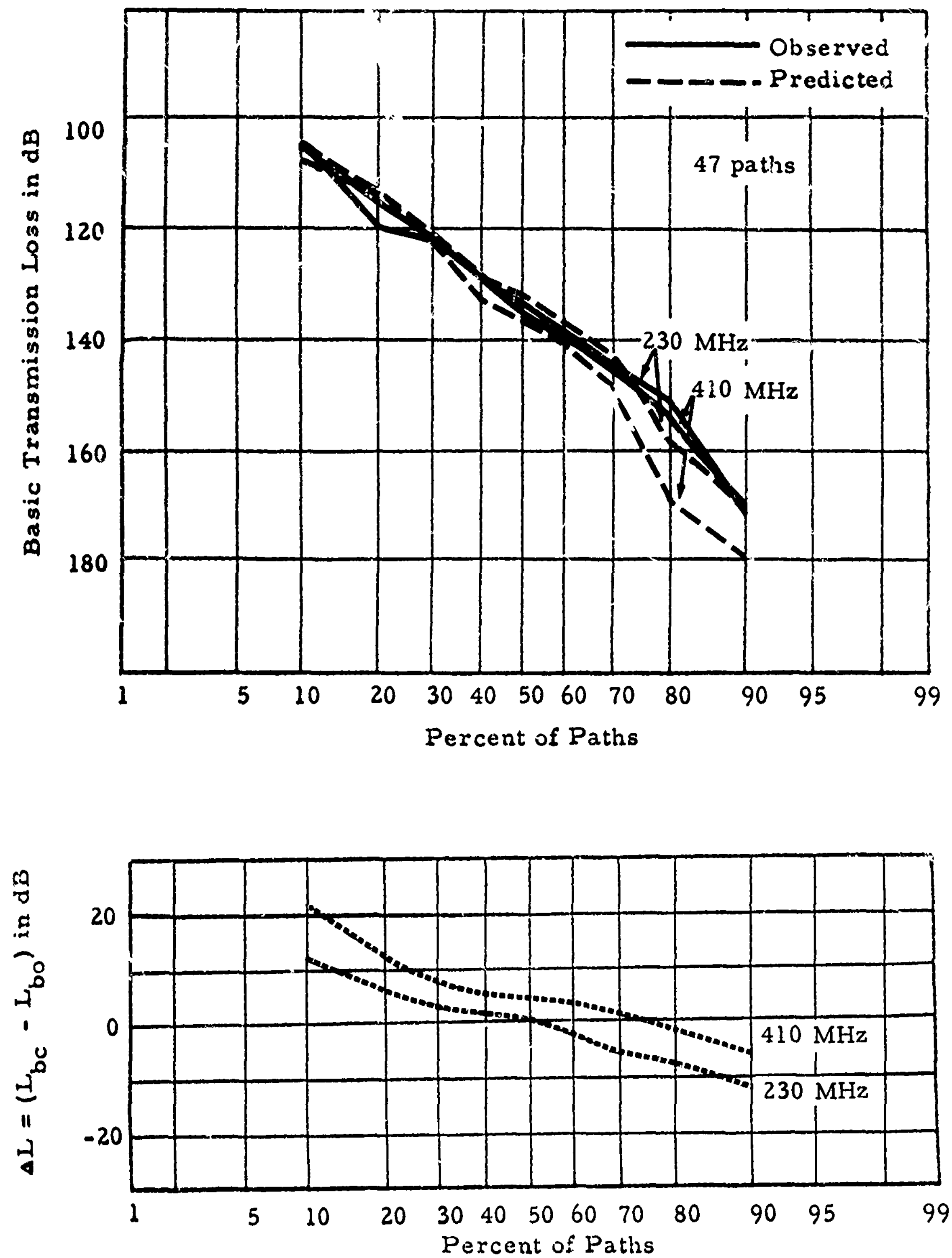



Figure 30. Cumulative distributions of basic transmission loss, observed and predicted, and of ΔL, Gunbarrel Hill, Colorado, R-1, $h_{g2}$=2 m, f=230 and 410 MHz.

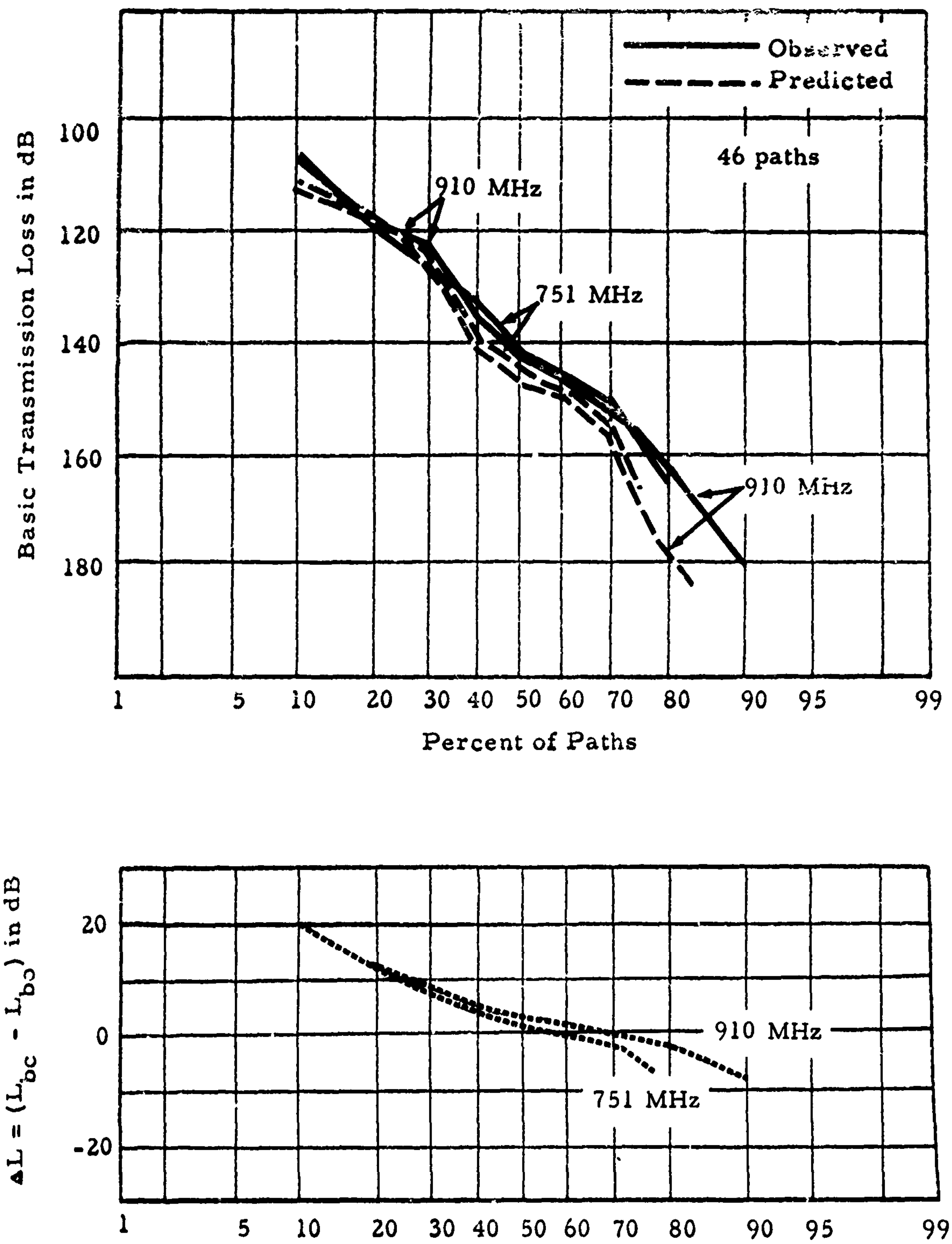



Figure 31. Cumulative distributions of basic transmission loss, observed and predicted, and of $\Delta L$, R-1, $h_{g2}$=2 m, f=751 and 910 MHz.

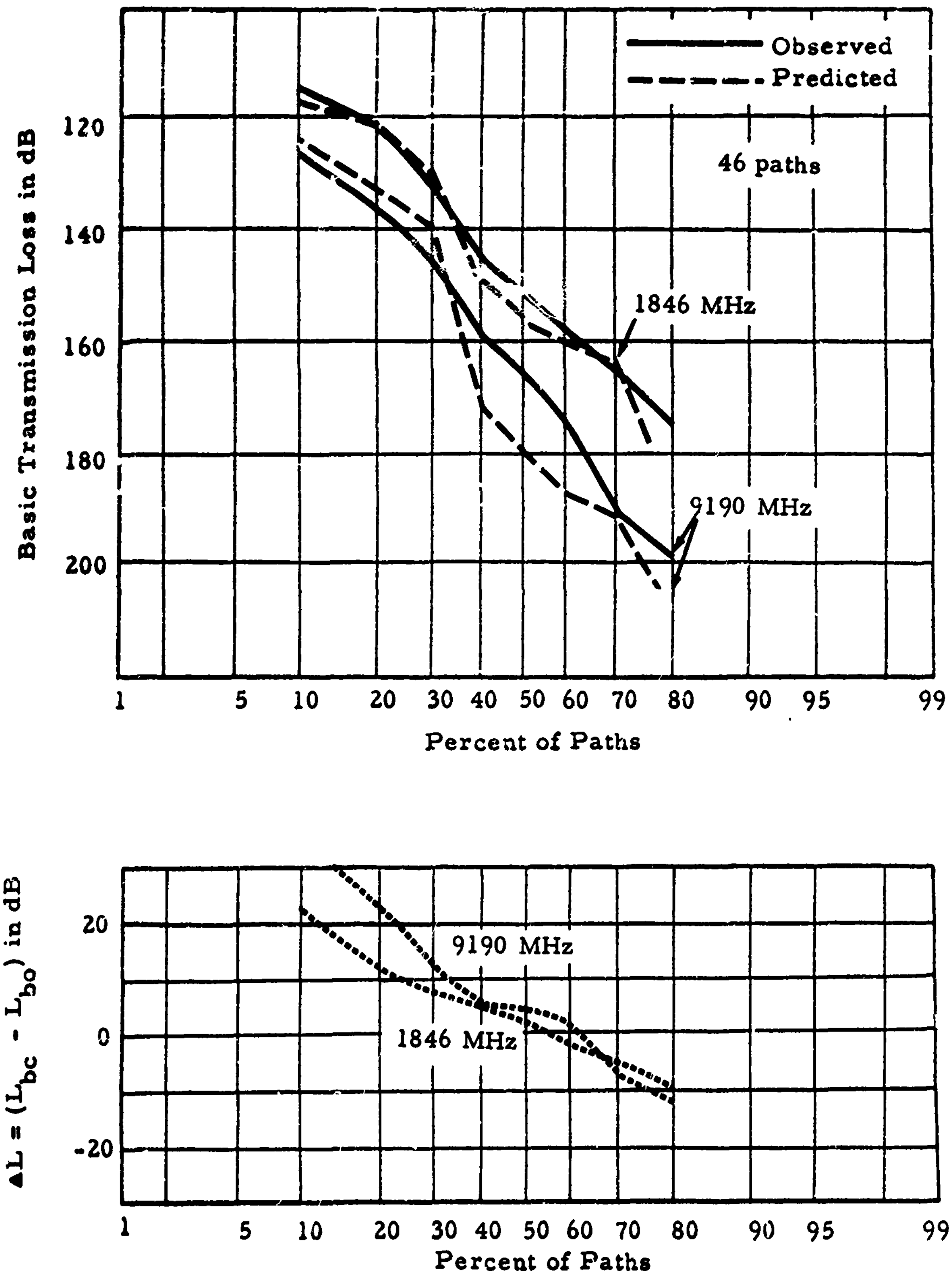



**Figure 32.** Cumulative distributions of basic transmission loss, observed and predicted, and of $\Delta L$, R-1, $h_{g2}=2$ m, f=1846 and 9190 MHz.

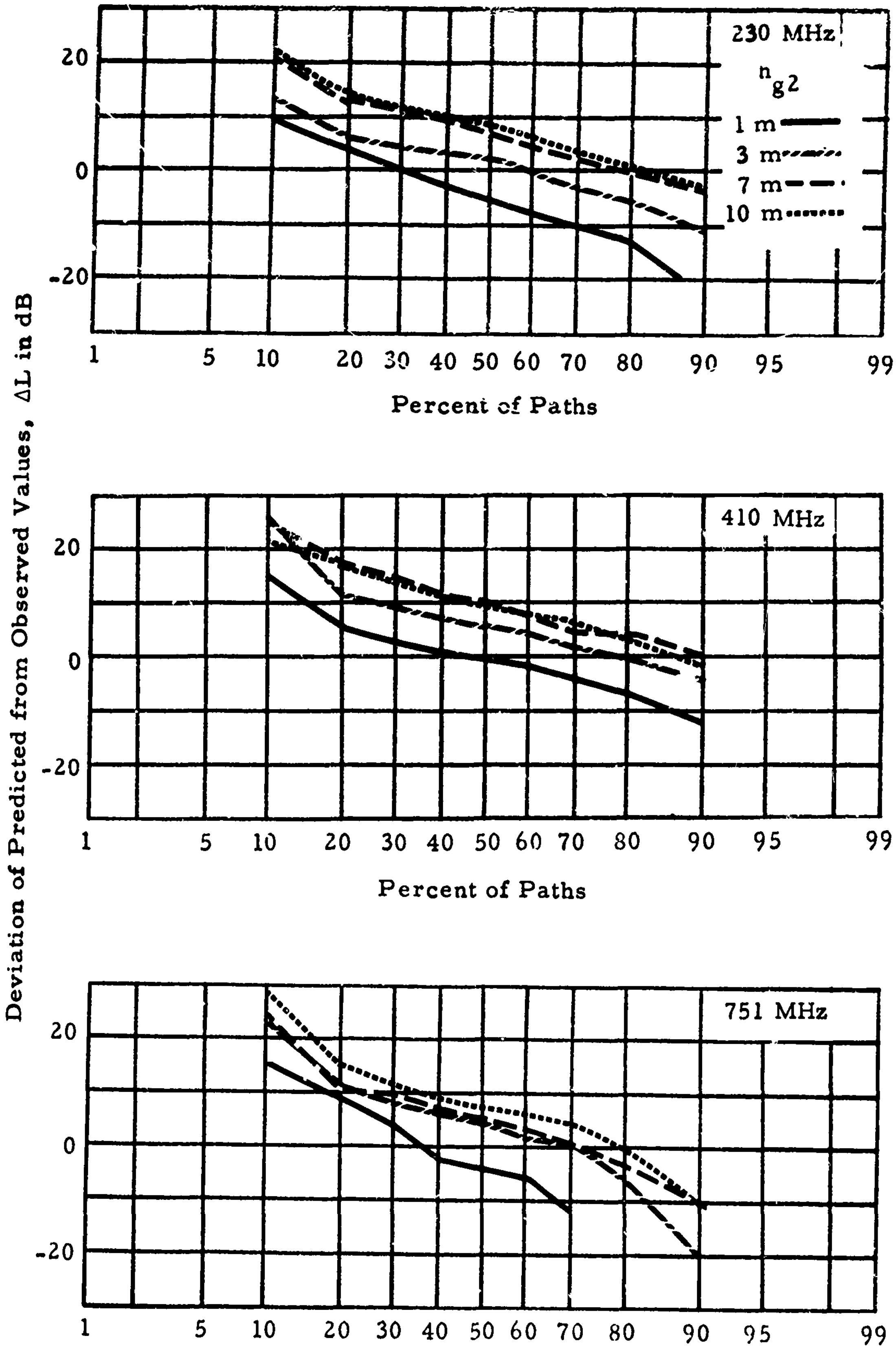



Figure 33. Cumulative distributions of ΔL showing the effects of increasing receiver height, R-1, f=230, 410, and 751 MHz.

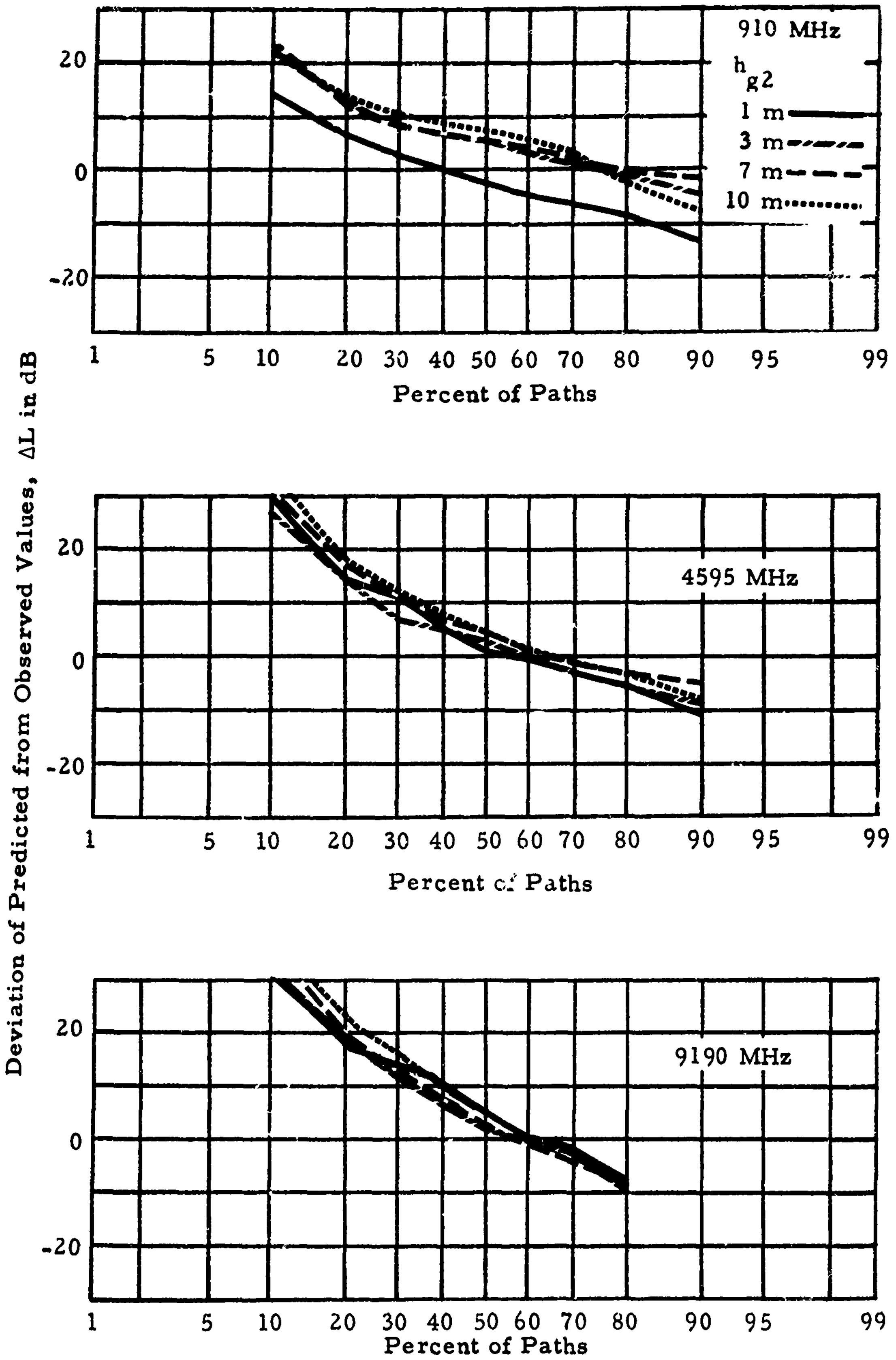



Figure 34. Cumulative distributions of ΔL showing the effects of increasing receiver height, R-1, f=910, 4595, and 9190 MHz.

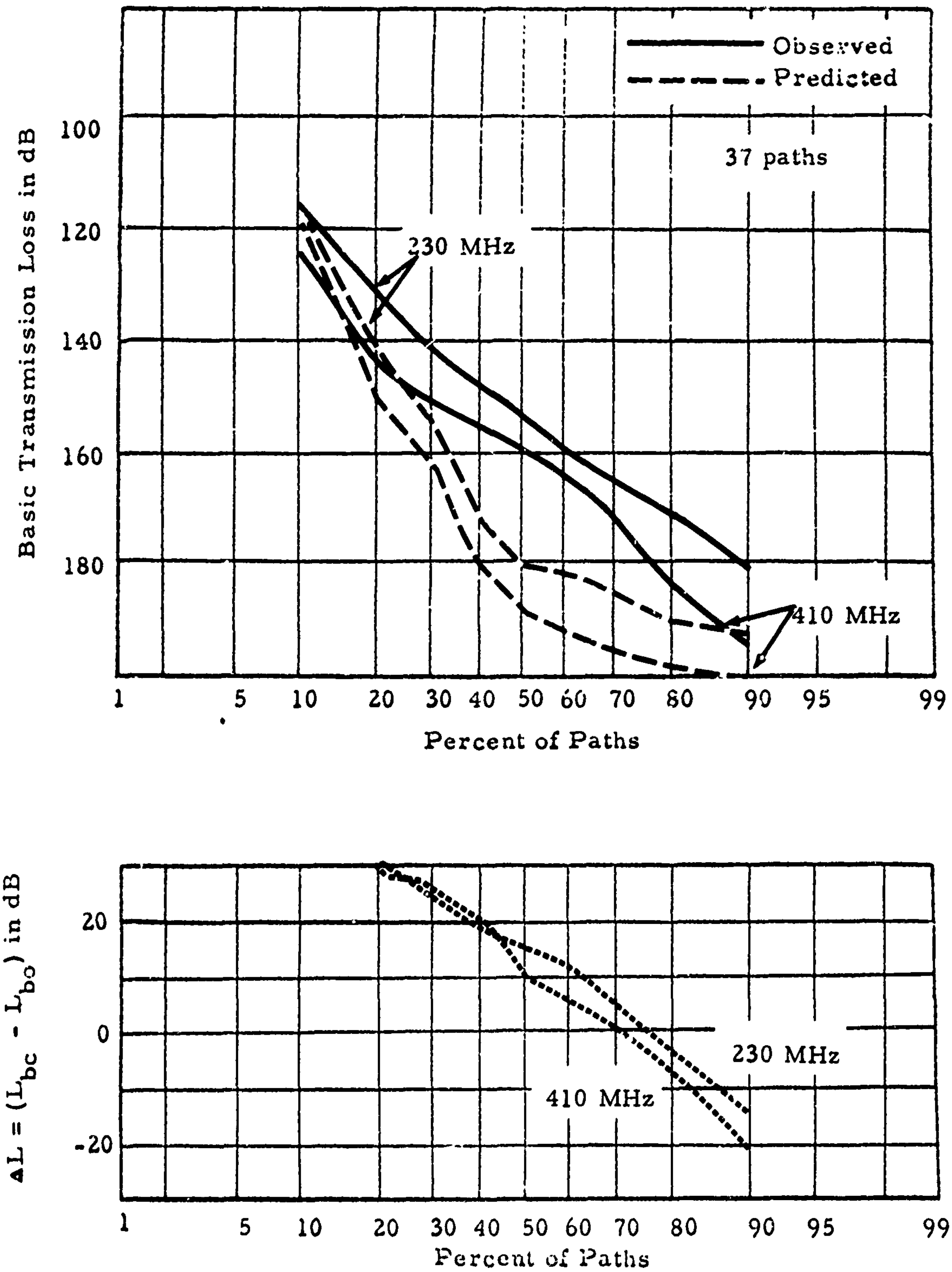



Figure 35. Cumulative distributions of basic transmission loss, observed and predicted, and of $\Delta L$, Fritz Peak, Colo., R-2, $h_{g2}$=2 m, f=230 and 410 MHz.

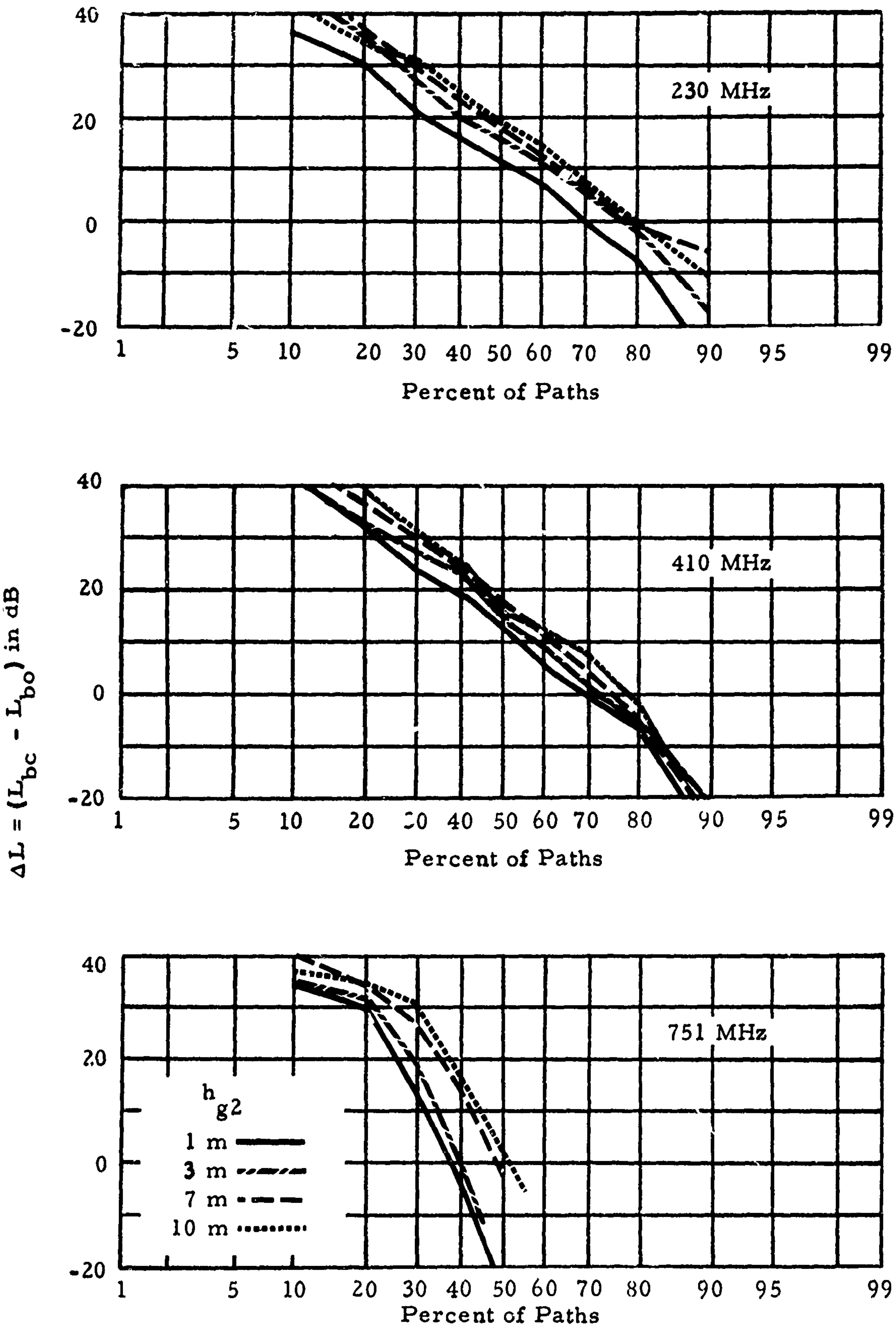



Figure 36. Cumulative distributions of $\Delta L$ showing the effects of increasing receiver height, R-2, f-230, 410, and 751 MHz.

heights of 1, 3, 7, and 10 m at frequencies of 230, 410, and 751 MHz. In this area also the deviations become more positive with increasing antenna height. At the higher frequencies no such comparisons could be made because more than half of the measurements were in the noise.

For both the R-1 and the R-2 data an unusually large proportion of the paths are either line-of-sight or one-horizon diffraction paths. The lack of agreement with increasing antenna height and the large predicted losses for the R-2 data suggest that the models for line-of-sight and one-horizon diffraction paths should be re-examined and possibly modified.

### 3.2 Virginia Paths

The results of measurements made in Virginia have not been completely analyzed. Terrain profiles have been read for 51 of the rather short paths. Of these 30 are line-of-sight paths and 5 are one-horizon paths. No tabulation of parameters is included for the 21 trans-horizon paths, as they would probably not be truly representative of the large number of measurement paths from seven transmitter sites in this area.

The measurements reported here were made with transmitter heights of 11.3 and 15.0 m and receiver heights of 12.1 and 15.0 m. Figures 37, 38, and 39 show cumulative distributions of basic transmission loss observed and predicted and of their differences for the 51 paths for which terrain profiles are available. These figures show good agreement between predicted and observed values, with a tendency to predict too much loss at 76 MHz and not enough at 2180 and 8395 MHz. In this area there is considerable forestation for which no allowance is made in the present prediction model. Such surface clutter would cause much more attenuation at the higher than at the lower frequencies, and

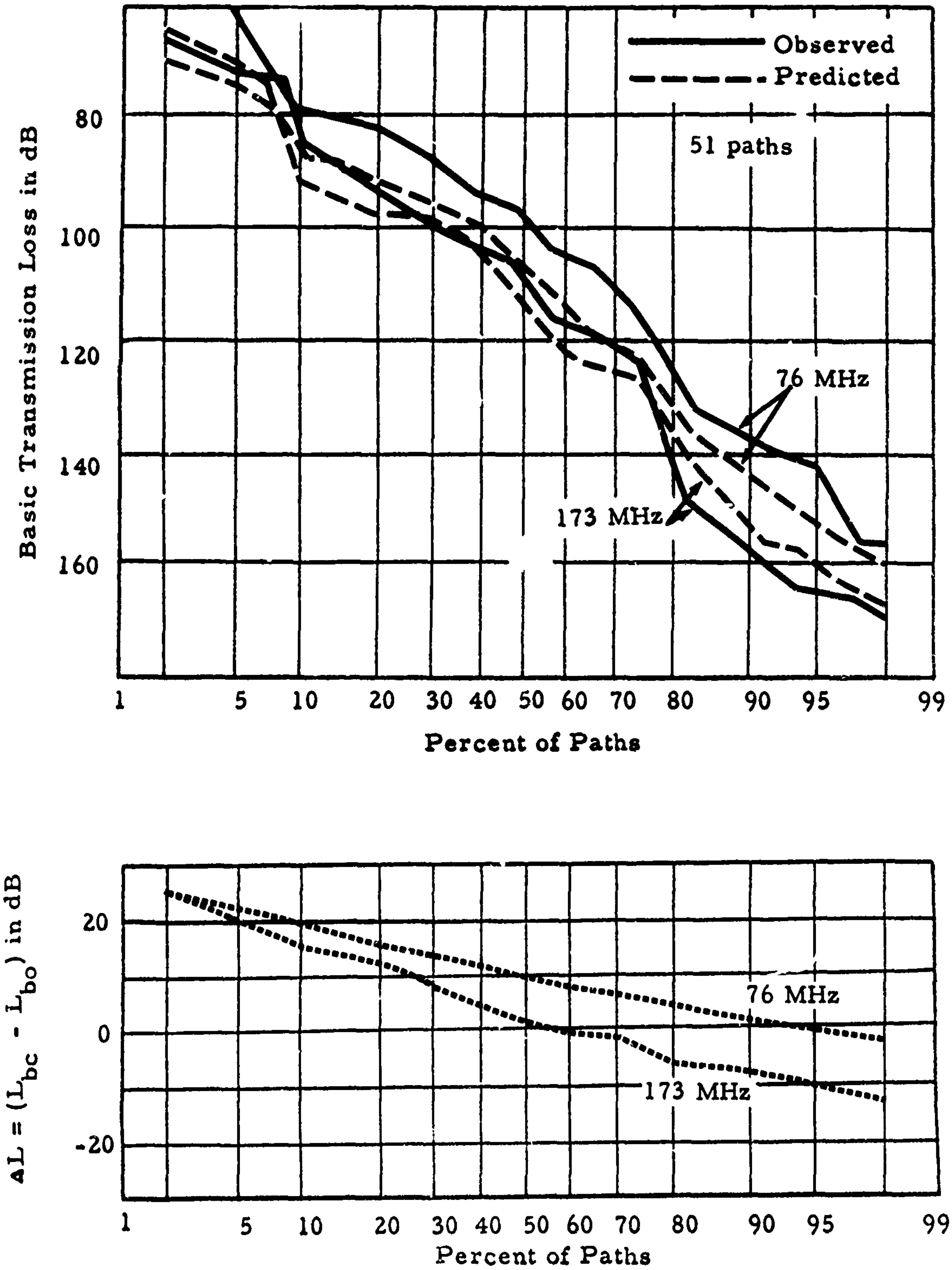



Figure 37. Cumulative distributions of basic transmission loss, observed and predicted, and of ΔL, Virginia, f=76 and 173 MHz.

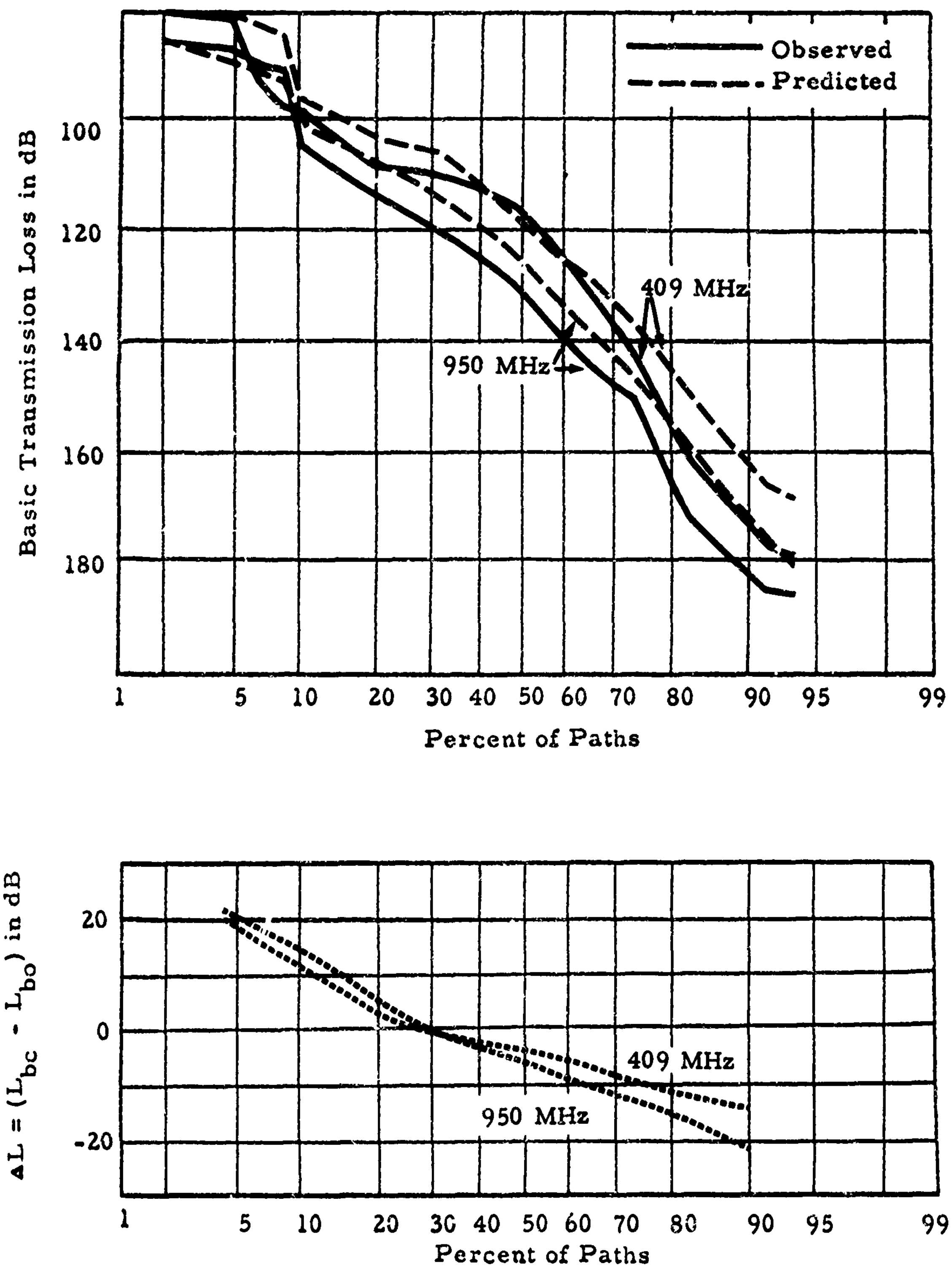
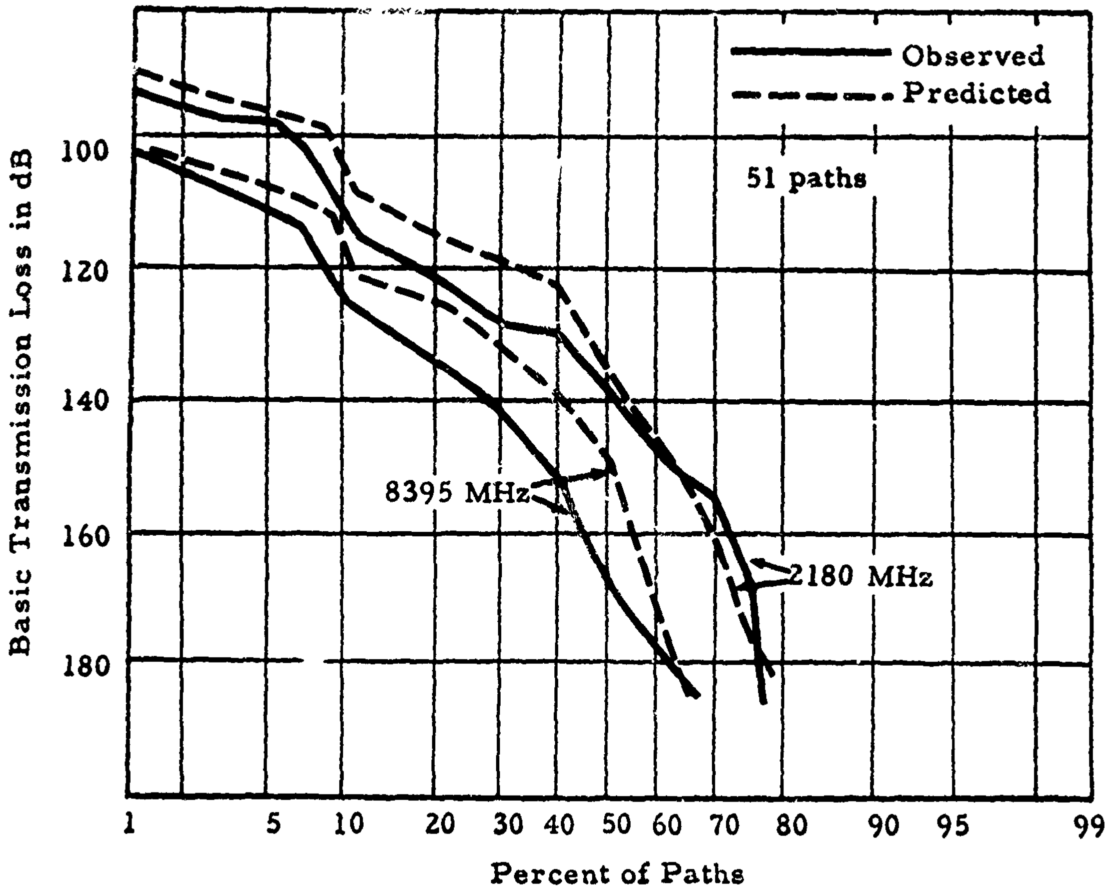



Figure38. Cumulative distributions of basic transmission loss, observed and predicted, and of ΔL, Virginia, f=409 and 950 MHz



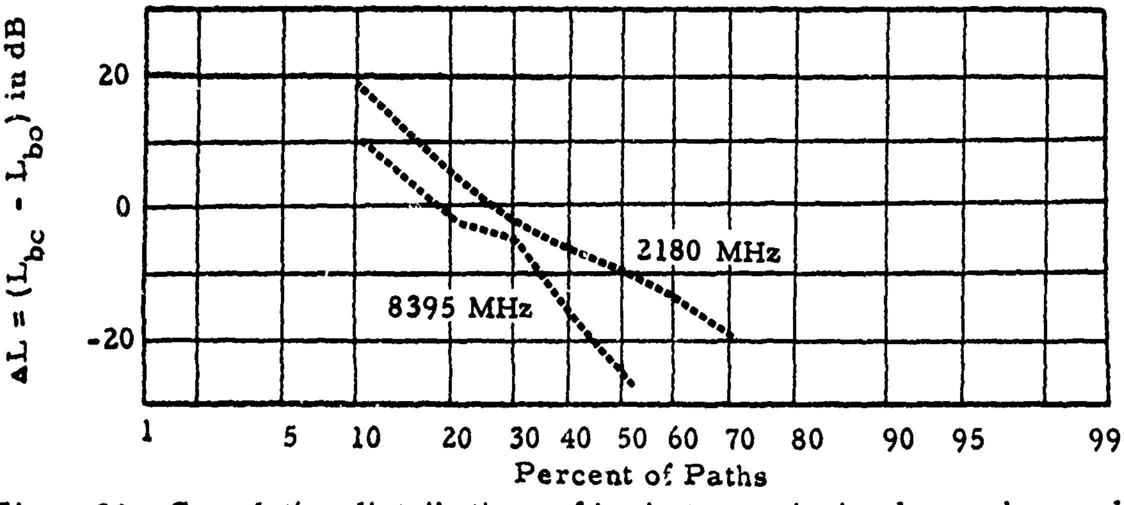




Figure 39. Cumulative distributions of basic transmission loss, observed and predicted, and of $\Delta L$, Virginia, f=2180 and 8395 MHz.

may be the explanation of these differences. This possiblity should be further investigated when more of these paths have been studied.

### 3.3 Wyoming, Idaho, and Washington

The measurements in Wyoming, Idaho, and Washington were limited to frequencies of 230 and 416 MHz, with very low antennas. The transmitting antennas were fixed at 0.75 and 3 m above ground, while the receiving antennas were raised continuously from 0.75 to 3 m. Both transmitting and receiving units were mobile, and sites were chosen without regard to propagation conditions.

Cumulative distributions of parameters for 47 paths in Wyoming and 30 paths in Idaho are listed in table 2. The parameters listed are for transmitting and receiving antenna heights of 0.75 m. Increasing both antenna heights to 3 m has little effect on the path parameters $d_{L1}$, $d_{L2}$, $d_L$, and $\theta_e$. However, with the lower heights we assume that the effective heights are equal to the structural heights, while with the 3 m antennas effective heights are estimated. These effective heights exceed the structural heights for about half of the paths in Wyoming, and for a few paths this increase is more than 30 m. The estimated effective heights in Idaho exceed the structural heights for about one-third of the paths.

The computer model is limited to situations where the distance from each antenna to its horizon is not less than one-tenth of the corresponding distance $d_{LS1,2}$ over a smooth earth. With antenna heights of 0.75 m, $d_{LS1,2} \simeq 3.5$ dB and their sum $d_{LS} \simeq 7$ dB. Table 2 shows that for many paths, especially in Wyoming, the horizon distances are less than one-tenth of these smooth earth values. The prediction

Table 2. Cumulative Distributions of Path Parameters, Wyoming and Idaho

| Para-meter | Min | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | |
| | Laramie Range, Wyoming, 47 paths, $h_{g1}=h_{g2}=0.75$ m | | | | | | | | | |
| $d$ | 3.6 | 6.0 | 7.8 | 8.8 | 10.0 | 13.9 | 17.6 | 19.8 | 21.9 | 26.1 |
| $\Delta h$ | 53.8 | 65.5 | 87.8 | 99.4 | 112.0 | 120.4 | 136.7 | 159.2 | 183.4 | 204.0 |
| $d_{L1}$ | 0.1 | 0.2 | 0.4 | 0.6 | 1.3 | 1.5 | 1.7 | 2.9 | 4.4 | 8.8 |
| $d_{L2}$ | 0.1 | 0.2 | 0.3 | 0.4 | 0.6 | 1.1 | 2.0 | 3.1 | 4.9 | 7.8 |
| $d_L$ | 0.2 | 0.7 | 1.8 | 2.0 | 2.3 | 2.9 | 4.2 | 5.6 | 8.4 | 15.8 |
| $\theta_e$ | -3.0 | 12.5 | 19.5 | 23.3 | 28.9 | 36.6 | 49.4 | 53.0 | 71.7 | 88.4 |
| | 2 line-of-sight, 8 1-horizon paths | | | | | | | | | |
| | Idaho, 30 paths, $h_{g1}=h_{g2}=0.75$ m | | | | | | | | | |
| $d$ | 10.8 | 15.0 | 17.1 | 18.4 | 20.4 | 20.8 | 21.4 | 23.4 | 27.2 | 32.8 |
| $\Delta h$ | 8.6 | 24.8 | 46.6 | 52.8 | 59.2 | 62.8 | 70.4 | 81.3 | 102.4 | 116.2 |
| $d_{L1}$ | 0.3 | 1.2 | 2.0 | 2.4 | 3.7 | 8.0 | 11.1 | 13.9 | 15.2 | 19.8 |
| $d_{L2}$ | 0.4 | 1.3 | 1.5 | 2.4 | 3.6 | 5.1 | 6.6 | 8.4 | 10.2 | 13.2 |
| $d_L$ | 4.7 | 5.0 | 10.5 | 12.3 | 13.0 | 14.8 | 16.2 | 17.6 | 20.5 | 24.0 |
| $\theta_e$ | -3.4 | -0.1 | 1.8 | 3.9 | 7.0 | 11.5 | 15.3 | 17.3 | 20.2 | 24.2 |
| | 1 line-of-sight, 9 1-horizon paths | | | | | | | | | |

Column header "Percentage" spans 10–90.

model was modified to allow for this as follows:

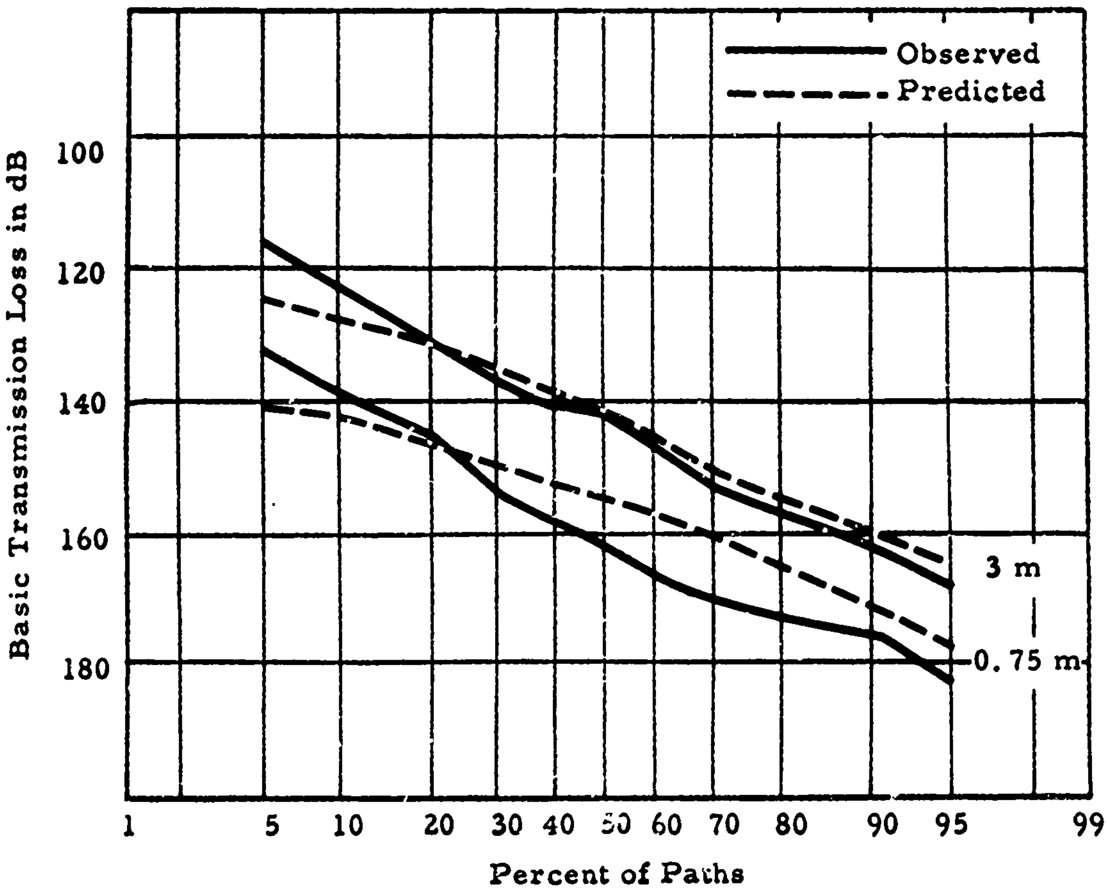
for $d_L < d_{LS}$ $$\Delta L_c = 10 \log_{10} (d_{LS}/d_L) \text{ dB}, \tag{2a}$$

for $d_L \geq d_{LS}$ $$\Delta L_c = 0 \text{ dB}. \tag{2b}$$

Then for low antennas (less than 3 m) over irregular terrain, the calculated median basic transmission loss is modified by adding $\Delta L_c$ to the computed value $L_{bc}$ for transhorizon paths.

Figures 40 and 41 show cumulative distributions of basic transmission loss observed and predicted, and of the differences $\Delta L$ between these values for each path for frequencies of 230 and 416 MHz in Wyoming. Figures 42 and 43 present the same information for the paths in Idaho. For both the 0.75 and 3 m antennas the predicted values show good agreement with measurements. In all cases the standard deviation of $\Delta L$ is about 9 or 10 dB. This represents the location or path-to-path variability caused by factors not included in the prediction model. In Idaho the predicted values with antenna heights of 0.75 m tend to underestimate the transmission loss. The reason for this is not clear at present.

The measurement paths in Washington fall naturally into two groups, the first consisting of 15 paths near Ritzville where the terrain is relatively smooth farm land, the second of 53 paths in rugged and mountainous terrain. Of the latter group 14 paths have a common receiver site in the Spokane river valley near Fort Spokane and extend into the surrounding forested, mountainous terrain, while the remaining paths are in rugged country west of Ritzville where steep hills, coulees, and deep canyons with almost vertical walls occur. Distributions of parameters for these two groups of paths are listed in table 3. In the



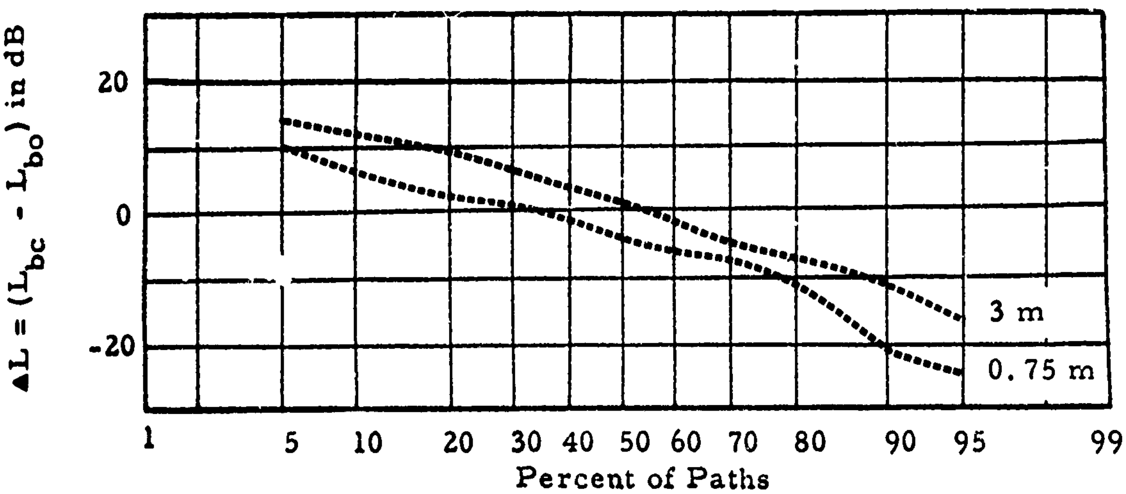
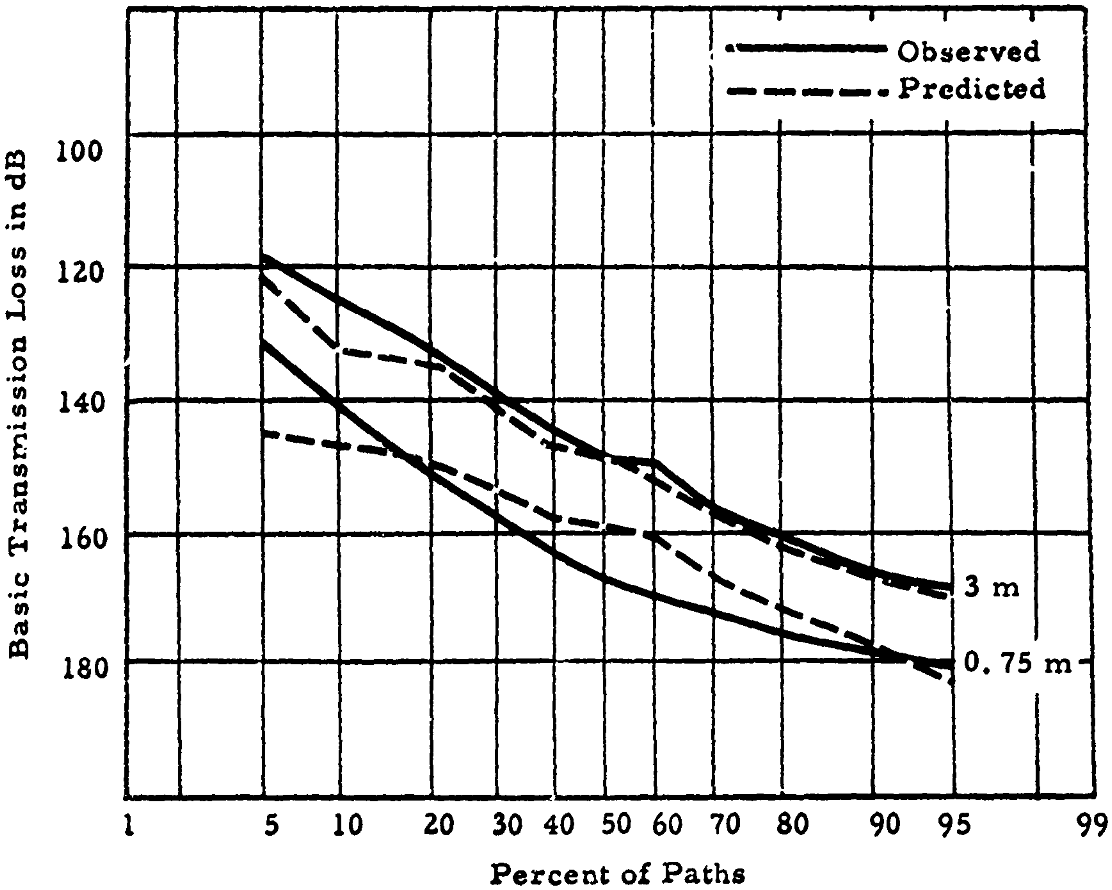




**Figure 40.** Cumulative distributions of basic transmission loss, observed and predicted, and of $\Delta L$, Laramie range, Wyoming, f=230 MHz.



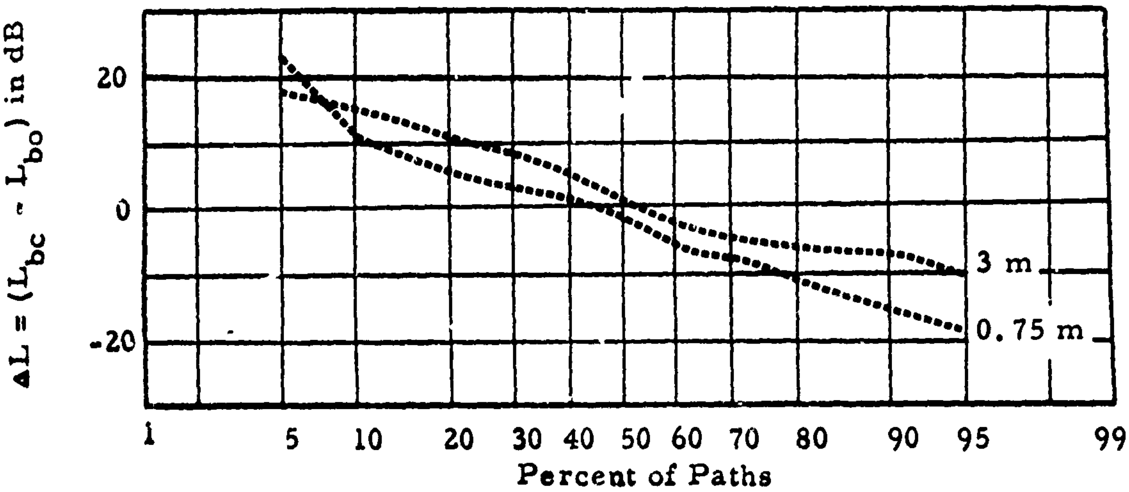




Figure 41. Cumulative distributions of basic transmission loss, observed and predicted, and of $\Delta L$, Wyoming, f=416 MHz.

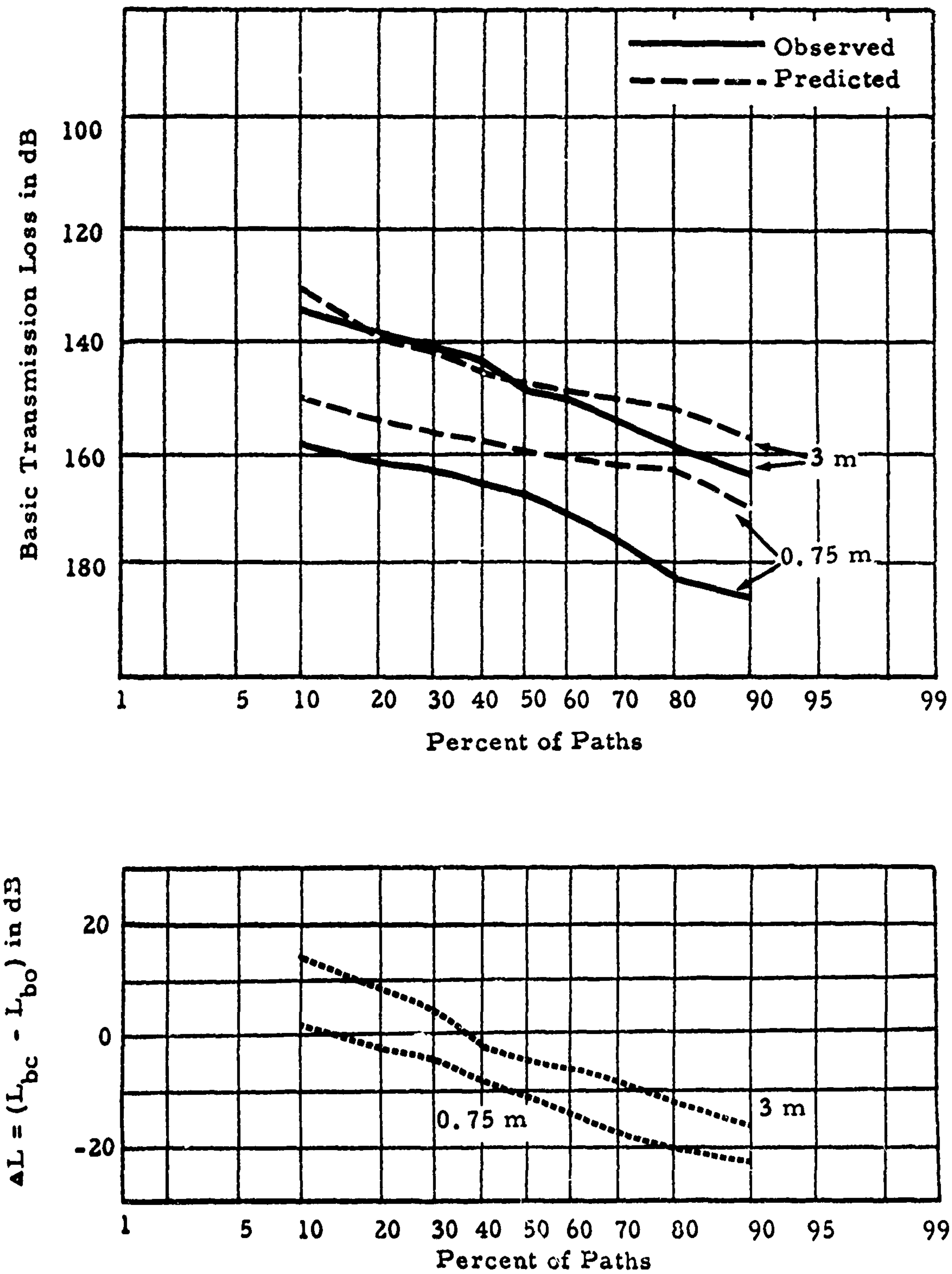



Figure 42. Cumulative distributions of basic transmission loss, observed and predicted, and of $\Delta L$, Idaho, f=230 MHz.

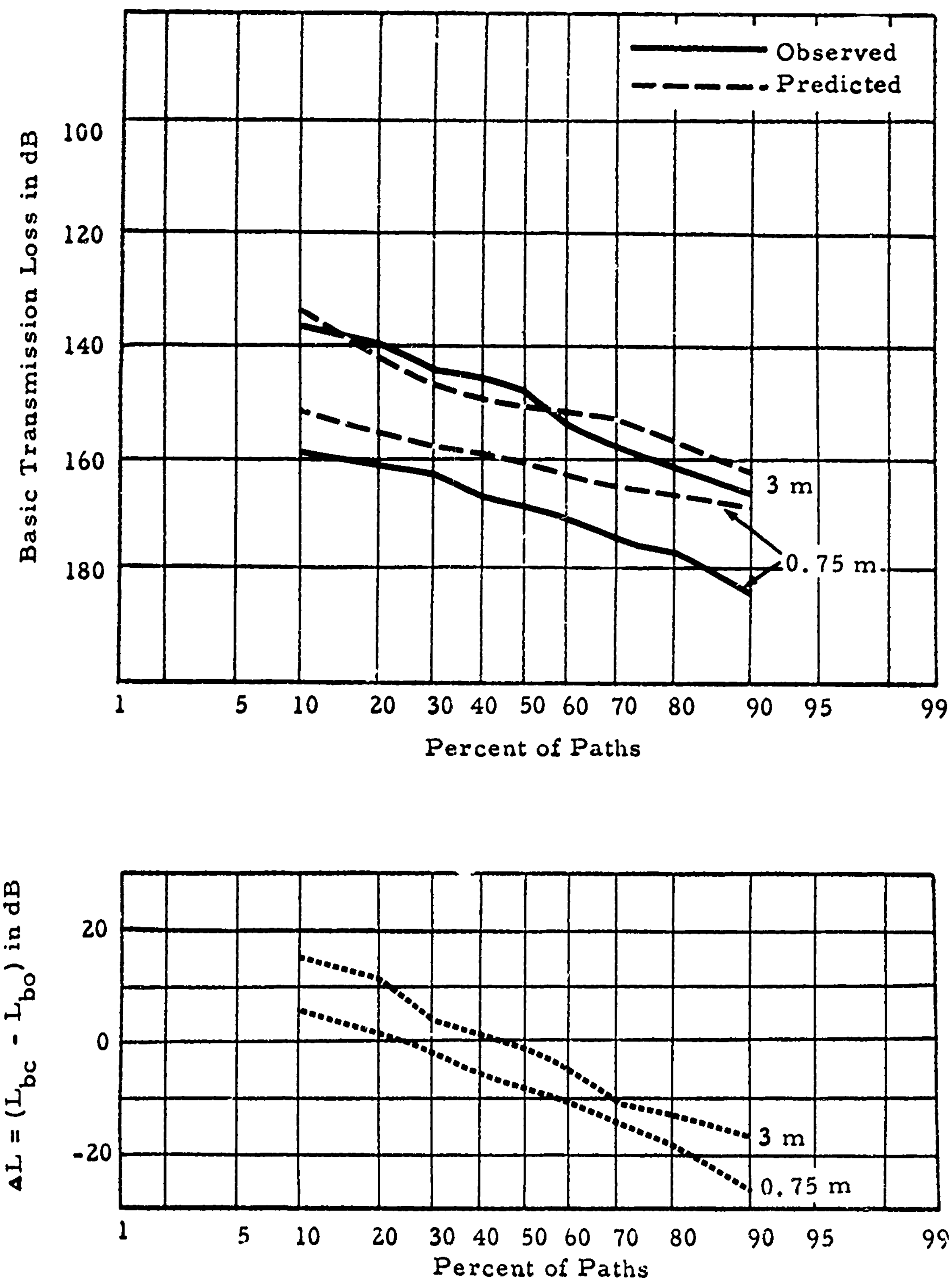



Figure 43. Cumulative distributions of basic transmission loss, observed and predicted, and of ΔL, Idaho, f=416 MHz.

Table 3. Cumulative Distributions of Path Parameters, Washington

| Parameter | Percentage: Min | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 |
|---|---|---|---|---|---|---|---|---|---|---|
| | Ritzville, 15 paths, $h_{g1}=h_{g2}=0.75$ m | | | | | | | | | |
| d | 9.4 | 9.9 | 11.4 | 18.6 | 19.8 | 22.3 | 22.8 | 23.7 | 29.6 | 49.0 |
| $\Delta h$ | 19.6 | 29.1 | 44.2 | 65.4 | 67.6 | 70.0 | 78.8 | 80.3 | 139.0 | 195.0 |
| $d_{L1}$ | 1.5 | 1.7 | 2.0 | 2.0 | 2.3 | 2.5 | 3.7 | 4.5 | 7.5 | 9.7 |
| $d_{L2}$ | 0.2 | 0.2 | 0.9 | 1.7 | 3.3 | 6.4 | 7.6 | 9.5 | 12.9 | 14.1 |
| $d_L$ | 1.7 | 2.6 | 6.4 | 9.9 | 10.2 | 11.2 | 11.8 | 12.6 | 14.9 | 16.4 |
| $\theta_e$ | 0.9 | 0.9 | 1.6 | 2.4 | 3.0 | 4.0 | 8.3 | 12.4 | 16.1 | 19.4 |
| | no line-of-sight, 3 1-horizon paths | | | | | | | | | |
| | Rugged terrain, 53 paths, $h_{g1}=h_{g2}=0.75$ m | | | | | | | | | |
| d | 1.4 | 3.2 | 9.0 | 12.6 | 17.5 | 22.6 | 24.5 | 26.8 | 31.9 | 37.3 |
| $\Delta h$ | 2.3 | 85.4 | 128.2 | 178.7 | 193.4 | 257.5 | 321.4 | 378.3 | 424.6 | 500.0 |
| $d_{L1}$ | 0.1 | 0.5 | 0.8 | 1.0 | 1.1 | 1.8 | 2.1 | 3.1 | 5.6 | 13.7 |
| $d_{L2}$ | 0.1 | 0.2 | 0.6 | 1.2 | 2.0 | 3.4 | 8.1 | 12.0 | 15.8 | 20.5 |
| $d_L$ | 0.9 | 1.7 | 2.3 | 3.6 | 5.4 | 8.7 | 12.2 | 17.3 | 22.4 | 29.0 |
| $\theta_e$ | -2.1 | 5.0 | 11.4 | 15.2 | 32.6 | 42.0 | 50.8 | 58.5 | 70.2 | 157.4 |
| | 1 line-of-sight, 15 1-horizon paths | | | | | | | | | |

first group terrain ranges from rather smooth to quite hilly, with a median value $\Delta h$ = 70 m. The terrain in the second group ranges from hilly to mountainous, with a median $\Delta h$ value of 260 m. The terrain in the latter group is more rugged than that in the Wyoming area, while the former group is rather comparable to the measurement area in Idaho. The group of paths in rugged terrain contains an unusually large proportion of one-horizon paths where the obstacle is an isolated hill or ridge. The parameters tabulated are for antenna heights of 0.75 m. Raising the antennas to 3 m increases the horizon distances slightly and causes some reduction in median values of $\theta_e$. Estimates of the effective antenna heights exceed the structural heights for more than half of the paths in rugged terrain and become quite large in a few cases.

Cumulative distributions of observed and predicted values of basic transmission loss and their differences are shown in figures 44 through 47. The 15 paths in the Ritzville area are rather too small a sample from which to draw conclusions but, as with the Idaho paths, they show that the predicted values are less than the observed values of transmission loss at both frequencies. The paths in rugged terrain on the other hand show less loss than is predicted. In the latter case the high proportion of single horizon paths suggest that the model for such paths should be revised.

### 3.4 Measurements and Predictions at VHF

A large measurement program with low antennas at frequencies of 20, 50, and 100 MHz was carried out in the Colorado plains and mountains and in northeastern Ohio. All of the measurements in Colorado were made from a common transmitter site, northeast of Boulder. Receiver sites were chosen at nominal distances from the transmitter without regard to propagation conditions. The measurements

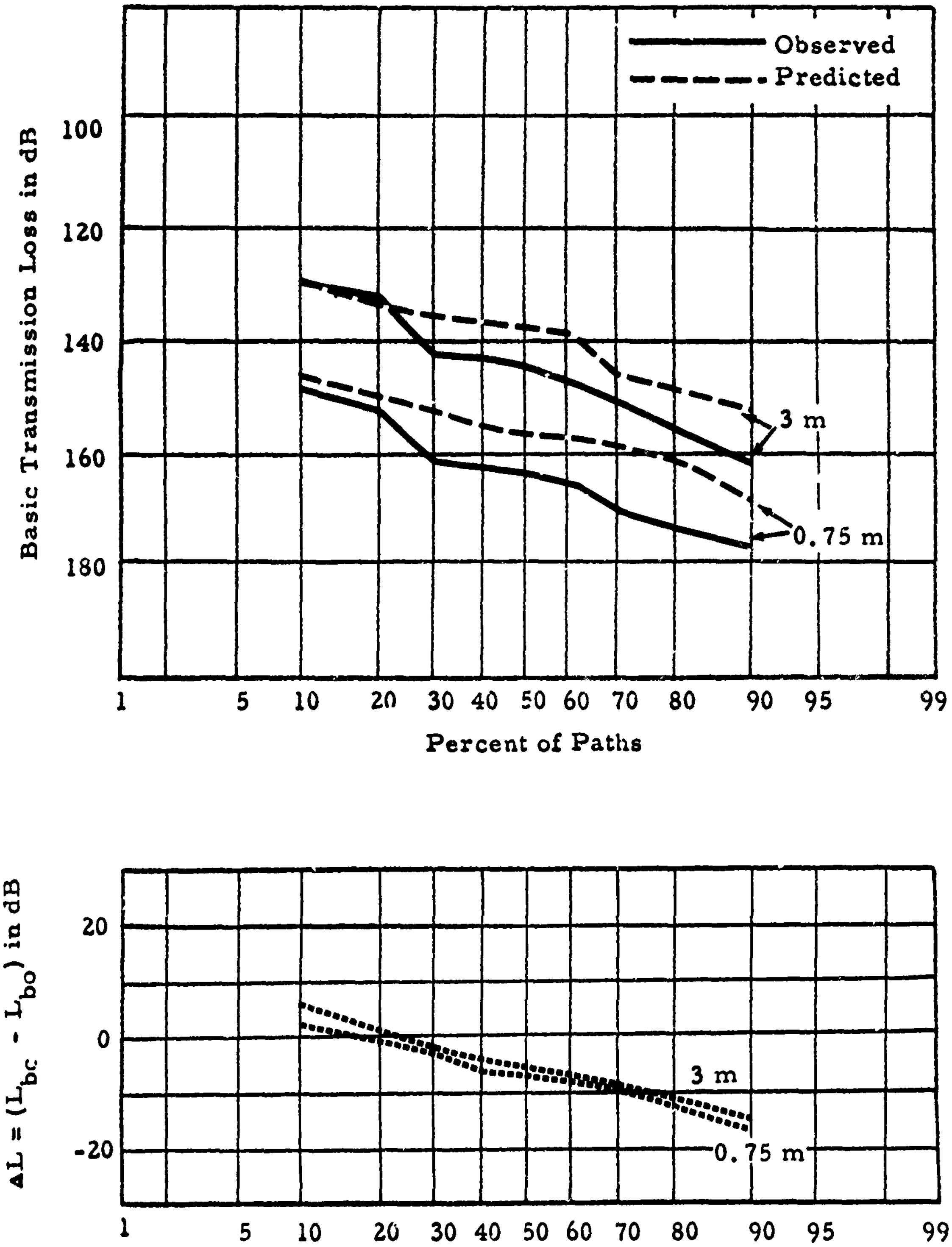



Figure 44. Cumulative distributions of basic transmission loss, observed and predicted, and of ΔL, Ritzville, Washington, f=230 MHz.

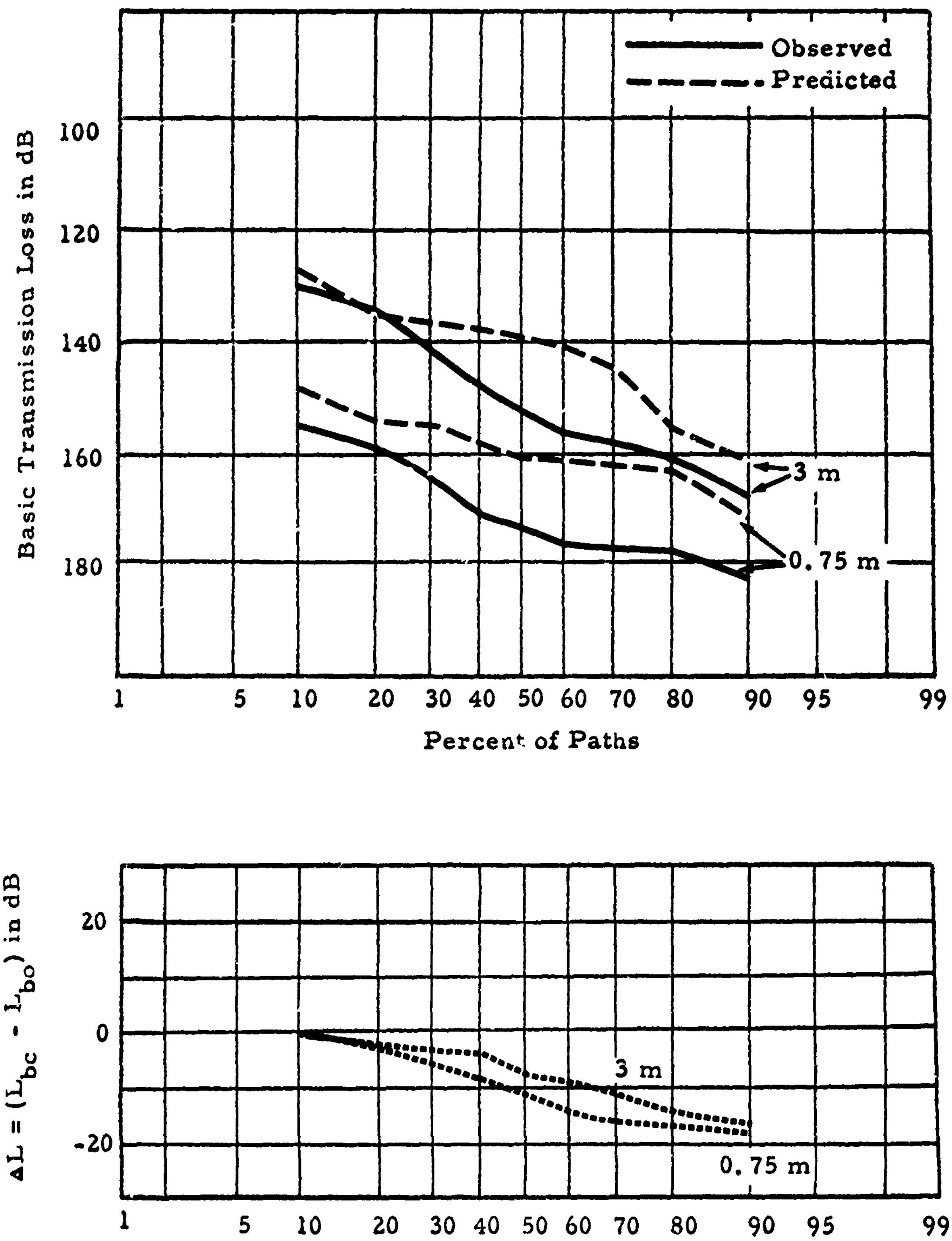
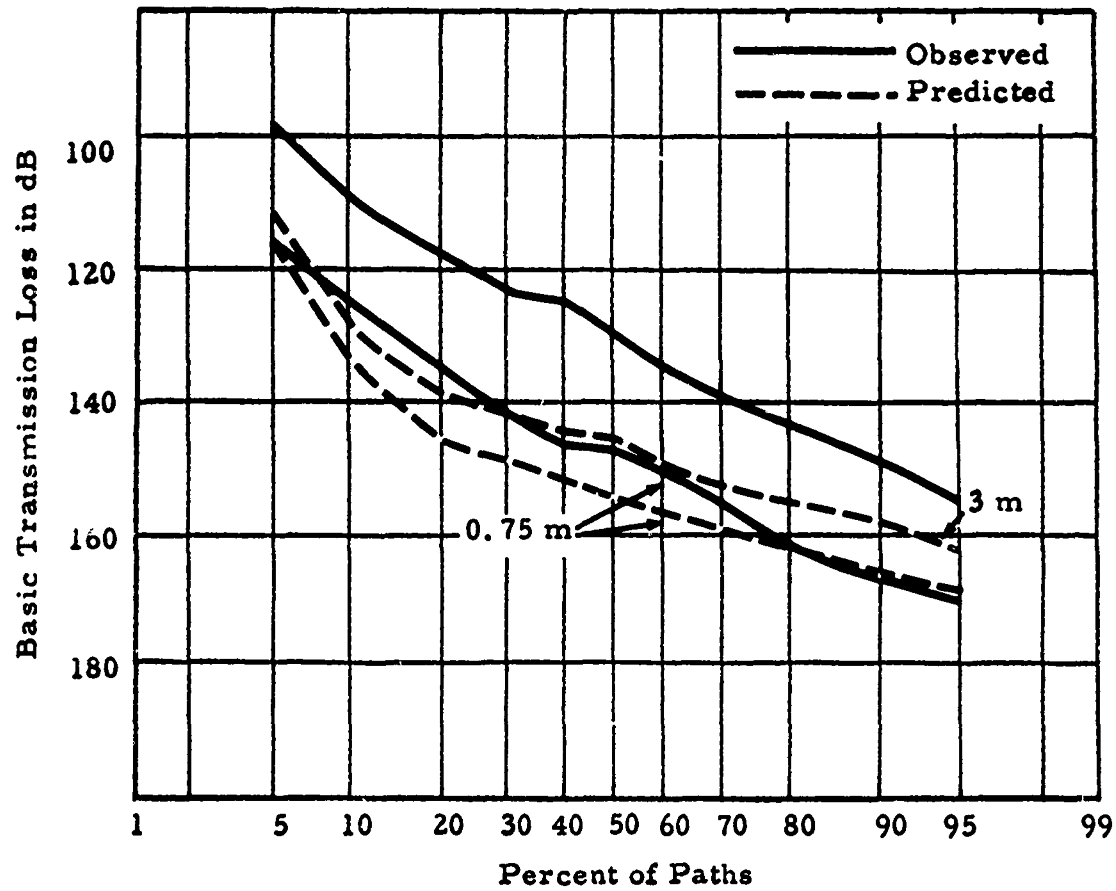



Figure 45. Cumulative distributions of basic transmission loss, observed and predicted, and of $\Delta L$, Ritzville, Washington, f=416 MHz.



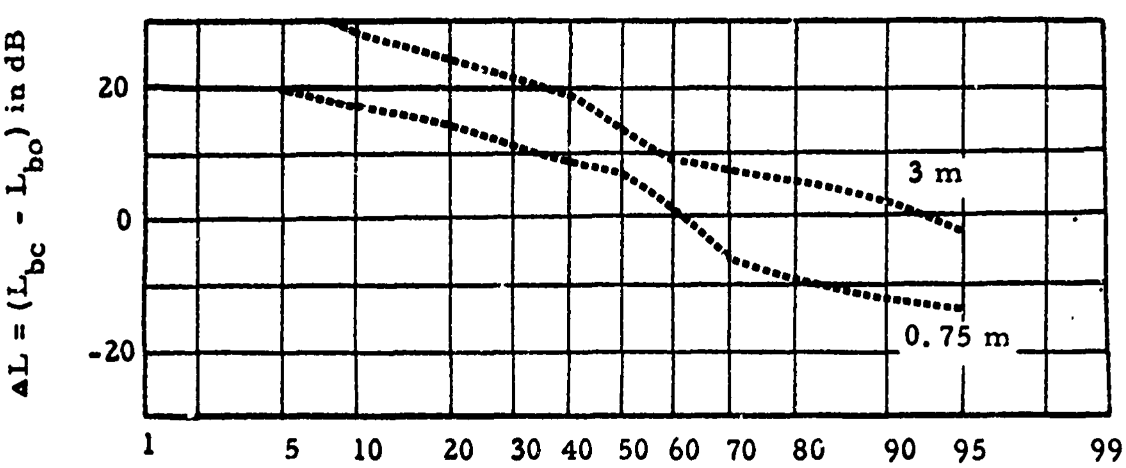




Figure 46. Cumulative distributions of basic transmission loss, observed and predicted, and of ΔL, Rugged terrain, Washington, f=230 MHz.

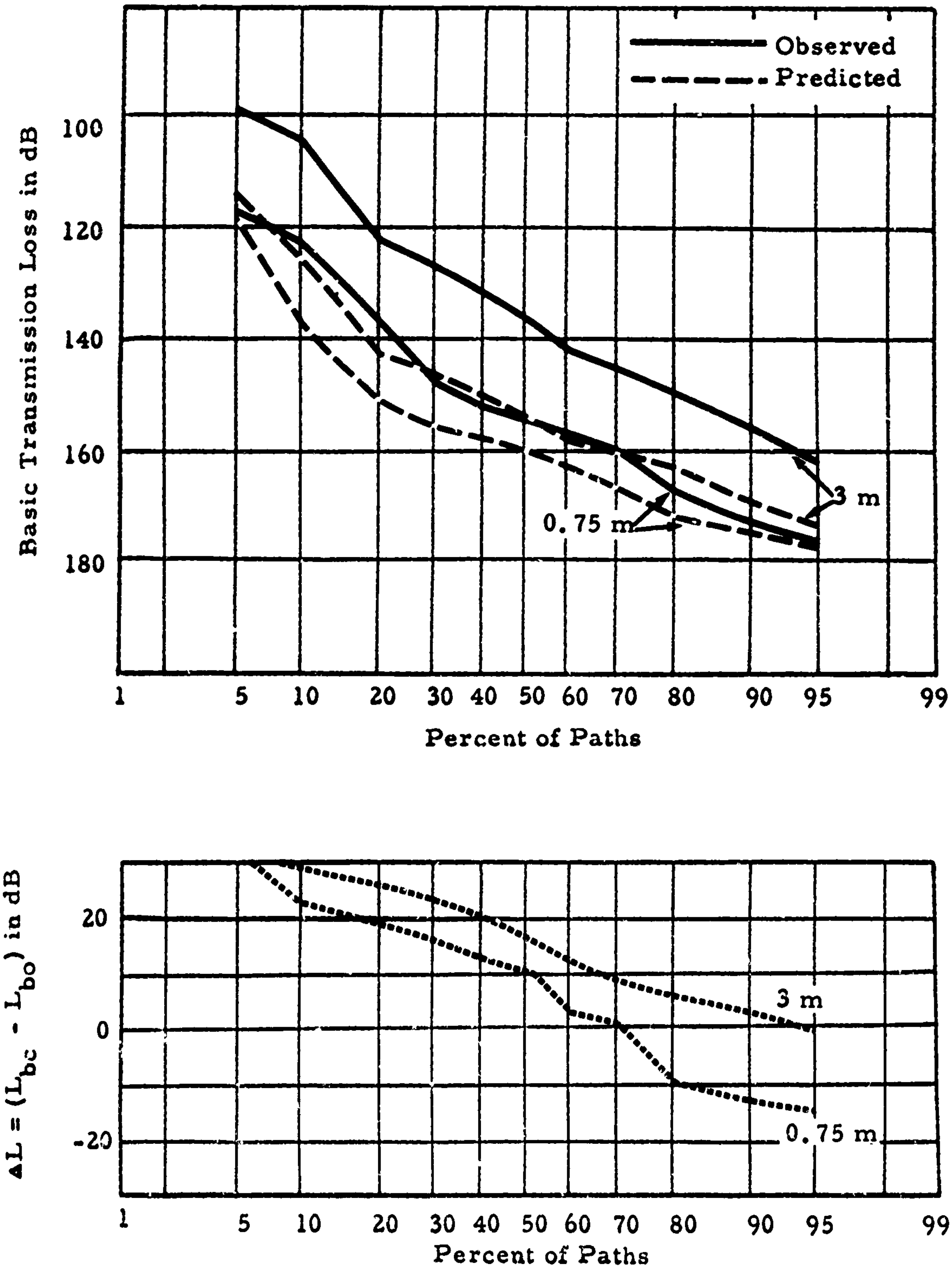



Figure 47. Cumulative distributions of basic transmission loss, observed and predicted, and of $\Delta L$, Rugged terrain, Washington, f=416 MHz.

in Ohio were made from one central and five peripheral transmitters to receiver sites similarly selected at nominal distances from each transmitter.

Path profiles were read for about 490 paths and parameters calculated for each of them. Point-to-point predictions were then calculated for each path at each frequency and antenna height combination used in the measurement program. Tables 4, 5, and 6 show cumulative distributions of parameters for the following paths: 184 in the Colorado plains, 48 in the Colorado mountains, and 255 in northeastern Ohio. In all cases the parameters are for randomly selected "principal" sites, and where more than one receiver height was used the lower height is represented. Table 4 lists distributions of parameters in the Colorado plains for 184 paths with a median length of 50 km at 100 MHz, and 132 paths with a median length of 30 km at the lower frequencies. In this area the terrain is somewhat rolling, with a median value of the terrain parameter $\Delta h \simeq 95$ m but with a total range of nearly 300 m which corresponds closely to the terrain characteristics of the Ohio area. The Colorado mountain paths are over the most rugged area considered in this report, with a median $\Delta h \simeq 580$ m and values ranging over 1500 m. The advantageous siting of the transmitter in the Colorado plains is indicated by the median $d_{L1}$, which is much larger than the median $d_{L2}$ for the randomly selected receiver sites. The same advantage is observed in the mountains paths, but to much less an extent in Ohio where six transmitter sites were chosen.

Figures 48 through 53 show cumulative distributions of basic transmission loss, observed and predicted, and of their differences at frequencies of 20, 50, and 100 MHz for each group of paths. In each case the measurements with vertical polarization are considered, and at 100 MHz receiver heights of 3 and 9 m are shown. The data at

Table 4. Cumulative Distributions of Path Parameters, Colorado Plains

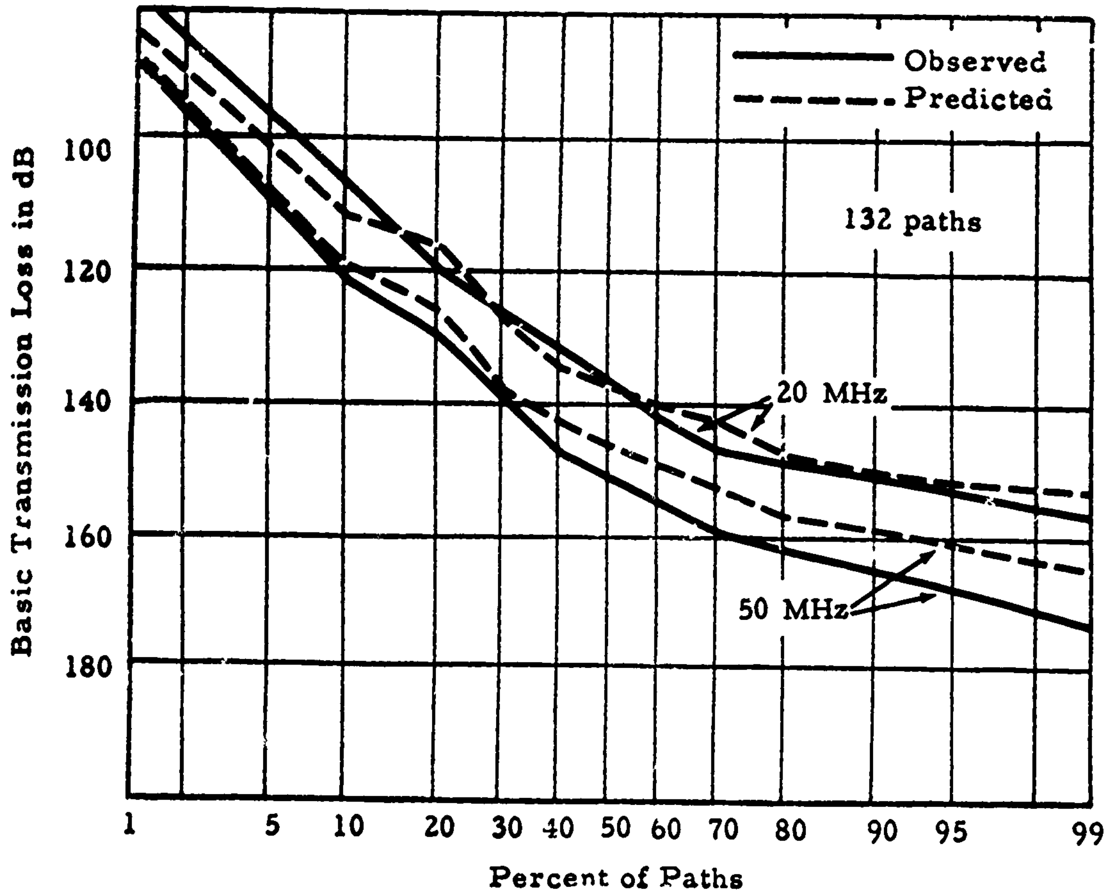
| Para-meter | Min | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Percentage | | | | | |
| | | | | 100 MHz, $h_{g1}$= 4 m, $h_{g2}$= 3 m, 184 paths | | | | | | |
| d | 0.6 | 5.0 | 13.0 | 26.6 | 30.2 | 49.6 | 49.9 | 50.4 | 80.0 | 80.3 |
| $\Delta h$ | 1.0 | 57.9 | 66.7 | 78.7 | 87.0 | 96.5 | 106.7 | 128.8 | 151.7 | 197.2 |
| $d_{L1}$ | 1.0 | 2.6 | 9.0 | 10.3 | 11.3 | 12.1 | 16.2 | 21.6 | 24.8 | 29.4 |
| $d_{L2}$ | 0.5 | 0.5 | 1.0 | 1.5 | 2.0 | 3.5 | 6.2 | 10.0 | 19.0 | 28.8 |
| $d_L$ | 2.0 | 9.5 | 12.1 | 13.7 | 19.2 | 22.6 | 28.2 | 30.2 | 37.6 | 49.8 |
| $\theta_e$ | -6.5 | -3.4 | -1.6 | 0.1 | 3.6 | 5.6 | 8.6 | 12.1 | 16.9 | 25.2 |
| | | | | 26 line-of-sight, 34 1-horizon paths | | | | | | |
| | | | | 50 MHz, $h_{g1}$=4 m, $h_{g2}$=0.55 m, 132 paths | | | | | | |
| d | 0.6 | 5.0 | 9.6 | 19.6 | 20.0 | 30.0 | 30.2 | 49.6 | 49.8 | 50.0 |
| $\Delta h$ | 1.0 | 47.3 | 69.6 | 81.4 | 90.0 | 97.8 | 107.2 | 120.1 | 147.2 | 187.8 |
| $d_L$ | 2.0 | 5.0 | 9.8 | 12.1 | 13.7 | 18.6 | 22.1 | 29.0 | 30.1 | 39.3 |
| $\theta_e$ | -4.5 | -2.0 | 0.1 | 2.0 | 5.2 | 9.4 | 11.2 | 17.0 | 22.1 | 34.2 |
| | | | | 22 line-of-sight, 28 1-horizon paths | | | | | | |
| | | | | 20 MHz, $h_{g1}$=3.3 m, $h_{g2}$=1.3 m, 132 paths | | | | | | |
| $d_L$ | 2.0 | 5.0 | 9.9 | 12.4 | 14.4 | 19.3 | 22.6 | 29.3 | 30.2 | 41.0 |
| $\theta_e$ | -4.5 | -2.2 | 0.4 | 2.6 | 5.6 | 8.9 | 11.0 | 16.3 | 20.7 | 34.6 |
| | | | | 24 line-of-sight, 30 1-horizon paths | | | | | | |

Table 5. Cumulative Distributions of Path Parameters, Colorado Mountains, 48 Paths

| Para-meter | Percentage Min | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 |
|---|---|---|---|---|---|---|---|---|---|---|
| | 100 MHz, $h_{g1}$=4 m, $h_{g2}$=3 m | | | | | | | | | |
| d | 5.0 | 9.8 | 19.6 | 19.7 | 29.3 | 30.1 | 30.4 | 49.8 | 50.0 | 50.2 |
| $\Delta h$ | 253.4 | 362.4 | 429.9 | 477.3 | 508.9 | 579.5 | 629.1 | 720.5 | 811.6 | 957.8 |
| $d_{L1}$ | 3.4 | 4.4 | 4.5 | 4.5 | 6.6 | 7.8 | 9.2 | 11.4 | 13.5 | 15.3 |
| $d_{L2}$ | 0.5 | 0.5 | 0.5 | 1.0 | 1.4 | 1.5 | 2.5 | 3.0 | 5.8 | 10.4 |
| $d_L$ | 4.9 | 5.0 | 6.6 | 8.1 | 10.1 | 11.6 | 12.8 | 15.0 | 16.8 | 22.1 |
| $\theta_e$ | 22.9 | 56.0 | 60.7 | 75.6 | 112.2 | 139.4 | 155.2 | 166.1 | 198.6 | 298.4 |
| | no line-of-sight, 5 1-horizon paths | | | | | | | | | |
| | 50 MHz, $h_{g1}$=4 m, $h_{g2}$=0.55 m | | | | | | | | | |
| $d_L$ | 4.9 | 5.0 | 6.6 | 8.1 | 10.1 | 11.5 | 12.8 | 15.0 | 16.8 | 22.1 |
| $\theta_e$ | 23.3 | 57.3 | 62.5 | 77.2 | 115.9 | 140.4 | 158.9 | 168.0 | 203.0 | 302.0 |
| | no line-of-sight, 5 1-horizon paths | | | | | | | | | |
| | 20 MHz, $h_{g1}$=3.3 m, $h_{g2}$=1.3 m | | | | | | | | | |
| $d_L$ | 4.9 | 5.0 | 6.6 | 8.1 | 10.1 | 11.5 | 12.8 | 15.0 | 16.8 | 22.1 |
| $\theta_e$ | 23.4 | 57.3 | 62.1 | 76.8 | 115.2 | 140.2 | 157.8 | 166.9 | 202.1 | 301.0 |
| | no line-of-sight, 5 1-horizon paths | | | | | | | | | |

Table 6. Cumulative Distributions of Path Parameters, N.E. Ohio, 255 Paths

| Parameter | Min | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 |
|---|---|---|---|---|---|---|---|---|---|---|
| | Percentage | | | | | | | | | |
| 100 MHz, $h_{g1}$=4 m, $h_{g2}$=3 m | | | | | | | | | | |
| $d$ | 9.8 | 10.0 | 19.9 | 20.0 | 29.8 | 30.0 | 30.2 | 50.0 | 50.1 | 50.3 |
| $\Delta h$ | 15.7 | 50.5 | 63.8 | 77.0 | 85.9 | 94.7 | 107.3 | 124.8 | 143.8 | 169.8 |
| $d_{L1}$ | 0.5 | 1.5 | 2.5 | 4.0 | 4.5 | 5.0 | 8.5 | 14.7 | 20.5 | 25.0 |
| $d_{L2}$ | 0.5 | 0.5 | 1.0 | 1.0 | 2.0 | 3.0 | 4.5 | 6.3 | 11.0 | 16.2 |
| $d_L$ | 1.0 | 4.0 | 5.5 | 7.0 | 10.0 | 15.0 | 19.1 | 23.3 | 28.1 | 34.6 |
| $\theta_e$ | -3.3 | 0.1 | 3.2 | 5.3 | 7.1 | 8.8 | 10.8 | 13.4 | 19.0 | 31.3 |
| 22 line-of-sight, 25 1-horizon paths | | | | | | | | | | |
| 50 MHz, $h_{g1}$=4.2 m, $h_{g2}$=1 m | | | | | | | | | | |
| $d_L$ | 1.0 | 4.0 | 5.5 | 6.5 | 9.9 | 15.0 | 19.1 | 22.9 | 26.8 | 33.9 |
| $\theta_e$ | -2.9 | 0.1 | 3.7 | 5.6 | 7.5 | 9.6 | 11.9 | 14.8 | 19.8 | 32.8 |
| 17 line-of-sight, 25 1-horizon paths | | | | | | | | | | |
| 20 MHz, $h_{g1}$=3.7 m, $h_{g2}$=3 m | | | | | | | | | | |
| $d_L$ | 1.0 | 4.0 | 5.2 | 6.7 | 10.0 | 15.0 | 19.1 | 23.2 | 27.9 | 34.6 |
| $\theta_e$ | -3.3 | 0.1 | 3.2 | 5.4 | 7.2 | 8.8 | 10.9 | 13.5 | 19.2 | 31.3 |



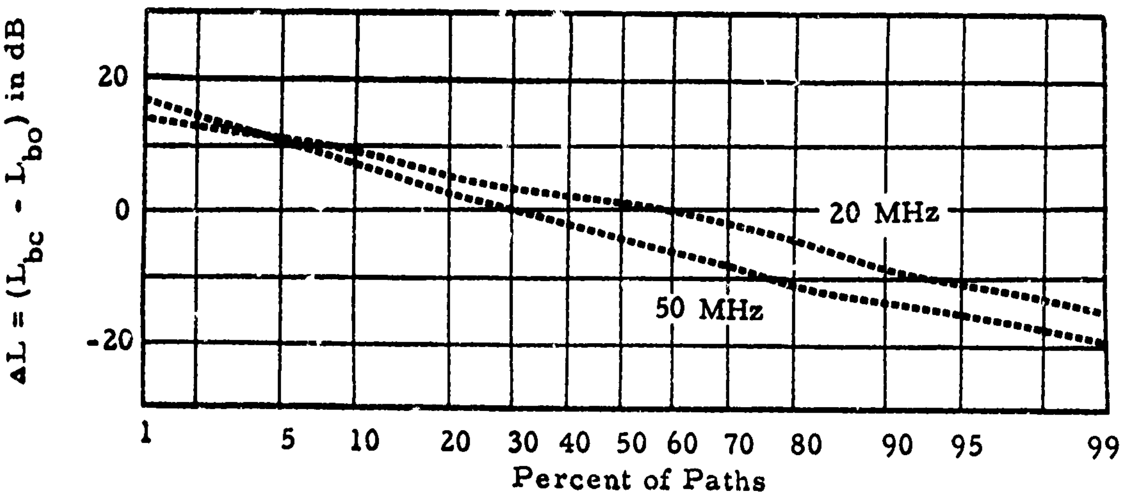




Figure 48. Cumulative distributions of basic transmission loss, observed and predicted, and of $\Delta L$, Colorado plains, medians $\Delta h$=95 m, f=20 and 50 MHz.

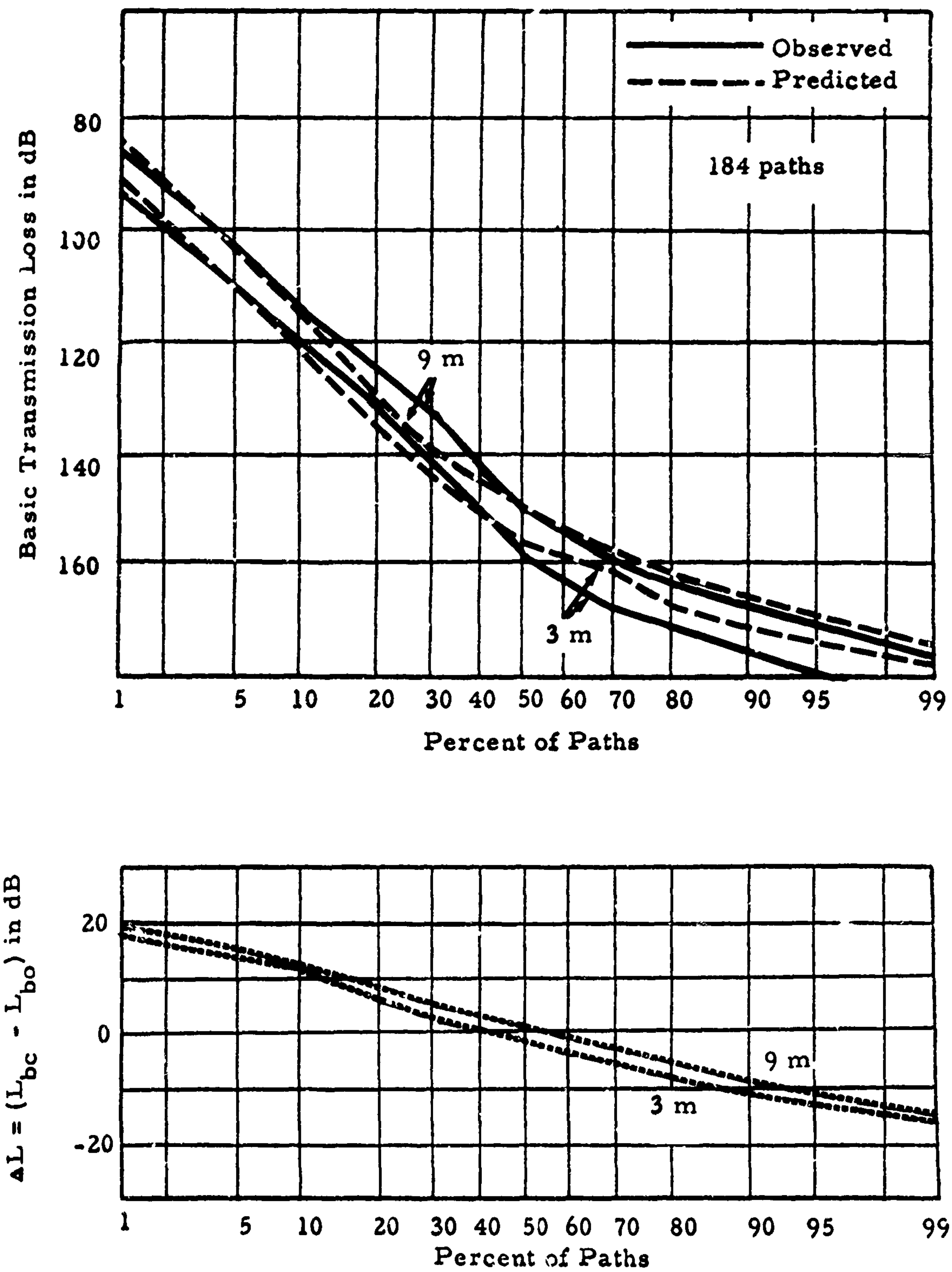
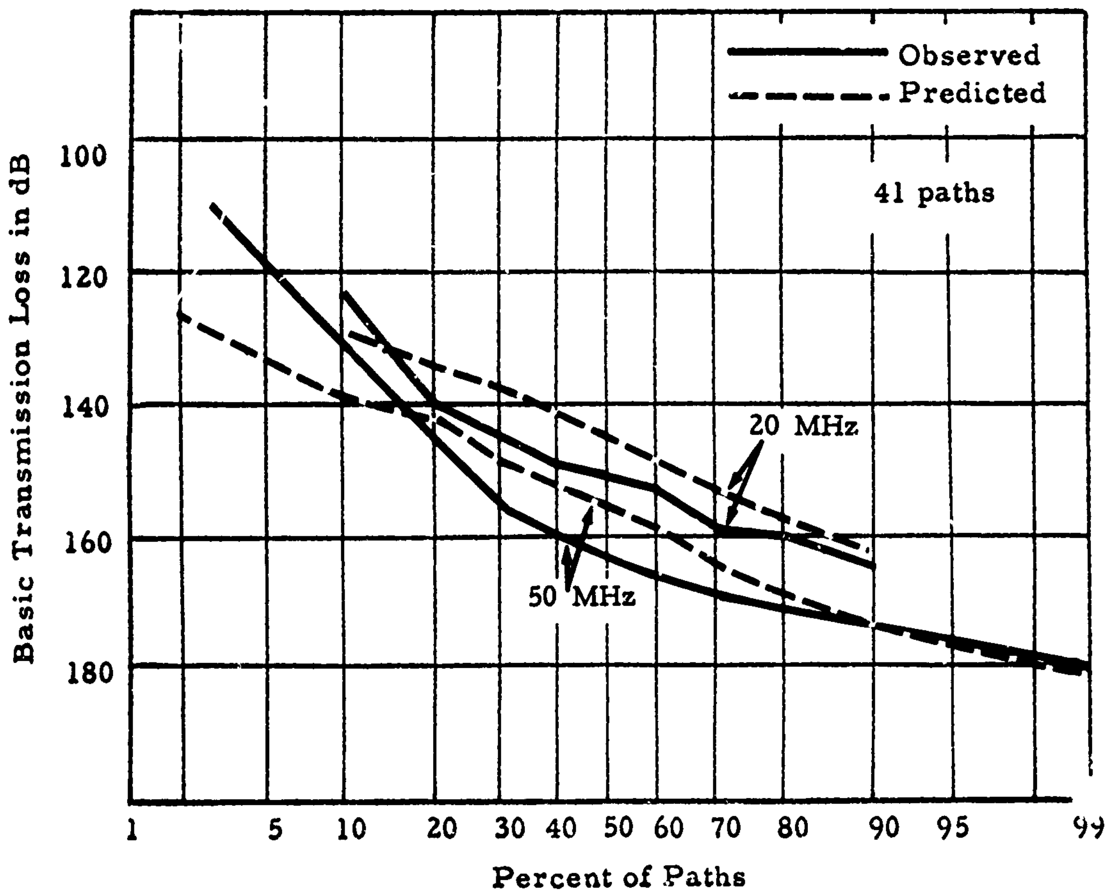



Figure 49. Cumulative distributions of basic transmission loss, observed and predicted, and of $\Delta L$, Colorado plains, median $\Delta h$=95 m, f=100 MHz.



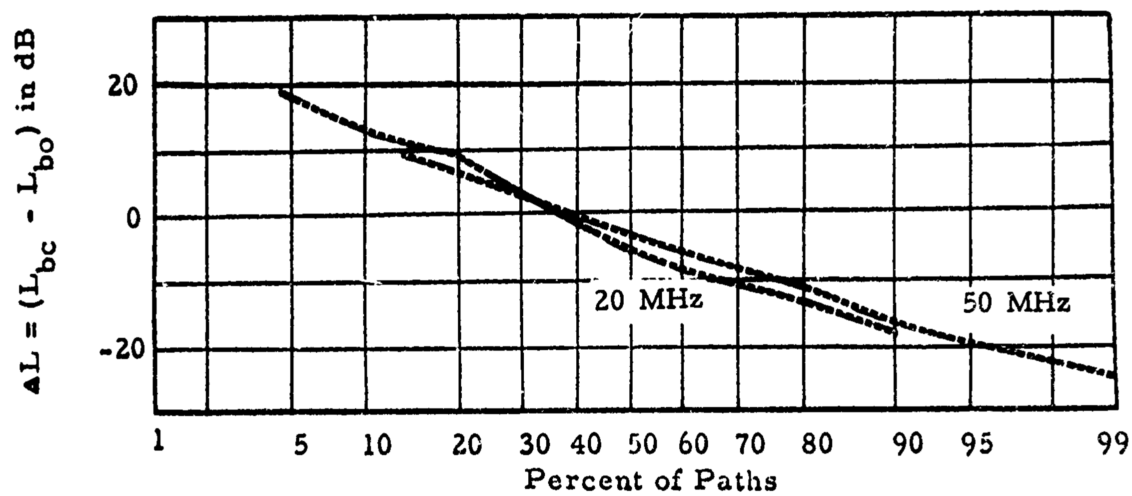




Figure 50. Cumulative distributions of basic transmission loss, observed and predicted, and of ΔL, Colorado mountains, median Δh=580 m, f=50 and 20 MHz.

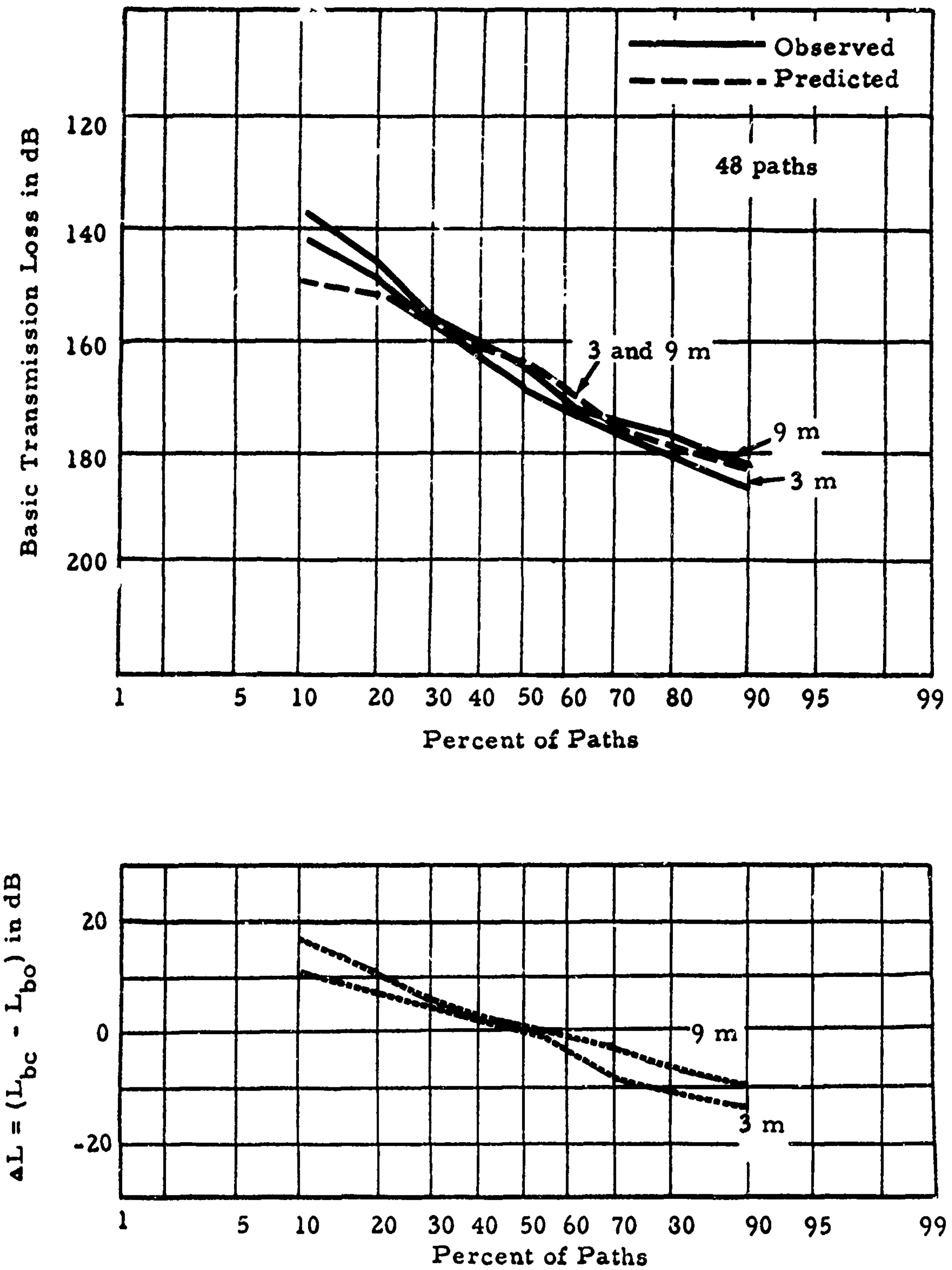



Figure 51. Cumulative distributions of basic transmission loss, observed and predicted, and of $\Delta L$, Colorado mountains, median $\Delta h$=580 m, f=100 MHz.

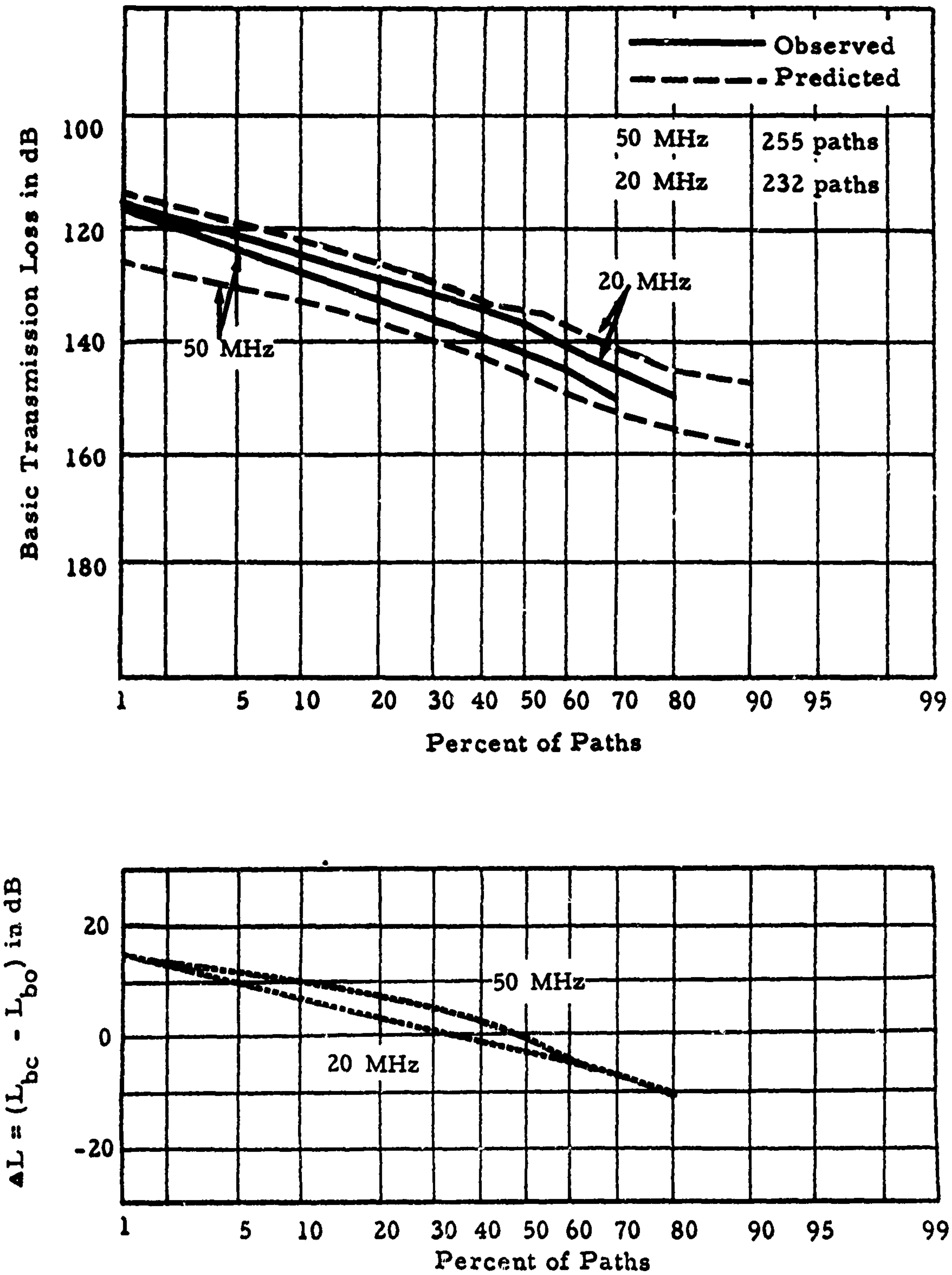



Figure 52. Cumulative distributions of basic transmission loss, observed and predicted, and of $\Delta L$, northeastern Ohio, median $\Delta h$=95 m, f=20 and 50 MHz.

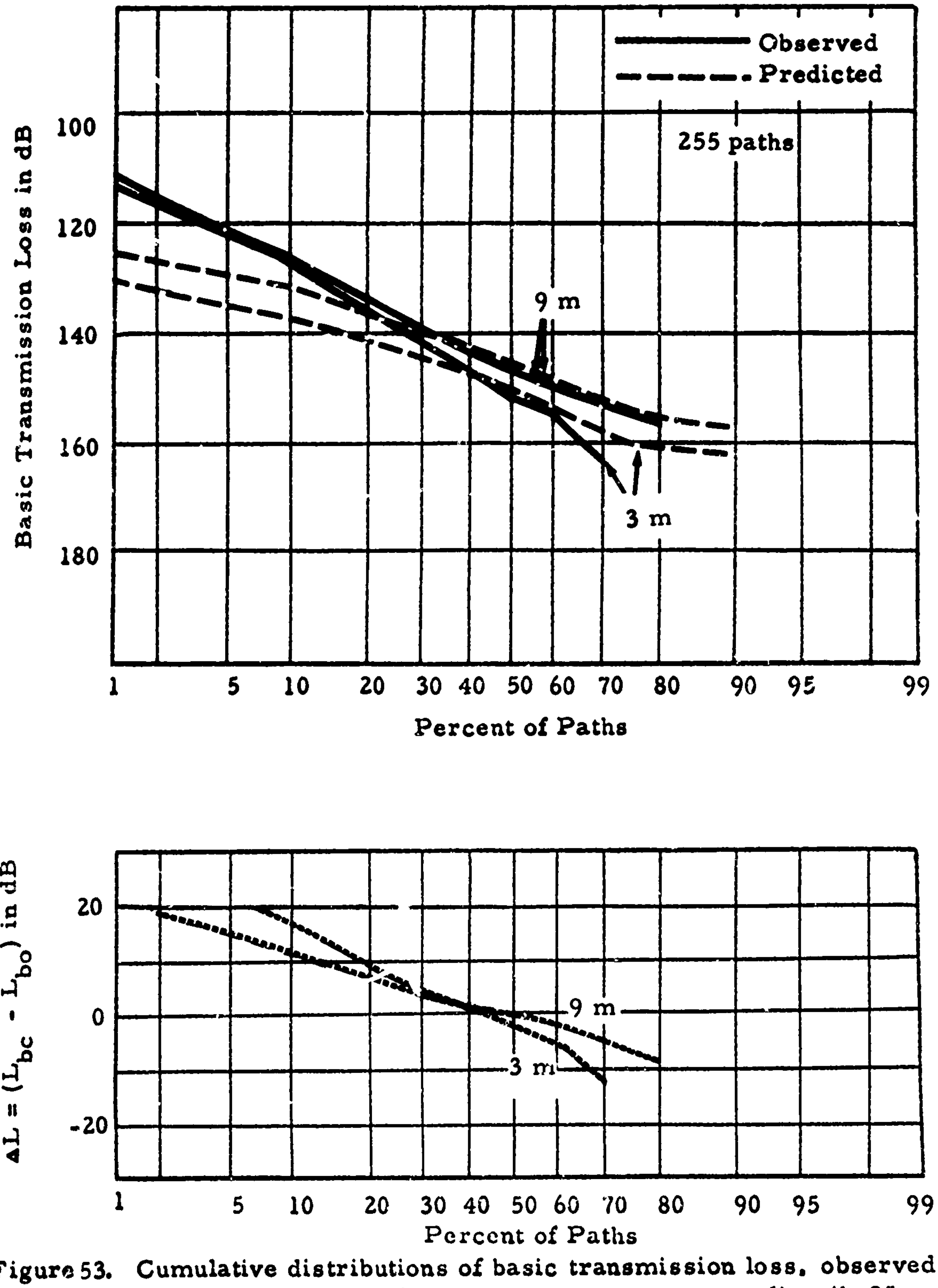



Figure 53. Cumulative distributions of basic transmission loss, observed and predicted, and of $\Delta L$, northeastern Ohio, median $\Delta h$=95 m, f=100 MHz.

50 MHz are shown in a single distribution as the differences between measurements with receiver heights of 0.55 and 1.7 m were considered negligible. In figures 52 and 53 the distributions are curtailed because some of the measurement attempts failed with the signal "in the noise". In all cases good agreement between predicted and measured values is observed. The distributions of differences between predicted and observed values for individual paths show standard deviations of 8 to 10 dB, which represent the path-to-path or location variability caused by factors not considered in the prediction model.

Comparison of these figures with the area predictions shown in figures 23 through 29 show the improved agreement with measured values when individual path parameters are used in calculations rather than estimates of median values as a function of terrain irregularity and path length.

### 3.5 Established Communication Links

Comparisons between point-to-point predictions and the large amount of data recorded with low antennas over irregular terrain have suggested certain possible weaknesses in the prediction models described by Longley and Rice (1968). We, therefore, decided to test these models against a large amount of data collected over established propagation paths in various parts of the world. These recordings differ from those previously discussed as they represent actual established communication links that have been monitored for periods ranging from a few weeks to more than a year in some cases. This group of some 550 paths was studied, because they represent a wide range of frequencies, terrain types, path lengths, and antenna heights, and because they could be separated into large enough groups of line-of-sight, one-horizon diffraction, two-horizon diffraction, and forward-scatter paths to provide needed information. For each path the coordinates of antenna locations are accurately known; path profiles have been carefully read from detailed topographic maps and used to determine the required parameters for each path. A report on these paths and the long-term variability of transmission loss is in preparation.

Cumulative distributions of parameters for each group of paths are shown in table 7. In each group a range of frequencies from 40 to nearly 10,000 MHz, terrain types from smooth to mountainous, and a wide range of path lengths are represented. For the line-of-sight paths distributions of effective antenna heights are also shown, as this parameter is particularly important for these paths.

Values of basic transmission loss were calculated for each path using the methods described by Rice et al.(1967) and the computer methods described by Longley and Rice (1968). In each case these calculated values were compared with the long-term median value of basic transmission loss derived from measurements. Figures 54 through 57 show cumulative distributions of basic transmission loss, observed and predicted by both of these methods, and their differences $\Delta L$.

Figure 54 shows that for known line-of-sight paths the earlier method calculates values that are too small by as much as 13 dB at the median, while the later "computer method" agrees well at the median but overestimates the loss by a wide margin for many of these paths. Several possible modifications of the methods were considered. Of these the best agreement with data was obtained by calculating the attenuation below free space $A_{cs}$ as a function of the terrain parameter $\Delta h$, frequency f, effective antenna heights $h_{e1,2}$, and path length d. This attenuation is added to the free space loss to give calculated values of basic transmission loss:

$$L_{bc} = L_{bf} + A_{cs} \text{ dB}, \tag{3a}$$

Table 7. Cumulative Distributions of Path Parameters, for Established Communication Links

| Parameter | Min | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Percentage | | | | | |
| | | | | | 84 line-of-sight paths | | | | | |
| f | 40 | 76 | 100 | 187 | 210 | 516 | 952 | 1310 | 4650 | 6825 |
| d | 11.9 | 18.6 | 27.5 | 42.7 | 69.0 | 80.5 | 100 | 113 | 125 | 143 |
| $\Delta h$ | 2 | 18 | 22 | 46 | 56 | 88 | 126 | 191 | 302 | 454 |
| $h_{e1}$ | 3.9 | 18.3 | 48.3 | 70.0 | 210 | 342 | 599 | 831 | 985 | 1021 |
| $h_{e2}$ | 1.5 | 5.8 | 13.1 | 25.1 | 38 | 41 | 50 | 67 | 124 | 286 |
| min. of $h_{e1,2}$ | 1.5 | 5.8 | 12.2 | 18.3 | 19 | 38 | 41 | 47 | 63 | 86 |
| | | | | | 46 one-horizon diffraction paths | | | | | |
| f | 53 | 60 | 90 | 160 | 190 | 230 | 570 | 1000 | 2860 | 7270 |
| d | 10.4 | 50.9 | 76.0 | 76.4 | 98 | 101 | 113 | 122 | 128 | 195 |
| $\Delta h$ | 29 | 73 | 76 | 84 | 89 | 90 | 93 | 114 | 160 | 415 |
| | | | | | 83 two-horizon diffraction paths | | | | | |
| f | 41 | 60 | 92 | 98 | 101 | 160 | 190 | 210 | 492 | 1046 |
| d | 22 | 75 | 80 | 94 | 118 | 126 | 138 | 152 | 184 | 228 |
| $\Delta h$ | 2 | 5 | 46 | 73 | 96 | 102 | 116 | 126 | 135 | 285 |
| | | | | | 340 scatter paths | | | | | |
| f | 42 | 65 | 92 | 97 | 107 | 190 | 400 | 580 | 950 | 2100 |
| d | 76 | 150 | 195 | 205 | 225 | 265 | 295 | 335 | 365 | 480 |
| $\Delta h$ | 4 | 22 | 38 | 65 | 95 | 105 | 135 | 175 | 250 | 345 |

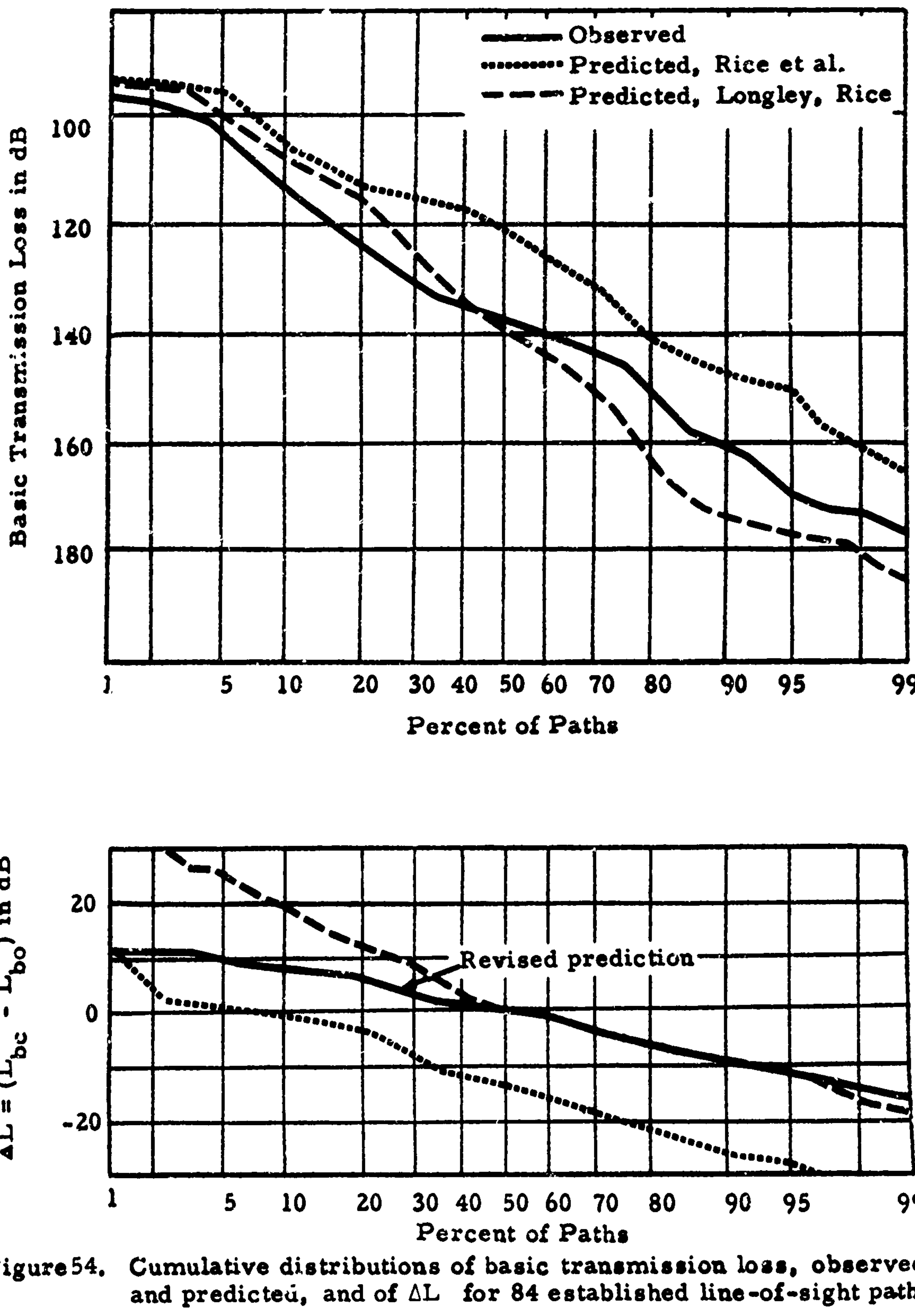



Figure 54. Cumulative distributions of basic transmission loss, observed and predicted, and of $\Delta L$ for 84 established line-of-sight paths.

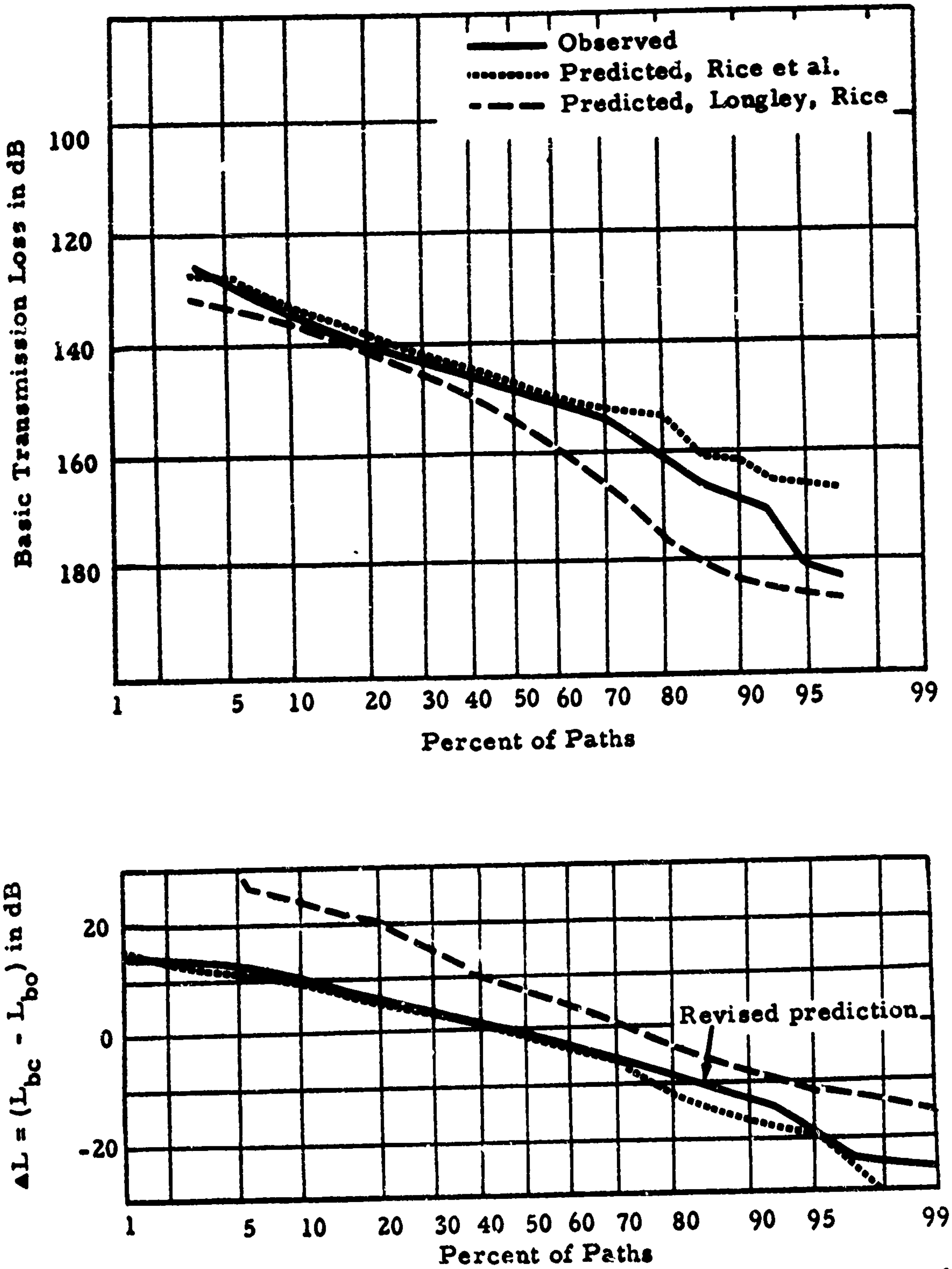



Figure 55. Cumulative distributions of basic transmission loss, observed and predicted, and of $\Delta L$ for 46 established one-horizon diffraction paths.

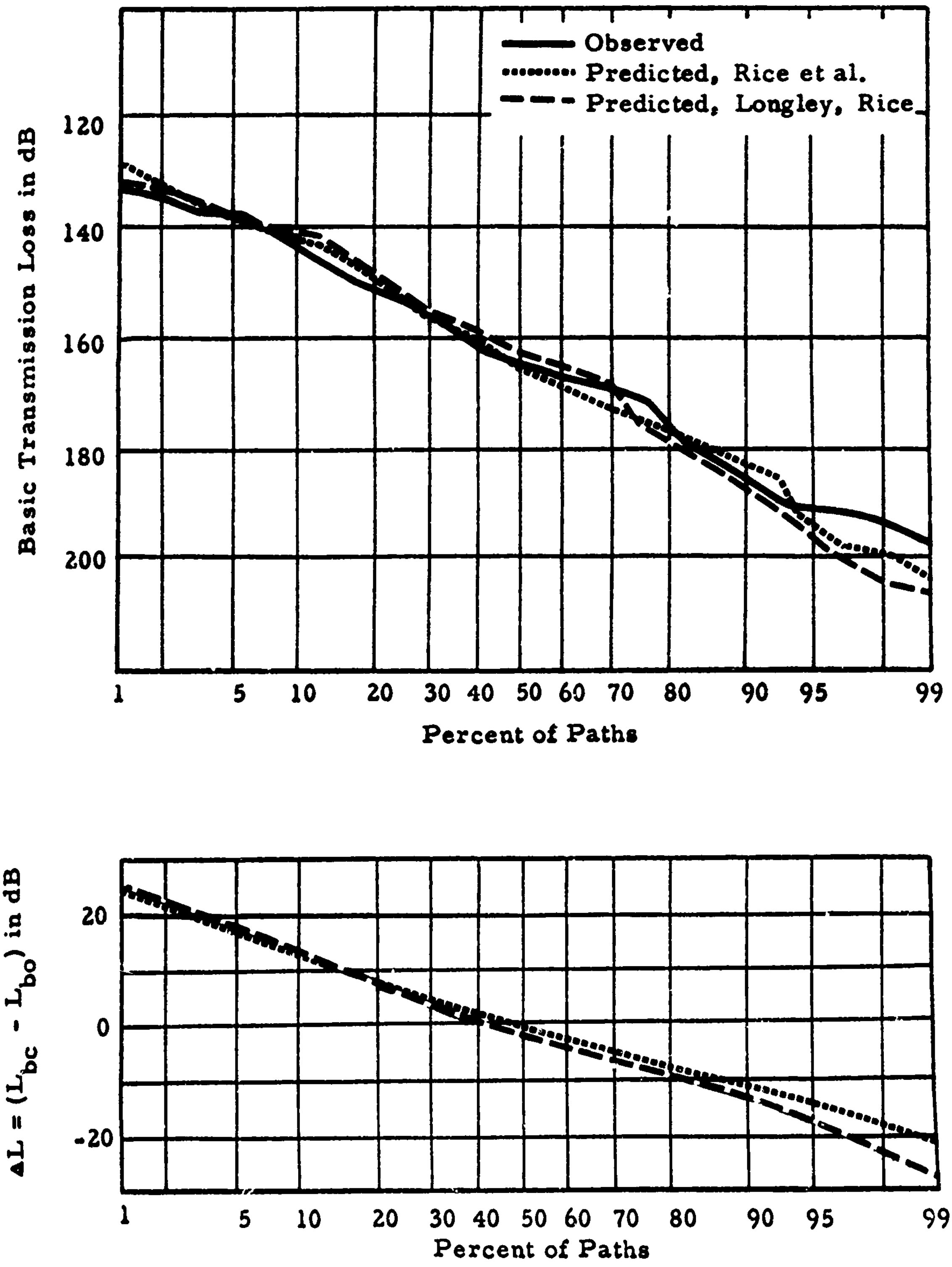



Figure 56. Cumulative distributions of basic transmission loss, observed and predicted, and of $\Delta L$ for 83 established two-horizon diffraction paths.

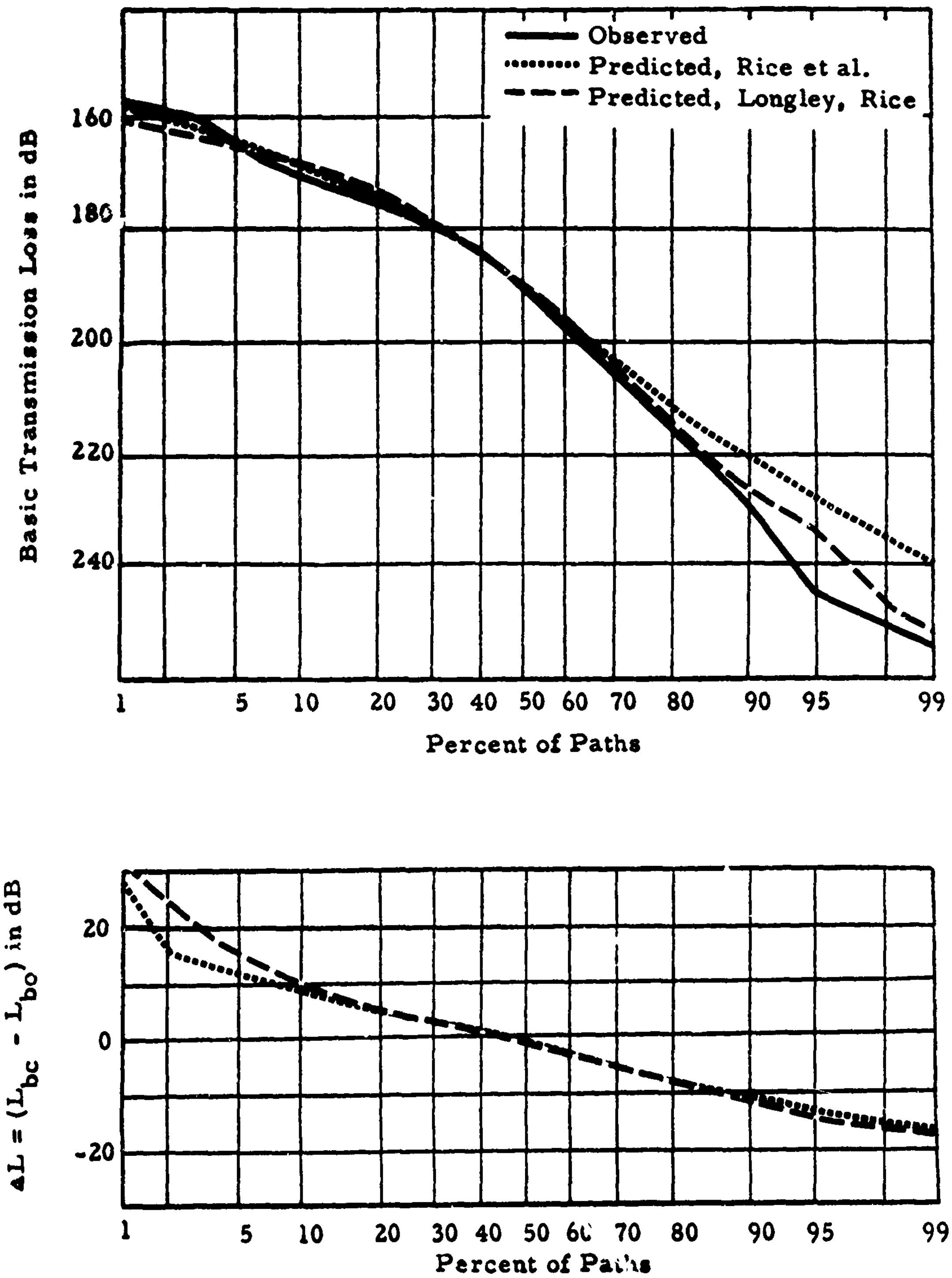



Figure 57. Cumulative distributions of basic transmission loss, observed and predicted, and of $\Delta L$ for 340 established forward scatter paths.

$$L_{bf} = 32.45 + 20 \log_{10} f + 20 \log_{10} d \quad \text{dB}, \tag{3b}$$

$$A_{cs} = 9 \left[1 + \exp(-0.01\, \Delta h)\right] - 3.5 \log_{10} (\min h_{e1,2}/\lambda) + 0.07\, d \quad \text{dB}. \tag{3c}$$

In these equations f is in MHz, d in km, with $\Delta h$, $h_{e1,2}$, and $\lambda$ in m. This "revised prediction" gives excellent agreement with measured values for these 84 line-of-sight paths. Values calculated using this method will be compared with line-of-sight paths in the various data groups previously discussed.

Figure 55 shows calculated and observed values and their differences for 46 single-horizon paths. For some paths in this group the single horizon is an isolated mountain peak or ridge, while for others it is the surface of the sea or the bulge of the earth's surface. For most of these paths the earlier methods of Rice et al. (1967) give good results, but the computer method of Longley and Rice (1968) predicts too much attenuation. In this case also several modifications of the computer method were tested. The best comparison with data is obtained using Fresnell-Kirchoff knife-edge diffraction calculations, allowing for ground reflections with a function $G(\bar{h}_{1,2})$ described in the earlier report (Rice et al., 1967). Criteria to determine when $G(\bar{h})$ should be used depend upon whether or not the radic ray has first Fresnel zone clearance above the terrain between an antenna and its horizon. For computer application this condition is approximated when the effective antenna height exceeds the maximum width of the first Fresnel zone. The computer method was therefore revised to calculate the knife-edge attenuation $A(v,0)$, using the parameters for the path, and the total attenuation as

$$A_{cd} = A(v,0) - G(\bar{h}_1) - G(\bar{h}_2) \quad \text{dB}, \tag{4}$$

where

$$\bar{h}_1 = 5.74\,(f^2/a_1)^{1/3}\ h_{e1}, \quad a_1 = d_{L1}^{\ 2}/2\,h_{e1}, \text{ and} \tag{5a}$$

$$\bar{h}_2 = 5.74\,(f^2/a_2)^{1/3}\ h_{e2}, \quad a_2 = d_{L2}^{\ 2}/2\,h_{e2}. \tag{5b}$$

When $$h_{e1,2} > 0.5\,\sqrt{\lambda\, d_{L1,2}} \quad \text{let } G(\bar{h}_{1,2}) = 0; \tag{6}$$

otherwise $G(\bar{h})$ is read from figure 7.2, volume 1 of Rice et al. (1967). Mathematical functions have been fitted to these curves for use in the computer method. In equations (4) through (6) all heights and distances are in km and the frequency is in MHz. The predicted value of basic transmission loss $L_{bc}$ is then obtained by adding the free space loss $L_{bf}$ to the calculated attenuation $A_{cd}$, as shown in equations (3a) and (3b).

A cumulative distribution of the differences between observed values and those calculated using this revised prediction method show excellent agreement.

Figures 55 and 56 show that both the earlier method and the computer method agree well with observed long-term median values for both two-horizon diffraction and forward scatter paths.

## 4. CONCLUSIONS

Several conclusions may be drawn from these comparisons of prediction methods with a large number of spot measurements and long-term recordings.

The "area" predictions, that do not require individual path profiles, define the medians of data as a function of distance either when the antenna sites are chosen at random, or the rules for site selection are clearly defined. The scatter of measured values about their median at each distance depends on site selection and the range of terrain irregularity in the group of paths considered. For homogeneous terrain the scatter of measured values is considerably less than for groups of paths with widely varying terrain characteristics.

In the current computer model terrain irregularity is characterized by a single parameter $\Delta h$. This can not completely describe the terrain characteristics of an area as, for instance, it gives no indication as to whether the irregularity consists of a few large hills and valleys or numerous small ones. Such differences would affect the parameters $h_{e1,2}$, $d_{L1,2}$, and $\theta_{e1,2}$ that are derived from $\Delta h$ in the area-prediction model. Further studies to develop a more complete model of terrain irregularity are in progress.

In areas with a large proportion of line-of-sight and one-horizon paths we tend to predict too much transmission loss, particularly with the higher antenna heights. For example, figures 1 to 4 and 6 to 9 show that for the R-1 and R-2 data the area predictions calculate somewhat more than the median measured loss. Table 1 shows that 25 of the 48 R-1 paths and 15 of the 43 R-2 paths are line-of-sight or single-horizon paths. Figures 33 to 36 show that the point-to-point method also predicts somewhat too much loss for these paths, especially with the higher receiver heights. Similar results are shown for the mountainous area in Washington, where 16 of the 53 paths are line-of-sight and single-horizon paths. Figures 21 and 22 for the area predictions and 46 and 47 for the point-to-point predictions show that we overestimate the transmission loss, especially for the 3 m antennas. These results indicate that the prediction models for line-of-sight and one-horizon diffraction paths tend to overestimate the attenuation caused by reflections from terrain. Tests of the point-to-point predictions against long-term medians of data over established communication links confirm this. Figures 54 and 55 show that the computer model, Longley and Rice (1968), overestimates the transmission losses for some

30 percent of the line-of-sight and all of the one-horizon paths. The point-to-point prediction models were revised to provide much better agreement with these measured values as shown. Figures 56 and 57 show excellent agreement between measured and predicted values for transhorizon diffraction and scatter paths.

In each group of measurements some deviation of predicted from observed values for individual paths occurs. For the single spot measurements this deviation may result in part from differences in diurnal and seasonal propagation conditions and in part from path-to-path differences. Variability in time may be appreciable, especially over the longer paths, but location or path-to-path variability is probably greater. The prediction method calculates a reference value that represents the long-term median transmission loss. Figures 54 to 57 compare calculated values with the long-term median of measurements for each path. In these groups the distributions of $\Delta L$ show path-to-path or location variability. The figures show this location variability to be normally distributed with a standard deviation $\sigma_{La}$ of 8 to 10 dB.

The results of comparisons with the Virginia data (figs. 11 to 14) indicate that we tend to overestimate transmission loss at the lowest frequency and underestimate it at the two highest frequencies. In this area the terrain is partly covered by deciduous trees that would cause considerably more attenuation at the higher than at the lower frequencies. The effects of vegetation and man-made structures should be further investigated.

The computer model 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 for all frequencies, distances, antenna heights, and terrain types tested these area predictions describe the medians of data, with the exception of areas with an unusually large proportion of line-of-sight and single-horizon paths, as previously noted. In areas where most of the measurements are over transhorizon paths the present model gives excellent results.

The point-to-point predictions, based on individual path profiles, agree well with data except for line-of-sight and single-horizon paths. Modifications of the computer method have been developed that agree well with the median values recorded over established paths. These modifications will be incorporated into the computer model and tested against measurements in the various areas.

These comparisons of predicted values of transmission loss, using the computer methods of Longley and Rice, with a large amount of data from measurement programs, show excellent agreement for transhorizon paths throughout the frequency range from 20 to 10,000 MHz for all tested antenna heights from less than 1 m to 2700 m and for terrain types ranging from very smooth plains to extremely rugged mountains. For known line-of-sight and single-horizon paths the predicted attenuation is greater than that observed. Modifications of the prediction model are described that provide excellent agreement with measurements for such paths.

## 5. REFERENCES

Barsis, A. P., M. J. Miles (1965), Cumulative distributions of VHF field strength over irregular terrain using low antenna heights, NBS Report 8891.

Barsis, A. P., M. E. Johnson, and M. J. Miles (1969), Analysis of propagation measurements over irregular terrain in the 76- to 9200-MHz range, ESSA Tech. Rept. ERL 114-ITS 82.

Hause, L. G., F. G. Kimmett, and J. M. Harman (1969), UHF propagation data for low antenna heights, ESSA Tech. Rept. ERL 134-ITS 93, Volumes I & II.

Johnson, M. E., M. J. Miles, P. L. McQuate, and A. P. Barsis (1967), Tabulations of VHF propagation data obtained over irregular terrain at 20, 50, and 100 MHz, ESSA Tech. Rept. IER 38-ITSA 38 parts I, II, and III.

Longley, A. G. and P. L. Rice (1968), Prediction of tropospheric radio transmission loss over irregular terrain, a computer method - 1968, ESSA Tech. Rept. ERL 79-ITS 67.

McQuate, P. L., J. M. Harman, and A. P. Barsis (1968), Tabulations of propagation data over irregular terrain in the 230- to 9200-MHz frequency range, part I: Gunbarrel Hill receiver site, part II: Fritz Peak receiver site, ESSA Tech. Rept. ERL 65-ITS 58.

Rice, P. L., A. G. Longley, K. A. Norton, and A. P. Barsis (1967), Transmission loss predictions for tropospheric communication circuits, vol. 1 and 2, NBS Tech. Note 101 (revised).



GPO 856-672

Unclassified
Security Classification

**DOCUMENT CONTROL DATA - R & D**

*(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)*

| | |
|---|---|
| 1 ORIGINATING ACTIVITY (Corporate author)<br>Environmental Science Services Administration<br>Boulder, Colorado | 2a. REPORT SECURITY CLASSIFICATION<br>Unclassified<br>2b. GROUP |

3 REPORT TITLE

Comparison of Propagation Measurements With Predicted Values in the 20 to 10,000 MHz Range

4 DESCRIPTIVE NOTES (Type of report and inclusive dates)

Final Report Phase D Part 6 July 1969- January 1970

5 AUTHOR(S) (First name, middle initial, last name)

A. G. Longley and R. K. Reasoner

| | | |
|---|---|---|
| 6 REPORT DATE<br>January 1970 | 7a. TOTAL NO. OF PAGES<br>103 | 7b. NO. OF REFS<br>7 |
| 8a. CONTRACT OR GRANT NO.<br>FO4701-68-F-0072<br>b. PROJECT NO.<br>c.<br>d. | 9a. ORIGINATOR'S REPORT NUMBER(S)<br>ESSA Techni:al Report ERL 148-ITS 97<br>9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)<br>SAMSO-TR-70-51 Vol. I | |

10 DISTRIBUTION STATEMENT

Distribution of this document is unlimited

| | |
|---|---|
| 11 SUPPLEMENTARY NOTES | 12. SPONSORING MILITARY ACTIVITY<br>USAF SAMSO<br>Norton AFB, Calif. 92409 |

13 ABSTRACT

Predictions of tropospheric transmission loss over irregular terrain using the computer methods described by Longley and Rice ~~(1968)~~ are compared with measurements, to determine their limits of applicability and define the boundary conditions for their use.

DD FORM 1 NOV 65 1473

Security Classification