OT REPORT 75-74

SENSOR PATH LOSS MEASUREMENTS ANALYSIS AND COMPARISON WITH PROPAGATION MODELS

U.S. DEPARTMENT OF COMMERCE Office of Telecommunications

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SENSOR PATH LOSS MEASUREMENTS
ANALYSIS AND COMPARISON WITH PROPAGATION MODELS

Anita G. Longley and George A. Hufford*

The data from a large measurement program at VHF and UHF are carefully evaluated, summarized and compared with values predicted from models of radio propagation over irregular terrain. Particular problems of low antennas and the effects of vegetation are considered. Modifications in prediction models are suggested for particular application to sensor systems.

Key words: Irregular terrain; low antennas; path loss; radio propagation; sensor communication; vegetation effects.

1. INTRODUCTION

A sensor system may operate with antennas placed virtually at ground level. Since little information was available regarding propagation at VHF and UHF with antennas placed close to the ground, a measurement program was planned and carried out during 1973 and 1974. It was designed to obtain data at 172 and 410 MHz over several types of terrain, at different seasons and times of day.

An earlier measurement program of somewhat limited scope, reported by Norris (1972), demonstrated the large path-to-path differences that can occur, particularly in mountainous terrain. Some variability from one period of time to another was also observed. This variability may be caused by changes in atmospheric and/or ground conditions.

Data were, therefore, obtained over as many paths as practicable, in areas with quite different types of terrain, and at different times of day and seasons of the year. The following three test areas were selected: First, an area at Eglin AFB, Florida, which represents flat terrain with heavy forest cover. Second, an area in the Graham Mountains near Fort Huachuca, Arizona, which represents highly irregular terrain with little vegetation. Third, an area in the rolling hills of the Hunter Liggett Military Reservation in California.

Climatic conditions in these areas were reviewed to determine which months would best represent seasonal extremes. The greatest seasonal differences at Eglin AFB and Hunter-Liggett are expected to occur during the wet and dry seasons. In the Hunter-Liggett area the dry summer months are usually best represented by conditions in July, with the rainy season in January and February. The dry season at Eglin is usually in November,

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with the rainy season in July and August. Unfortunately, only one set of measurements was made at Eglin because the planned return could not be implemented. In the Arizona mountain area no marked seasonal changes are expected, so two measurement periods in the late fall and the spring were considered adequate.

In order to observe possible diurnal changes in propagation conditions, data were obtained at various times throughout the day. In addition to seasonal and diurnal changes we wished to study short-term changes within each recording period of 15 to 20 min. Using the on-board computer in an automatic data acquisition system, 20 values within each recording period were obtained and their first four moments calculated. These values are used to obtain the mean, standard deviation and type of distribution for each record.

This report describes the three test areas, and summarizes the data obtained at each frequency for each path in the selected areas, nearly 800 sets of data. The measured values are compared with both discrete path and area predictions. Finally, modifications of the prediction models are suggested for application to sensor systems.

2. THE MEASUREMENT PROGRAM

This program was sponsored by the Advanced Research Projects Agency (ARPA). The measurements were carried out by personnel of the Lockheed Corporation of Tucson, Arizona, under contract to the U.S. Army Electronic Proving Ground (USAEPG).

In each of the three selected sites, 10 transmitters were deployed in a rather small area, with the receiving van located some distance to the north, south, east, and west to provide 40 propagation paths in each area. In all cases the transmitting antennas were placed with the center of radiation 0.35 m above ground. Transmission from each of the 10 sensors was at nominal frequencies of 172 and 410 MHz. The signals were received on antennas at three heights of 10, 3, and 0.35 m. Data were collected using an automatic path loss measurement system (APLMS), described in Appendix A.

At the beginning of each day a frequency search was made, and the peak frequency for each transmitter was stored in the computer for both the VHF and UHF signals. The frequency searches were repeated every fifth cycle, and updated if necessary to provide four frequency checks in every record of 20 cycles in a period of 15 to 20 min. During each cycle the pulse power of a transmitter remained on while two sets of five or more readings each were averaged to obtain the level of received power for each frequency. The first four moments for each group of 20 readings were calculated, and this information was recorded on magnetic tape for later analysis. Each tape record then contains the four moments, representing measured values, for each of 10 propagation paths at two frequencies and with three receiving antenna heights; 60 sets of four moments each in each record.

In some cases no data were recorded or individual cycles were missed. It is important to distinguish between various causes of such failures. Only those measurements when failure resulted from the signal being at or below threshold should be considered as valid data. A log of the operation was kept in the field in which known equipment failures were noted. Unfortunately, not all failures were observed or could be identified.

The data tapes from Eglin AFB and the first set from the Graham Mountains contain the first four moments of the readings obtained during each 15 to 20 min period as described above. These statistics provide the mean and variance of the data for each record and are used to compute the skewness and excess of each sample to describe the type of distribution obtained. Because of many irregularities observed in the first data tapes, the output was later changed to include the frequency searches, and the individual readings within each record.

The data on the magnetic tapes are recorded as available power in dBm. For comparisons between paths and with propagation models, we converted the recorded values to basic transmission loss by applying corrections for transmitter power, antenna gains, and line losses. These values were then grouped by frequency, path and receiver height in each area, and distributions of values within each group were obtained.

3. VALIDITY OF THE DATA

Several problems arose in determining the validity of the recorded measurements. Examination of the first set of records (from the Eglin area) showed that while there was usually little change in level between the 20 values obtained during a recording period, there were sometimes large variances, particularly at the higher frequency. Listings of the individual readings for several records were obtained and examined. These listings showed that one set of five readings might differ from the others by as much as 10 to 20 dB, indicating that they were operating on the skirts of the signal. In an effort to overcome this problem, the bandwidth was increased from 1 to 3 kHz. With the increased bandwidth the variance was reduced to values comparable to those at the lower frequency, but the sensitivity was somewhat reduced. Even with this change, the measurements continued to show somewhat erratic behavior.

An example of large unexplained variances in the Graham Mountain data is shown in table 1. The table lists some sample means and variances for both frequencies and all three receiver heights recorded over a period of nine hours. The data for path number 1 at 172 MHz show little change in mean level from one record to the next, and small variances within each recording period, but much larger variances and changes in mean level for data at 410 MHz. This trend is also typical of eight of the other paths during this period, but path number 4 shows a rather extreme case of malfunction. The field log indicated that transmitter 4 was out of service during the hours from 6 to 10 a.m., but was reported back in service at that time. However, at 172 MHz there is considerable change in the mean values from one period to the next, with variances as much as 128 dB^2, corresponding to a standard deviation of more than 11 dB. The record shows that for this period only 12 cycles were recorded, so there is evidently no consistency among these 12 values.

Because it appeared certain that some erroneous values were being recorded, we agreed that the tapes from the Hunter-Liggett area and the

Table 1. Sample Means and Variances, Graham Mountains

		172 MHz						410 MHz					
		10m		3m		0.3m		10m		3m		0.3m	
Path	Time	$\bar{x}$	s^2	$\bar{x}$	s^2	$\bar{x}$	s^2	$\bar{x}$	s^2	$\bar{x}$	s^2	$\bar{x}$	s^2
1	0629	92.2	0.04	92.5	0.05	102.8	0.05	105.6	5.7	100.3	18.8	105.5	5.4
	0727	92.2	0.11	92.4	0.09	102.6	0.14	104.7	1.9	97.9	2.4	103.4	1.4
	0823	92.5	0.03	92.9	0.04	103.0	0.13	107.4	4.6	101.0	8.0	106.3	6.2
	0911	92.4	0.02	92.7	0.02	103.1	0.07	105.9	0.8	98.6	0.8	103.9	0.7
	1000	89.6	0	90.1	0.04	100.5	0.23	105.9	9.6	100.1	22.9	105.1	13.8
	1059	89.7	0.02	90.1	0.03	100.3	0.09	105.1	9.5	99.0	27.4	103.5	17.7
	1156	89.8	0.04	90.3	0.07	100.5	0.08	103.2	0.7	96.9	12.9	101.3	1.9
	1303	89.5	0.01	90.0	0.01	100.2	0.08	102.7	0.6	95.2	0.3	100.5	0.5
	1419	92.1	0.01	92.5	0.03	102.6	0.05	107.7	0.9	99.9	1.8	105.2	1.9
4	1000	94.5	88.5	92.5	82.5	101.9	23.5	104.7	10.2	103.6	53.8	109.2	1.6
	1059	94.4	92.4	91.2	67.3	101.8	26.4	105.3	16.3	99.5	38.2	109.3	2.1
	1156	88.2	0.02	88.0	0.2	98.9	0.05	103.8	4.9	99.5	31.4	108.4	0.3
	1303	97.9	128.2	92.3	80.9	98.8	0.02	106.9	18.9	101.6	48.4	108.8	1.5
	1419	91.4	0.06	90.7	0.1	101.5	0.08	104.0	0.1	98.7	0.1	109.5	0.1

$\bar{x}$ sample mean, negative dBm

s^2 variance of the 20 readings in each sample, dB^2

second set from the Graham Mountains should include the frequency searches and the original 20 readings in addition to the computed four moments.

We then performed a minute examination of all data, including not only the data on all magnetic tapes, but also many computer listings from the field operation at Eglin AFB. This examination was necessary to try to distinguish between equipment irregularity and true propagation variability. We discovered some four different equipment failures that we could recognize in the data.

The tuning sequence sometimes failed and recordings were made either entirely off-frequency or on the skirts of the response curves. Sometimes failures were recognized in the field, but frequently they were not noted. In the Hunter-Liggett data, differences of 30 to 40 kHz between successive frequency searches are common and differences of 50 to 100 kHz occur. In view of the 3 kHz bandwidth employed in the measurements, it is not surprising that such frequency differences are often associated with marked changes in received signal level. Some examples of frequency changes and associated changes in received signal level are shown in table 2.

Table 2. Peak Frequencies and Individual Values of Received Power, Hunter-Liggett Area

	T4	T5	T7	T5	T7
freq.	172.541	.553	.556 MHz	410.502	.497 MHz
	-82.0	-77.2	-47.4	-73.5	-61.5
	-	-78.0	-47.4	-74.9	-62.5
	-82.0	-76.3	-47.8	-70.2	-61.6
	-81.8	-77.1	-47.6	-74.1	-60.0
	-81.7	-78.1	-48.2	-69.5	-61.9
freq.	172.566	.559	.556 MHz	410.505	.496 MHz
	-54.1	-51.4	-47.0	-63.9	-61.1
	-54.2	-50.4	-47.0	-64.2	-59.7
	-54.4	-50.5	-47.1	-61.8	-61.6
	-54.0	-51.7	-47.2	-62.2	-60.6
	-54.0	-51.1	-47.0	-64.8	-59.8

Received power values in the table are recorded in dBm, and show 10 successive readings from the 10 m receiving antenna for transmitters 4, 5, and 7. The values for T7 show practically identical frequency tuning for the two periods at both 172 and 410 MHz with consistent signal levels and standard deviations of 0.3 and 3.9 dB, respectively. Transmitter 4, on the other hand, shows a difference in tuning of about 25 kHz with associated differences in received power of more than 25 dB and a standard deviation of 13.9 dB. While the differences in frequency for T5 are not nearly as large, about 6 and 3 kHz, they are sufficient to cause changes in signal level of about 25 and 10 dB. In this connection, it is interesting to note that the mean value for this record from T4 shows 12 dB more loss than that for the hours immediately preceding and following this record. Differences in frequency tuning are very common in this area, so we recorded all instances where successive peak frequencies differed by more than 3 kHz. Individual readings that were obviously questionable showed such differences in tuning, but sometimes the data did not show obviously erratic behavior when frequency differences occurred.

In some cases, serious discrepancies in results occurred that were not related to changes in frequency tuning. One such example was observed on January 23 at 1600 hrs. There is no field record of any problems, but a sudden drop in signal level was observed from all transmitters at all receiving antenna heights for both frequencies. The mean values were lower by 10 to 20 dB, and unusually large standard deviations were recorded. Detailed examination showed that for the transmitters the peak frequency searches were consistent in all but one instance. The first 10 measured values for each of the 10 transmitters are quite consistent and the first two or three readings in the third group continue this trend, but the last few readings in the group show a drop in signal level of 25 to 30 dB. After the fourth peak frequency search, the signals are at normal levels for the first two readings, and then drop to levels near threshold again. Since these changes affect both frequencies for all transmitters at all receiving antenna heights, they appear to represent a malfunction in the receiving system. These were observed because the changes were large enough to be obvious, but similar smaller errors could easily be missed. To guard against including such spurious values, we developed a method of testing individual values within a record for consistency.

Timing problems which affected switching from high to low ports had been observed in the field. We also noted that switching from the high to low ports was sometimes incomplete with an additional insertion loss. Indeed, at times the switching from the middle receiving antenna to the lowest one failed entirely, and the recorded signal was actually that received on the middle antenna. Problems in timing were pointed up by special field tests. When the 172 MHz data were recorded first, much of the higher frequency data was lost. When the procedure was reversed, measuring the 410 MHz transmission first, much of the data at the lower frequency was lost.

The command circuit sometimes failed and a transmitter did not turn on at all. Usually continuous failures were noted in the field but intermittent failures often escaped notice.

Because of the large amount of data and the many problems encountered, we felt that it was essential to develop criteria for testing the validity of each individual value. Therefore, the test and evaluation criteria had to be automated. A computer program was written to weed out all data which showed the errors discussed here. This program removed all values that appeared questionable on the basis of comments in the log regarding field operations, tested all frequency searches and resulting changes in level, and tested each set of 20 values within a record for internal consistency. No automated comparisons were made, however, between records for successive hours. These carefully edited data were then used to obtain distributions of all records for each path, frequency, and receiver height.

Because individual readings were available and sudden changes in level were so common, we decided to describe these data in terms of median rather than mean values, and to obtain actual distributions directly rather than by means of the computed moments. In a normal distribution the median may be equated with the mean, and medians are much less affected by a few extreme values than are means. Also a single large value can make great changes in the third and fourth moments.

Since this information on frequency peak searches and individual readings is available only for the Hunter-Liggett data and the second set from Graham Mountains, it was not possible to edit the Eglin data in this fashion. The Eglin data were examined visually for unusual changes, and in many cases computer listings from the field records were examined to determine whether abrupt changes in level were associated with changes in frequency. The first half of the Graham Mountain data is based on mean values, and the second is obtained from distributions of data from the edited tapes.

A close study of the carefully edited data shows that there remain some records with unexplained and highly unlikely values, as will be described in later sections. One interesting anomaly that occurred several times was that all path losses were greatest during the first hour or two of the recording day. Perhaps it took both men and machines some time to warm up to the daily task.

4. VARIABILITY OF THE SIGNAL

As a general rule, the data from this series of measurements show little change in average path loss from hour-to-hour, and also little variation between the readings within each record. The latter is indicated by small variances, which are usually much less than a dB. The marked exceptions that occur have in most cases been found to result from equipment failure rather than from actual changes in propagation conditions.

While changes from one hour to the next are usually small, there are fairly large differences from day-to-day and from week-to-week. True seasonal differences are not clearly shown in these measurements. Only one period of time is covered in the Eglin area, and the two periods in the Graham Mountains did not exhibit the usual rainy and dry weather. While measurements were obtained at two quite different times in the Hunter-Liggett area, no clear seasonal differences are observed.

For a more detailed examination of fading characteristics, it is convenient to distinguish between long-term and short-term variations and to discuss them separately. The often large differences in path loss for paths of the same length are, to a great extent, dependent on the terrain type and for this reason will be discussed in the separate sections for each area.

4.1. Short-Term Fading

By short-term fading we mean those changes in received signal level that occur within a short period of time, an interval of seconds or minutes. Such fading is represented in the present study by the variation between the 20 readings within each record. These recordings are separated in time by about a minute.

For most of the data in the measurement program this short-term variability is small, particularly at the lower frequency. At 172 MHz the variance is typically much less than 1 dB^2, with a standard deviation usually less than 0.5 dB. At 410 MHz the variance is somewhat larger, but again standard deviations less than a decibel are usual and values of more than 2 dB are rare.

A few examples of successive readings are included to show some typical and some unusual values. A data listing obtained from the Eglin area shows the consistent values within a record that are typical for most paths. This record, part of which is listed in table 3, was obtained from the highest receiving antenna at receiver site 1 on Nov 19 at 1300. The table lists successive received power values, in negative dBm, at both VHF and UHF, from transmitters 1, 2, 4, and 5. The signals from the remaining transmitters were below threshold at UHF so they are not included in the table. There were no appreciable differences between sequential tunings, and close similarities within and between each group of five values are apparent. The small variation between values in this record are shown by the small standard deviations, $\sigma = 0.28$, 0.34, 0.21, and 0.25 dB at VHF and $\sigma = 0.59$, 0.30, 0.49, and 0.33 dB at UHF.

A similar record from the Eglin area shows rather larger variances at the higher frequency. This record is from receiver site 3, Nov 28 at 1800, with the highest receiving antenna. Values of path loss from transmitters 3, 5, 9, and 10 at both frequencies are listed in table 4. Again in this record there were no frequency changes following the peak searches, and the larger variation at UHF probably represents propagation conditions. The transmitting antennas were placed close to a grove of pine trees in the direction of R3.

It is interesting to note that the large standard deviation, $\sigma = 3.56$ dB, at VHF on channel 10 was caused by two large losses, indicated in the table by asterists, which show little relationship to the other 18

Table 3. A Typical Record Showing Little Short-Term Variability in Received Power, Eglin AFB.

	T1		T2		T4		T5		
	VHF	UHF	VHF	UHF	VHF	UHF	VHF	UHF	
	95.6	103.4	90.9	105.0	86.8	104.1	95.3	104.9	
	95.6	-	90.9	104.7	86.6	104.7	95.0	104.3	
	95.7	103.9	90.9	105.1	86.4	104.0	95.7	104.9	
	95.5	103.8	90.9	-	86.5	103.9	95.1	104.3	
	95.8	103.3	91.0	105.1	86.6	104.0	95.6	104.6	
	95.0	103.7	90.6	-	86.6	103.7	95.2	104.8	
	95.5	104.1	91.0	105.0	86.4	104.3	95.3	-	
	95.3	104.5	90.8	104.3	86.6	104.2	95.2	104.0	
	95.2	103.7	90.8	104.7	86.5	104.8	95.6	104.6	
	95.4	-	90.9	104.3	86.6	104.6	95.3	105.0	
	95.9	104.5	89.9	105.1	86.6	105.3	95.1	104.2	
	95.8	104.3	90.9	104.7	86.7	104.9	95.3	105.0	
	95.6	104.9	90.2	105.0	86.9	104.7	95.1	104.7	
	95.7	104.3	90.1	104.6	86.5	105.3	95.1	104.6	
	96.0	104.4	90.7	-	87.1	104.3	95.8	103.8	
	95.9	102.7	90.5	104.3	87.2	104.4	95.3	104.3	
	95.7	103.6	-	-	87.0	-	95.8	104.4	
	-	102.8	90.5	104.3	86.7	103.8	95.0	104.8	
	96.0	104.4	90.8	104.4	86.6	103.7	95.0	104.4	
	95.1	-	90.0	104.6	86.7	-	95.3	104.9	
Mean	-95.6	-103.9	-90.6	-104.7	-86.7	-104.4	-95.3	-104.9	dBm
σ	0.28	0.59	0.34	0.30	0.21	0.49	0.25	0.33	dB

Table 4. A Record Showing Short-Term Variability with Larger Variance at UHF

	T3		T5		T9		T10		
	VHF	UHF	VHF	UHF	VHF	UHF	VHF	UHF	
	50.8	75.0	68.8	87.0	59.4	71.0	62.1*	80.5	
	50.8	75.2	69.1	89.1	60.5	82.7	55.6	78.3	
	51.2	76.2	67.9	80.4	60.3	77.9	54.3	70.3	
	50.6	73.5	68.2	85.9	58.4	78.1	56.2	83.0	
	50.8	78.9	71.9	80.2	59.3	79.5	54.7	75.8	
	-	75.2	68.5	79.6	62.1	79.1	57.6	70.1	
	50.5	74.0	69.4	87.0	59.7	90.6	56.2	79.6	
	50.6	79.6	68.5	-	59.4	88.0	56.5	72.1	
	50.9	76.7	69.3	89.8	58.5	81.6	52.8	74.2	
	51.0	75.4	67.7	78.2	59.3	83.9	57.3	72.8	
	50.8	70.5	68.0	86.8	59.4	74.0	70.0*	73.5	
	50.7	70.1	69.4	86.7	59.5	80.3	56.5	76.3	
	51.1	77.7	67.5	91.0	59.1	76.3	56.5	72.0	
	51.1	77.2	69.3	86.2	60.1	79.2	56.0	65.6	
	50.4	76.5	70.0	87.1	58.1	84.3	56.5	77.7	
	50.7	75.4	67.8	88.8	59.2	89.1	59.6	74.1	
	50.5	71.7	68.0	-	58.4	76.8	53.1	71.1	
	50.7	70.9	68.3	83.2	59.5	87.3	58.1	68.2	
	50.7	78.1	68.1	85.7	59.0	76.0	56.7	69.1	
	50.8	77.3	69.4	88.8	61.6	90.1	58.3	67.3	
Mean	-50.8	-75.6	-68.8	-85.6	-59.5	-81.3	-57.2	-73.6	dBm
σ	0.22	2.42	1.01	3.65	0.98	5.44	3.56	4.54	dB

values. There are no similar sudden changes in level at VHF from the other transmitters indicating no general change in propagation conditions. These apparently accidental changes are also reflected in unusually large third and fourth moments with skewness of -2.2 and excess of 5.6. If these two readings are deleted, we find σ = 1.5 dB, the moments within the usual small range, and the mean path loss reduced by 1 dB. The larger variations at UHF seem to reflect real changes in signal level. These are plotted in figure 1 which shows distributions of received signal in dBm for both frequencies within the record at 1800, Nov. 28. On this plot a normal distribution would appear as a straight line. The distribution of signal at 172 MHz from T10 is the only one that does not approach a normal distribution. This could possibly indicate a different type of distribution, but more likely is attributable to the presence of erroneous readings (the two values previously noted).

The examples shown have been readings of received signal from the 10 m antennas. No clear-cut relationship has been noted between the height of the receiving antenna and short-term variability. An example of this is shown in figure 2 where distributions of data for all three receiving antenna heights are plotted. The data were recorded at receiver site 2 from transmitter 9 at Eglin AFB on Nov 24 at 1100. The mean, standard deviation, skewness, and excess for each distribution are listed in table 5. Again we find more variability in the UHF data, but no obvious change in distribution of path loss with height of the receiving antenna at either frequency. In the distributions at UHF the single large loss on the higher antenna and single small loss on the lowest one are accidental. These anomalies are evident in the skewness and excess of these two short-term distributions.

Table 5. Statistics of Short-Term Distributions Shown in Figure 2, Path T9-R2, Eglin AFB

Freq.	Ant.ht.	Mean	σ	Skewness	Excess
172 MHz	10 m	-69.3 dBm	1.1 dB	-0.1 dB	0.2 dB
	3 m	-75.3	1.7	-1.0	1.1
	0.35 m	-77.4	1.2	0.4	-0.6
410 MHz	10 m	-78.1	2.1	-2.4	6.0
	3 m	-85.1	2.9	-0.3	0.0
	0.35 m	-91.1	2.3	2.0	3.4

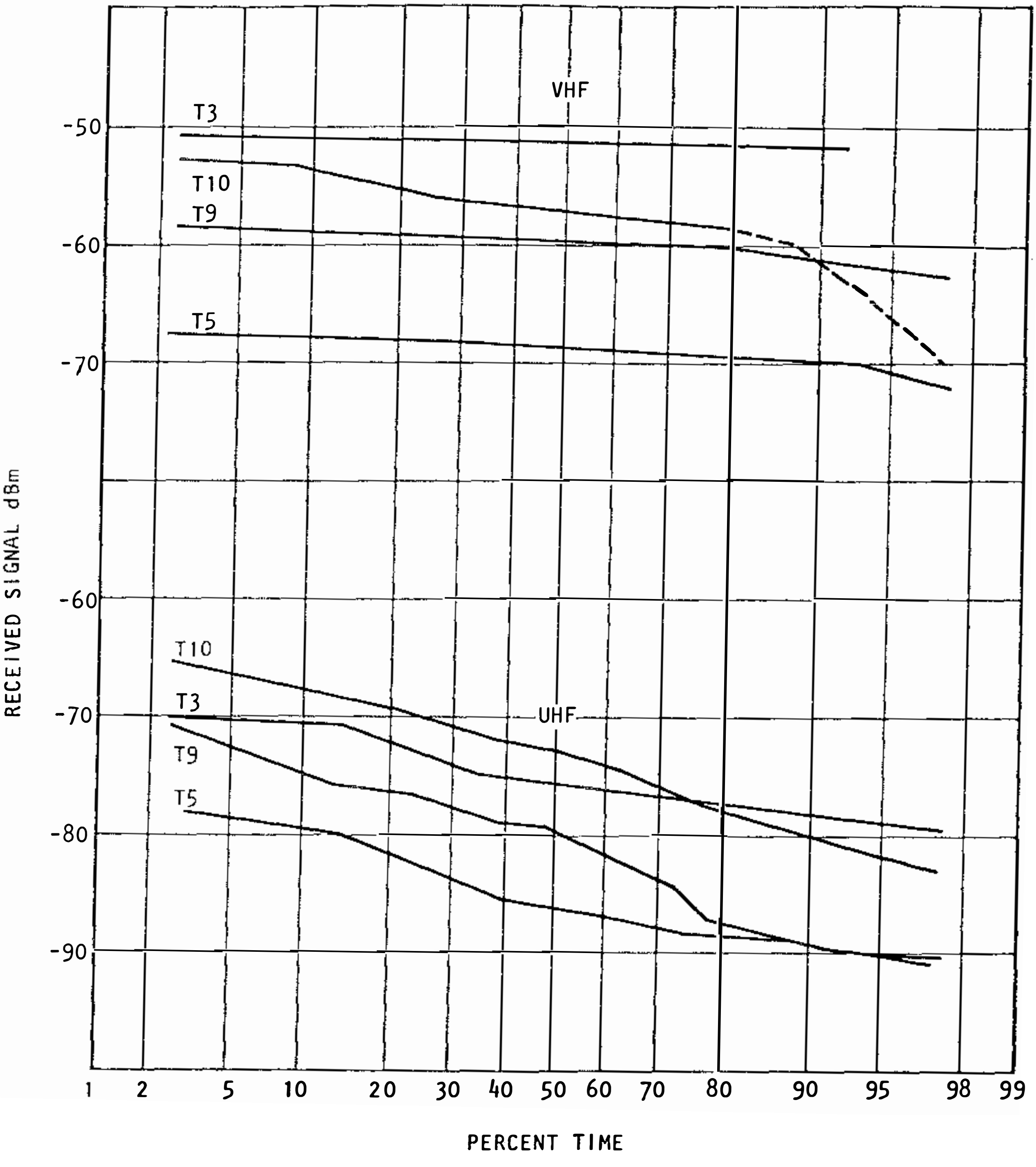

Figure 1. Short-term distributions of received signal values, receiver site R3, Eglin AFB, Nov 28, 1800.

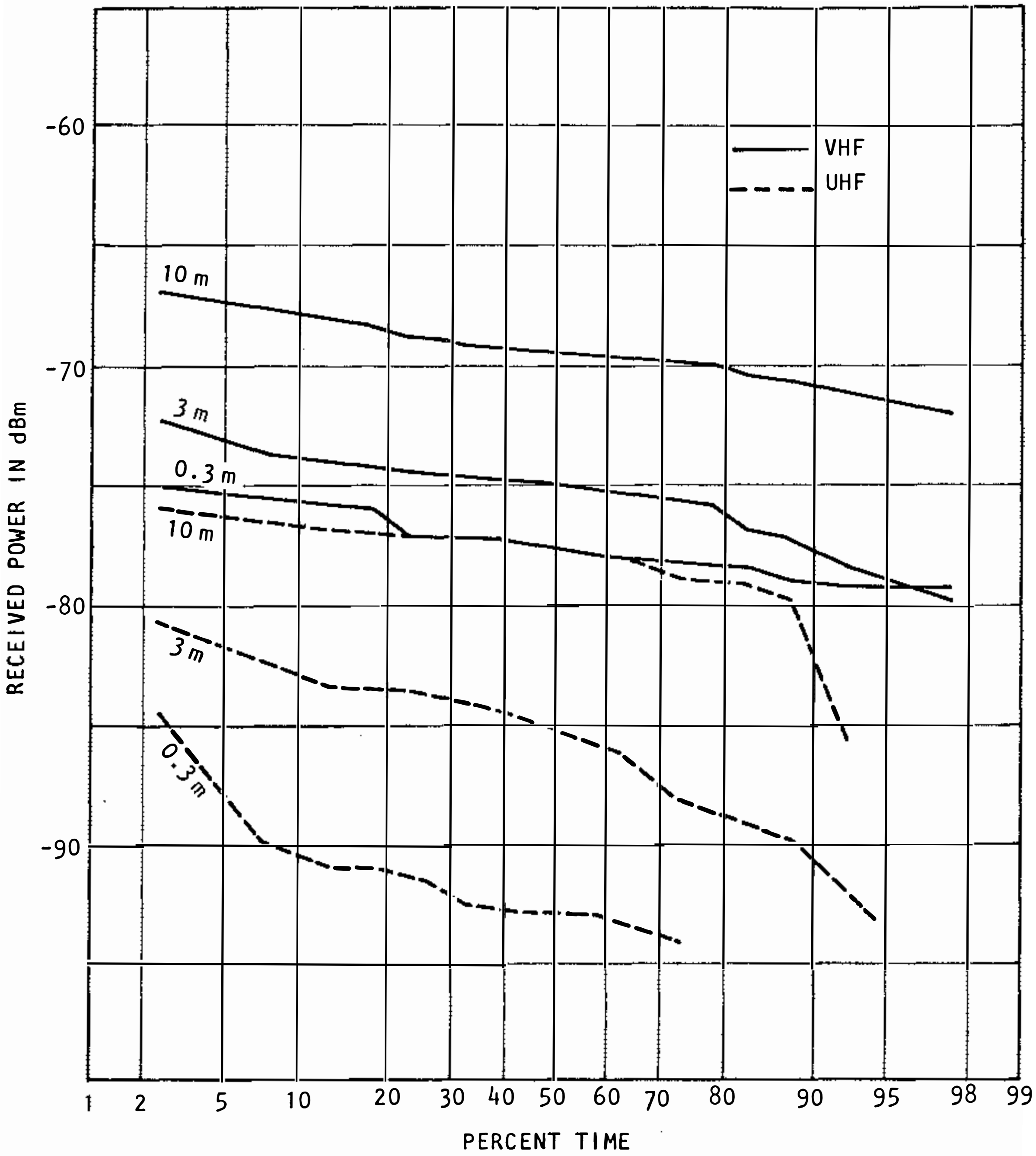

Figure 2. Short-term distributions of received signal values at VHF and UHF, with the 10, 3, and 0.3 m receiving antenna heights, path T9-R2, Eglin AFB, Nov 24, 1100.

For some paths rather large values of short-term fading are fairly common. These appear to be true propagation phenomena and may indicate that the receiver is near a null of a lobing pattern. Such nulls are common in multipath situations where interference between radio rays occurs. The relationship between direct and reflected rays can fluctuate in time producing appreciable short-term fading.

4.2. Long-Term Variability

Variability in signal level from one hour to the next, from day-to-day, week-to-week, and season-to-season, may be considered as long-term fading. To obtain an estimate of such fading a number of measurements were made over each propagation path. The recording periods usually lasted 14 to 16 consecutive hours, starting at various times of day. Measurements were made for two or more days at each receiver site, and the site was revisited about two weeks later.

Table 6 shows the date, time, and number of records obtained at each receiver site in each test area. In the Eglin area measurements were made from November 19 to December 15, giving a total of about 74 records at each receiver site. The first set of measurements in the Hunter-Liggett area was obtained in January and February with a second set in May and June, a total of 60 to 70 records in each set of measurements at each receiver site. In the Graham Mountain area the first set of measurements was made in September and October with a second set the latter part of April. During the October tests the signal was often "below threshold" at receiver sites 3 and 4. Plans were, therefore, altered. In an attempt to obtain valid readings the transmitters were moved to new locations and the signals recorded at a new receiver site, R5. Prior to the April set of measurements the equipment had been modified so that it was possible to record signals at R3 and R4, and no further tests were made at R5. Thus, there are about 60 records in each period at R1 and R2, with smaller samples from R3, R4, and R5.

The hours for each recording day were chosen so as to obtain data for all hours within a day. Four periods within the 24 hr day were examined to observe diurnal trends. No clear-cut changes in level with time of day are shown in the data, but sudden large changes occur within a day, and from one period to another. Some examples of this, in the Eglin data, are shown in figures 3 through 7.

These figures show basic transmission loss as a function of time of day for all three receiving antenna heights at each frequency. Figure 3 shows successive values for each hour, from noon through midnight to the following noon, over the path from transmitter 1 to receiver 1, T1-R1. At VHF there is no evidence of a diurnal trend. The data for successive hours, and for the November and December periods of time, are consistent with each other. (There is no November data for h3, the lowest receiving antenna height). Data recorded at UHF over this same path show November values at h2 nearly 8 dB and at h3 about 15 dB below the December values. Such large changes from one period of time to another tend to obscure whatever diurnal changes there may be.

Table 6. Recording Periods in Each Test Area

Date	Time	No of hrs	Total hrs	Date	Time	No of hrs	Total hrs
Eglin AFB.							
	R1				R2		
11/19	1100-0100	15		11/22	1000-0100	16	
20	0900-2300	15		23	1000-2300	13	
21	0700-2100	14		24	0800-2100	11	
12/10	1200-0300	15		12/7	1400-0500	16	
11	1400-0500	15	74	8	1400-0300	13	69
	R3				R4		
11/28	0800-2100	12		12/1	1000-0100	15	
29	1000-0100	16		3	0900-2300	15	
30	0900-2300	15		4	0700-1800	12	
12/12	1200-0300	16		14	1200-0300	15	
13	1400-0500	15	74	15	1400-0500	16	73
Graham Mountain Area.							
	R1				R2		
9/20	0600-1400	9		9/28	0800-2100	14	
26	1400-2100	8		10/1	1000-2400	14	
27	0900-2400	16		9	1300-0300	14	
10/11	1400-0300	14		10	1500-0600	16	
12	1500-0600	16	63				58
4/8	1700-0700	15		4/10	1800-0700	14	
9	1700-0600	14		11	1700-0600	14	
18	1000-2300	14		22	1000-2300	13	
19	0900-2200	14	57	23	0900-2200	13	54
	R3				R4		
10/2	1100-2400	13		10/5	1500-2400	10	
3	0700-2100	14	27	8	0700-2000	13	23
4/12	1700-0600	13		4/16	1800-0700	13	
15	1700-0600	14		17	1700-0600	14	
24	1000-2300	13		26	1000-2200	12	
25	0900-2200	14	54	27	1000-2300	12	51
	R5						
10/16	1000-2400	15					
17	0700-2100	15	30				

Table 6. Recording Periods in Each Test Area (Continued)

Date	Time	No of hrs	Total hrs	Date	Time	No of hrs	Total hrs
Hunter-Liggett Area.							
	R1				R2		
1/15	1100-0100	13		1/22	1500-0100	11	
21	1000-2300	14		23	1300-2300	11	
30	1200-0300	16		2/4	1500-0700	17	
31	1500-0500	15		5	1200-0500	17	
2/1	1400-0700	18	76	6	0900-0400	19	75
5/17	1700-0400	11		5/21	1700-0600	12	
20	1600-0500	8		22	1800-0500	12	
30	1100-2200	8		6/5	1000-2200	13	
31	1000-2000	11		6	1000-2200	13	
6/3	1000-2200	9		7	0900-2100	13	
4	1000-2100	12	60				63
	R3				R4		
1/24	1400-0100	12		1/28	1100-0100	14	
25	1000-2300	14		29	1000-2300	14	
2/7	1500-0700	17		2/12	1100-0300	17	
8	1100-0500	19		13	1500-0500	13	
11	1300-0300	15	77	14	1600-0700	16	74
5/23	1800-0600	13		5/28	1800-0300	10	
24	1700-0500	13		29	1900-0400	7	
6/9	1000-2200	13		6/12	1000-2200	12	
10	1000-2200	13		13	0900-2200	14	
11	0900-2100	13	65	14	0900-2100	13	56

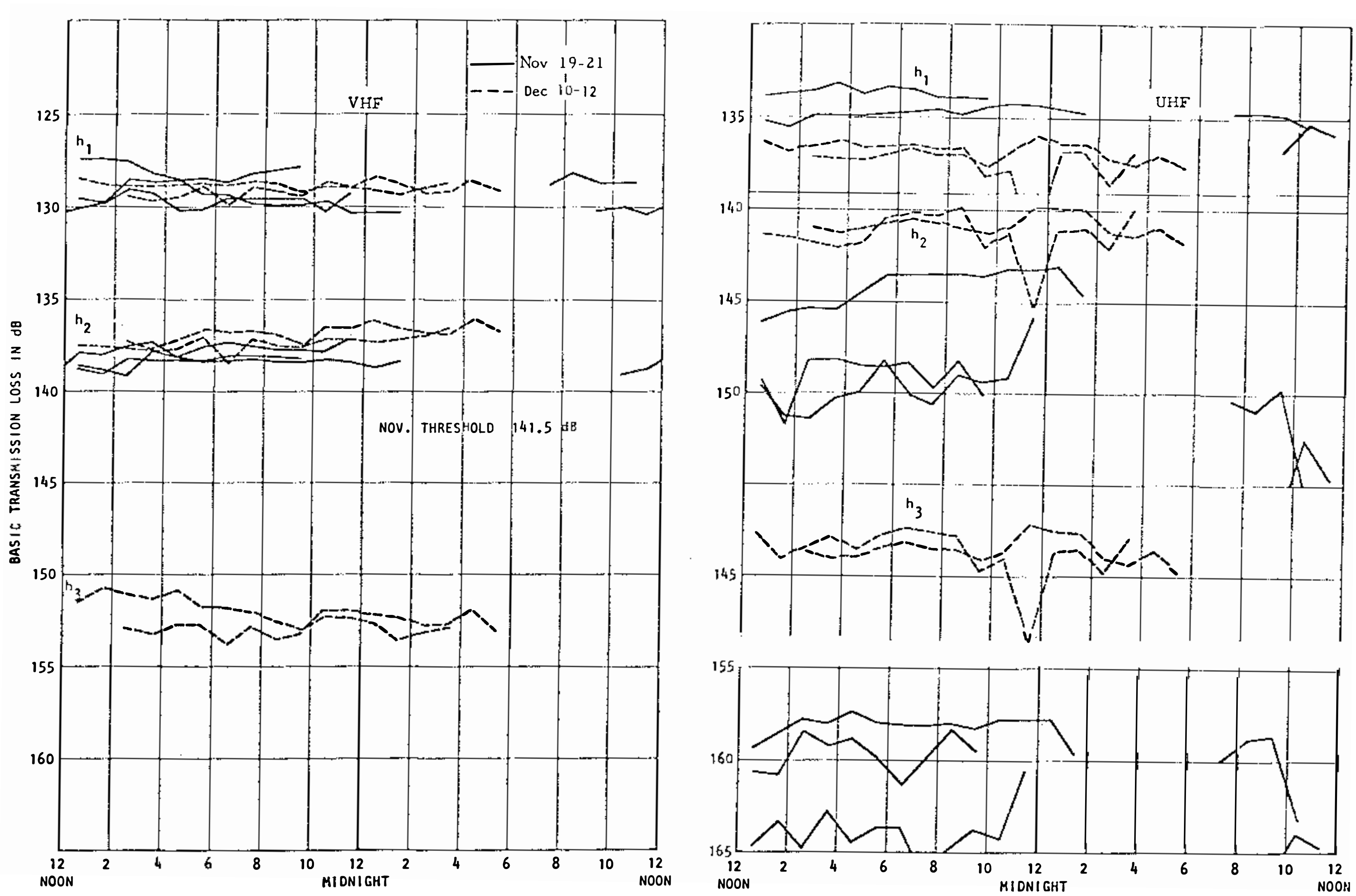

Figure 3. Values of basic transmission loss for successive hours of the day at all three receiving heights, T1-R1, Eglin AFB.

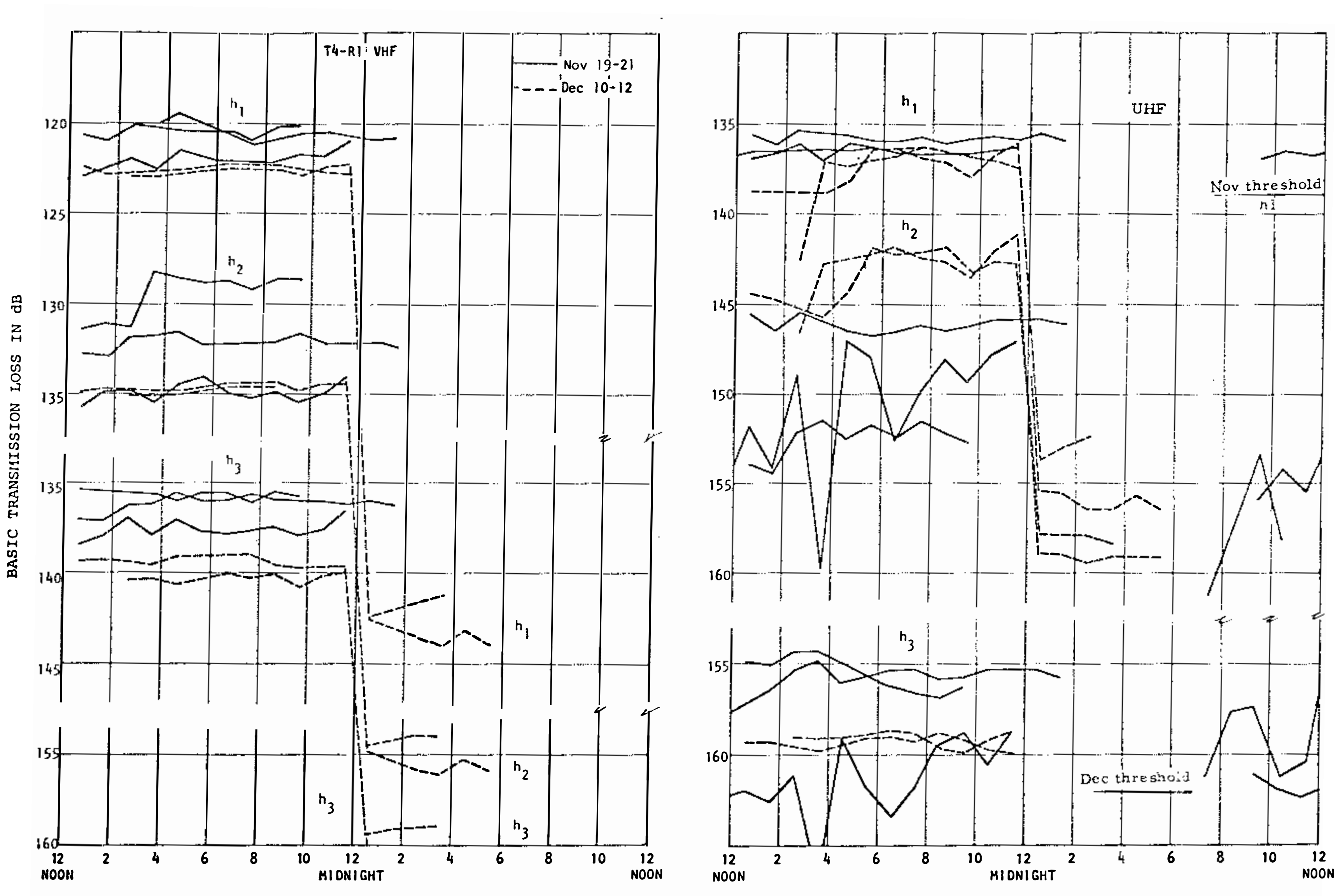

Figure 4. Values of basic transmission loss for successive hours of the day, T4-R1, Eglin AFB.

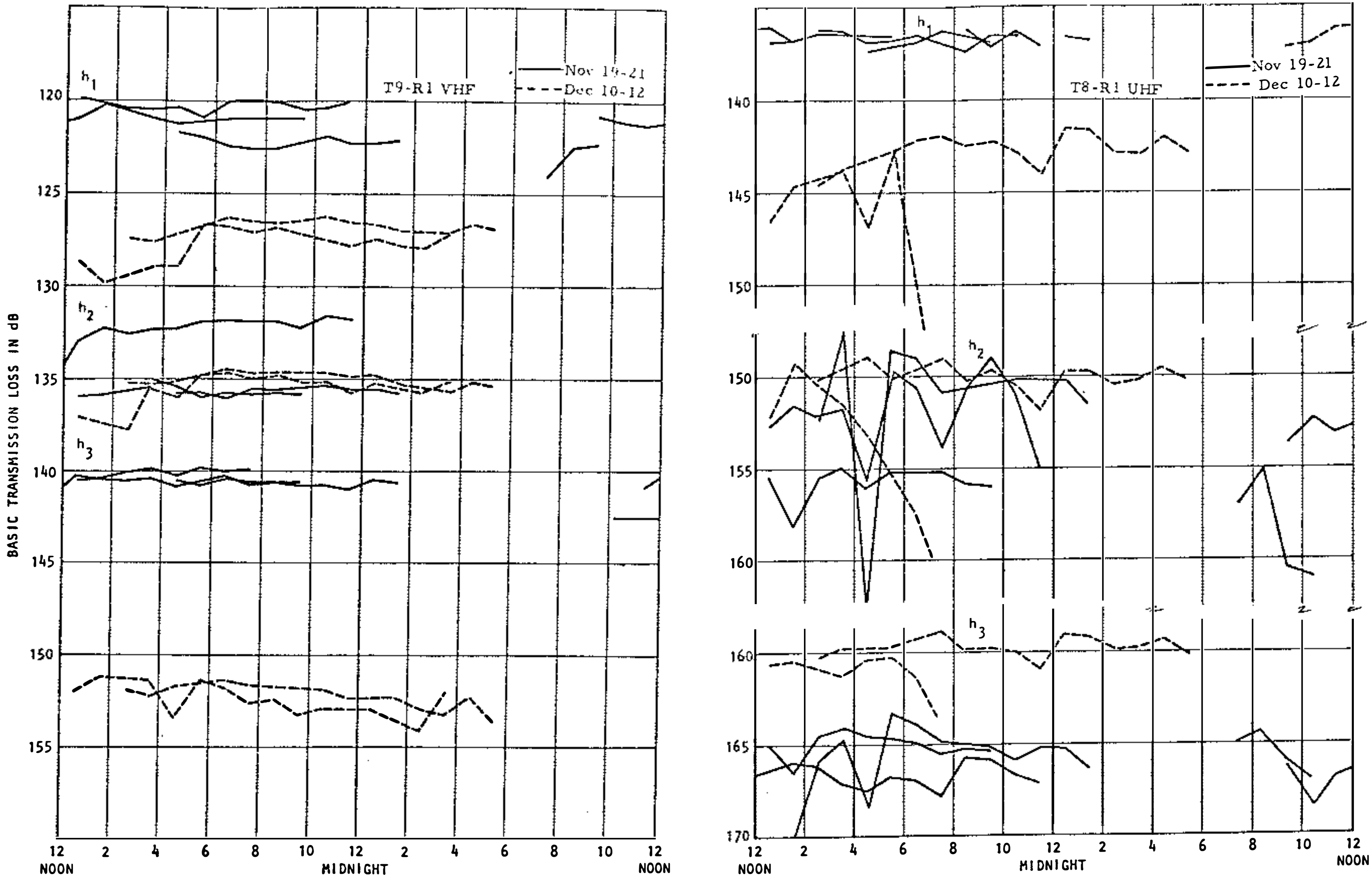

Figure 5. Values of basic transmission loss for successive hours of the day, T9-R1 VHF, and T8-R1 UHF, Eglin AFB.

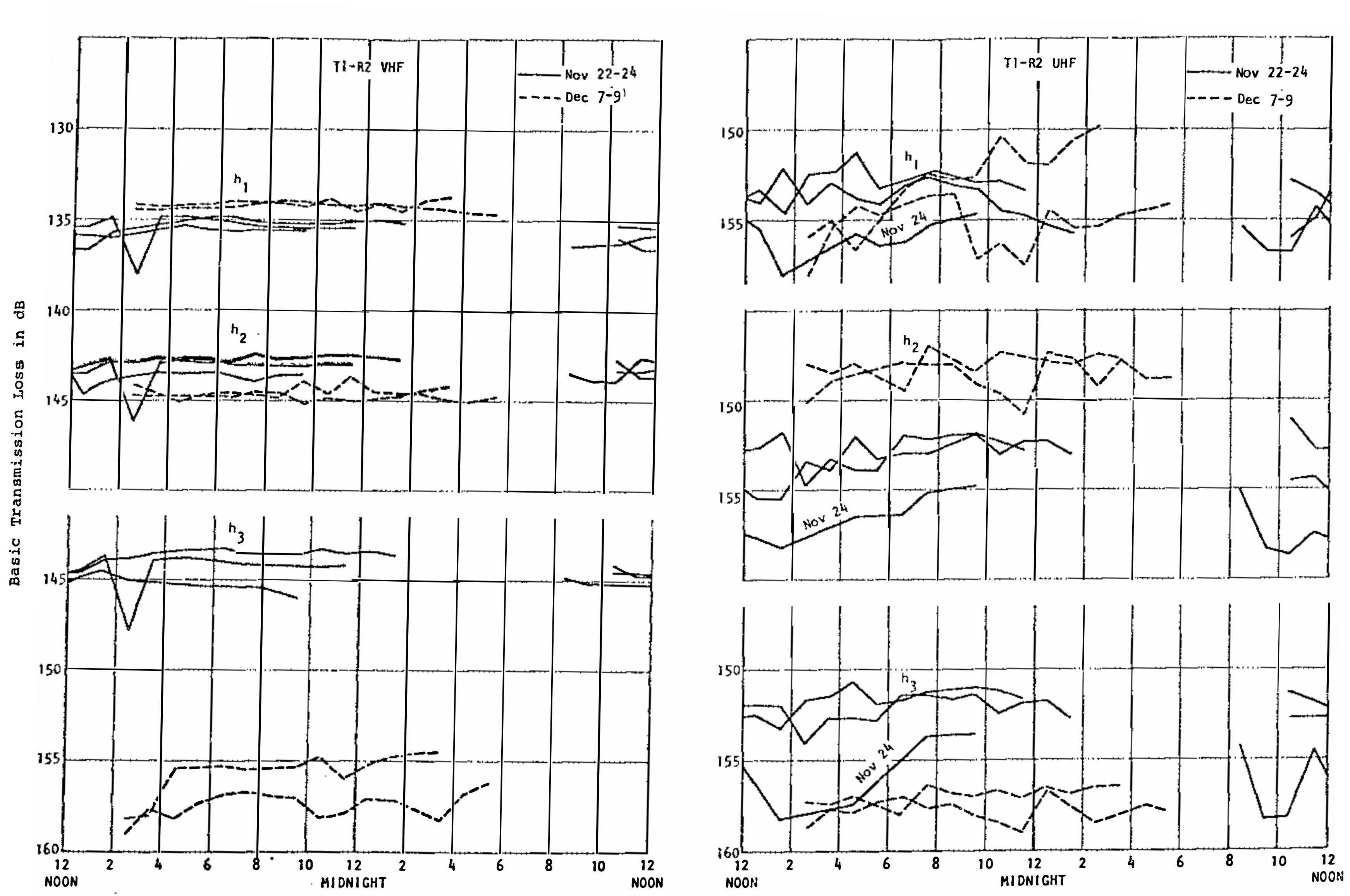

Figure 6. Values of basic transmission loss for successive hours, T1-R2, Eglin AFB.

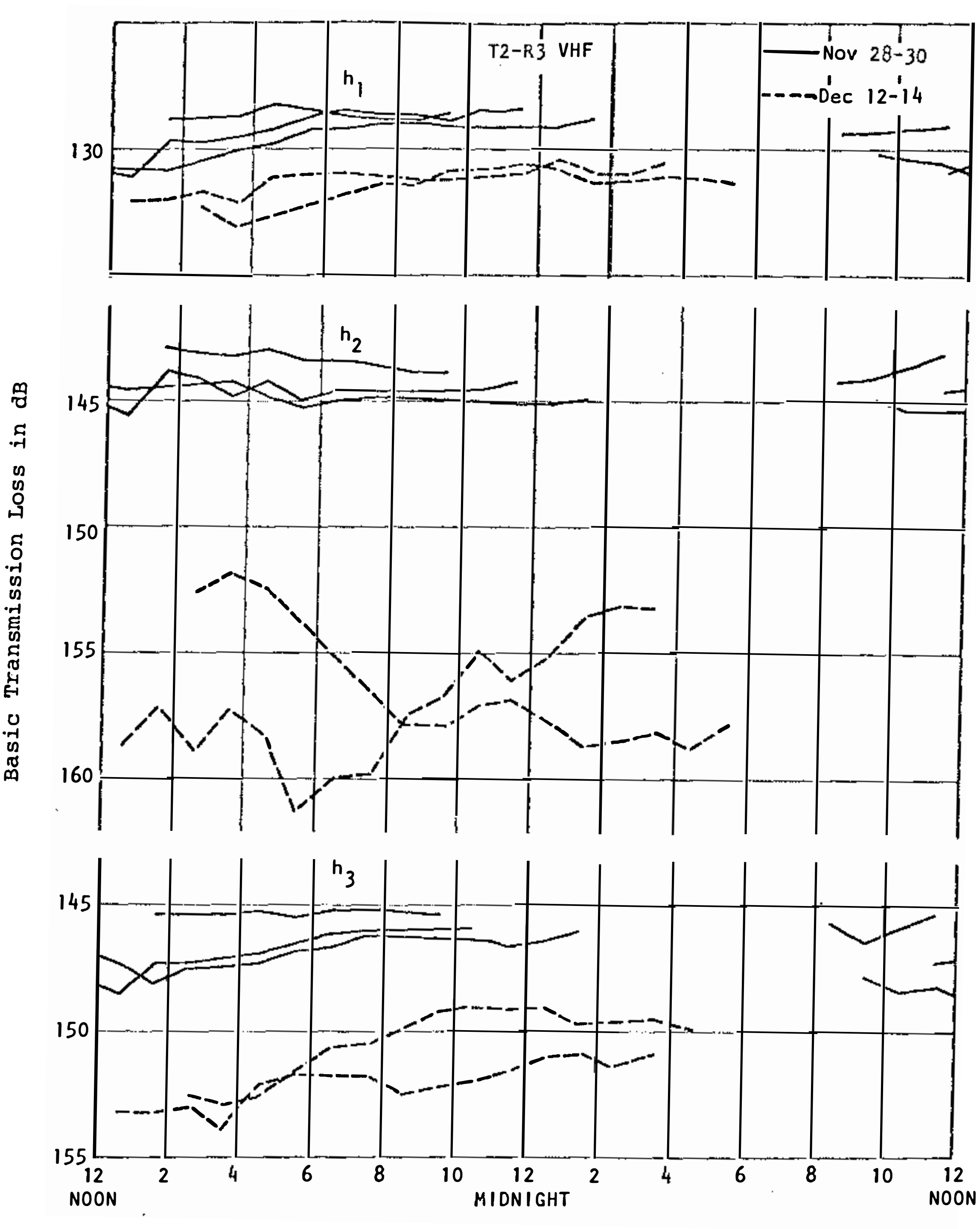

Figure 7. Values of basic transmission loss for successive hours, T2-R3, Eglin AFB.

The hour-to-hour data for path T4-R1, shown in figure 4, are fairly consistent at VHF but quite variable at UHF. The striking feature in this record is the sudden drop in all values at midnight on Dec 10 and 11. This sudden change of 20 dB within a period of an hour is not in keeping with the other data, and even though the records stay low for the next few hours this probably reflects some equipment failure, rather than a change in propagation conditions.

A similar change in level was observed on path T7-R1 at midnight, with a recovery to previous levels indicated at the end of the recording period, some 5 hours later. It is interesting to note in this connection, that in the UHF data for path T8-R1, as shown in figure 5, there is an earlier deep drop in signal level on one of these December nights but not on the other. In the same figure the VHF record for path T9-R1 shows quite consistent values for the December data, with no sudden changes in level, but on the lowest receiving antenna, h3, the signal is 20 dB lower than the level recorded in November.

The data shown in figures 3, 4, and 5, were obtained on Dec 10 and 11. To test whether or not this might be an unusual period of time, the data recorded on Dec 7 and 8 at R2 were also carefully examined. The VHF data for path T1-R2 plotted in figure 6 show the usual uniformity in level from one hour to the next. With the high and medium receiving antennas, h1 and h2, the November and December data are similar, but with h3 the December values are more than 10 dB below the November values. This change does not occur at UHF.

The data for path T2-R3 recorded on Dec 12 and 13 at R3, and plotted in figure 7, show a somewhat different relationship. The hour-to-hour changes at VHF show more loss in December than in November at all heights, but the greatest change is at h2.

Some day-to-day changes are shown in figures 8 and 9, which plot in sequence all recorded values over path T10-R1 at Eglin AFB. These plots show the close similarity between successive values that is usual at VHF, with somewhat greater changes at UHF. The VHF plots in figure 8 show fairly consistent and small differences between November and December values, the latter showing the greater loss. At UHF, as shown in figure 9, the changes from hour-to-hour and month-to-month are much greater. An interesting anomaly is shown in the record for Nov 21. The records for the two lower antennas show transmission loss values of 170 dB. These are 20 dB and 5 dB, respectively, below the levels for the previous day, and 30 dB below the VHF values for this same period of time. During this period no data were recorded from the highest antenna. The data summaries show the h1 value for this period as below threshold or > 139 dB rather than the extreme value of 170 dB listed for h2 and h3. The difference in sensitivity occurred because a high-gain preamplifier was used on the two lower antennas.

Because of these many irregularities in the data, whose source could not readily be determined, we decided to represent the accumulated data for each path in terms of a distribution of the individual values,

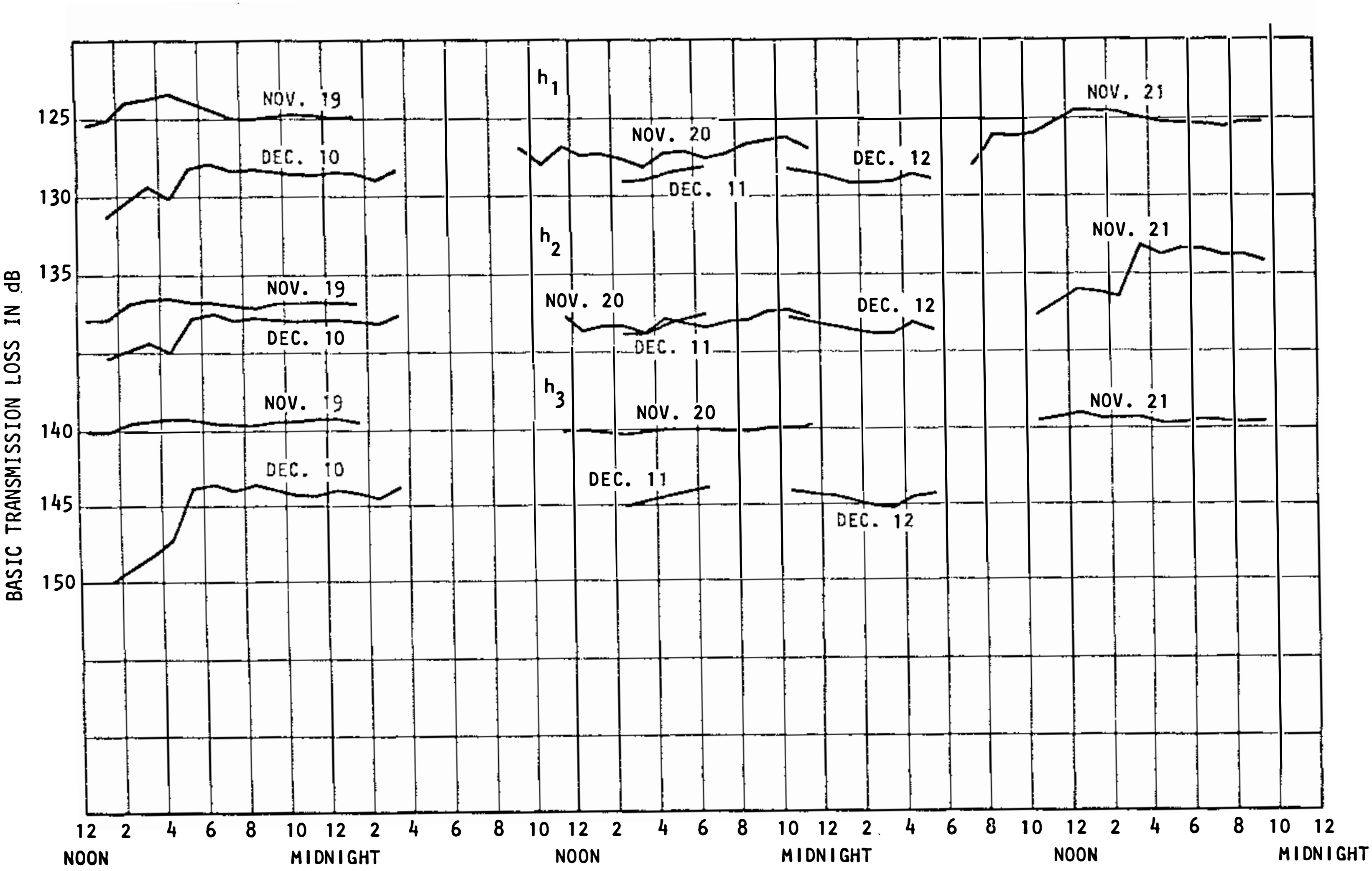

Figure 8. Successive recorded values at VHF, T10-R1, Eglin AFB.

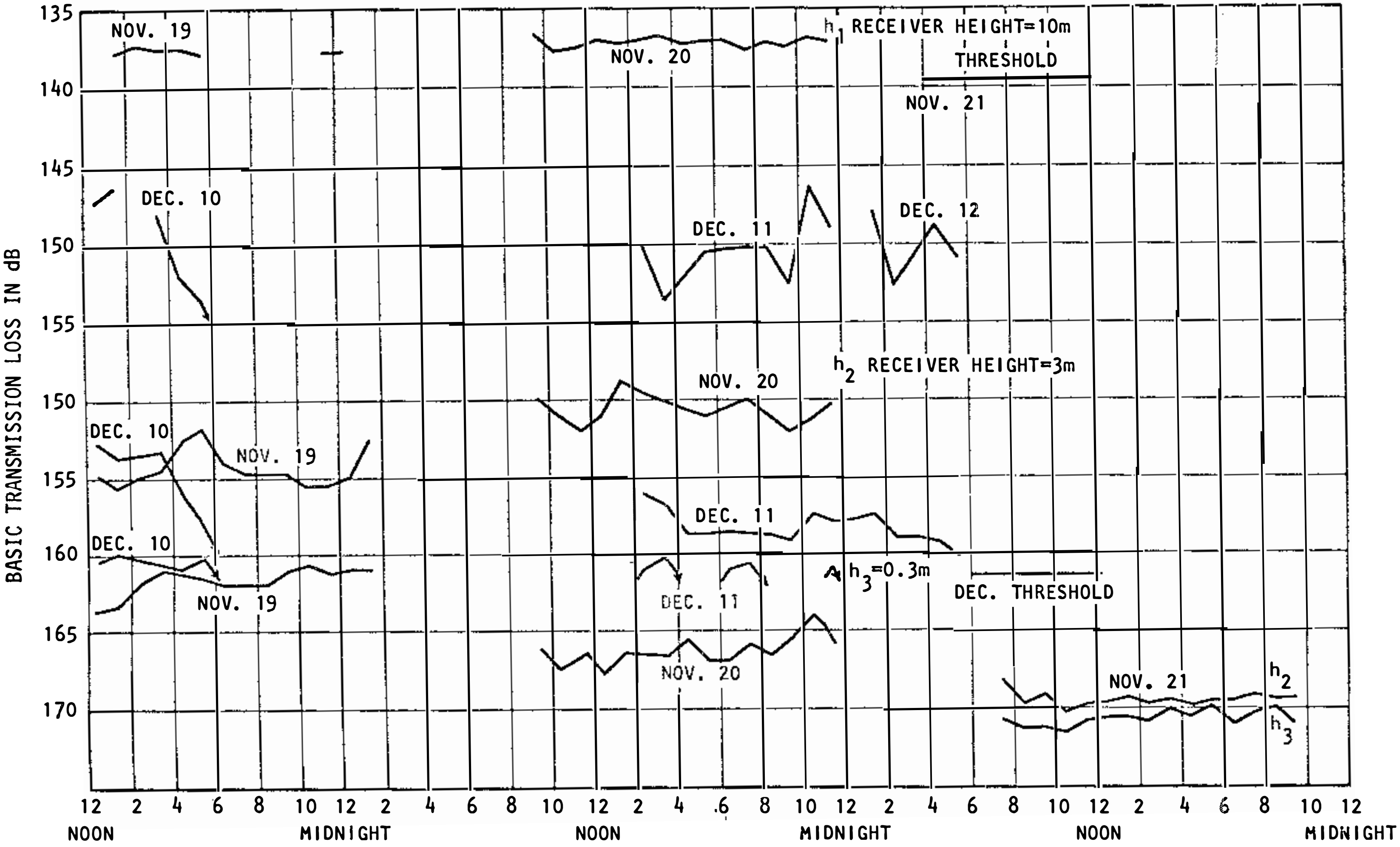

Figure 9. Successive recorded values at UHF, T10-R1, Eglin AFB.

rather than by a computed mean and variance. In this measurement program the sources of error that have been identified almost always result in additional loss. Such errors as failure in peak tuning, failure of the transmitter to turn on and switching errors give values that indicate excessive loss. The only known exception is the occasional failure to switch from receiving antenna 2 to antenna 3, but such known occurrences are rare. For these reasons we feel that the lower values of transmission loss, corresponding to higher received power, are probably a truer representation of propagation conditions than are the larger losses.

The data from all test sites are presented as distributions of basic transmission loss. These distributions are plotted in a series of figures in Appendix B of this report. The 10, 50, and 90% values of these distributions are tabulated and included in the detailed description of each measurement area.

5. THE EGLIN AREA

At Eglin AFB, Florida, the terrain is low and flat, with an average elevation of 50 to 60 m above sea level. Occasional small hills rise to 70 m and a few shallow stream beds cut through the area. The soil is sandy and granular, and its surface dries quickly even after a heavy rainfall. But when the surface is dry the soil about an inch beneath it remains moist. Maps indicate that, except for specially cleared portions, the entire area is heavily forested. Dense stands of pine trees rise to a height of 10 m or more, and some oak trees and scrub brush are present.

5.1. Description of the Test Site

The test site is located at and near Piccolo Field, a small and presently unused airstrip. The 10 transmitters were placed near runways of the field and along a nearby roadway, as shown in figure 10. The four receiver sites were selected near roads with sites R1 and R2 to the southeast, R3 to the northeast, and R4 to the northwest of the group of transmitters. Piccolo Field and areas along major roads have been cleared of trees, but otherwise the entire area is forested. In the cleared areas tall weeds, coarse grass, and small bushes are common.

Terrain profiles for the 40 measurement paths in this area were plotted from information read from topographic maps, and are included in the appendix to this report. The main features of note on the profiles are the stream valleys which are rather broad and shallow. The profiles from all transmitter sites to R1 and R2 cross Turkey Creek, and some cross several smaller streams as well. Except for the stream valleys the terrain for these 20 paths is quite flat, with the average elevation of the transmitters slightly higher than that of the receiver sites. R3, on the other hand, is situated on a small hill about 70 m above sea level, and is 12 to 15 m above all transmitter sites. The terrain just northwest of the transmitters rises slightly, forming an obstacle in several of the paths to R4.

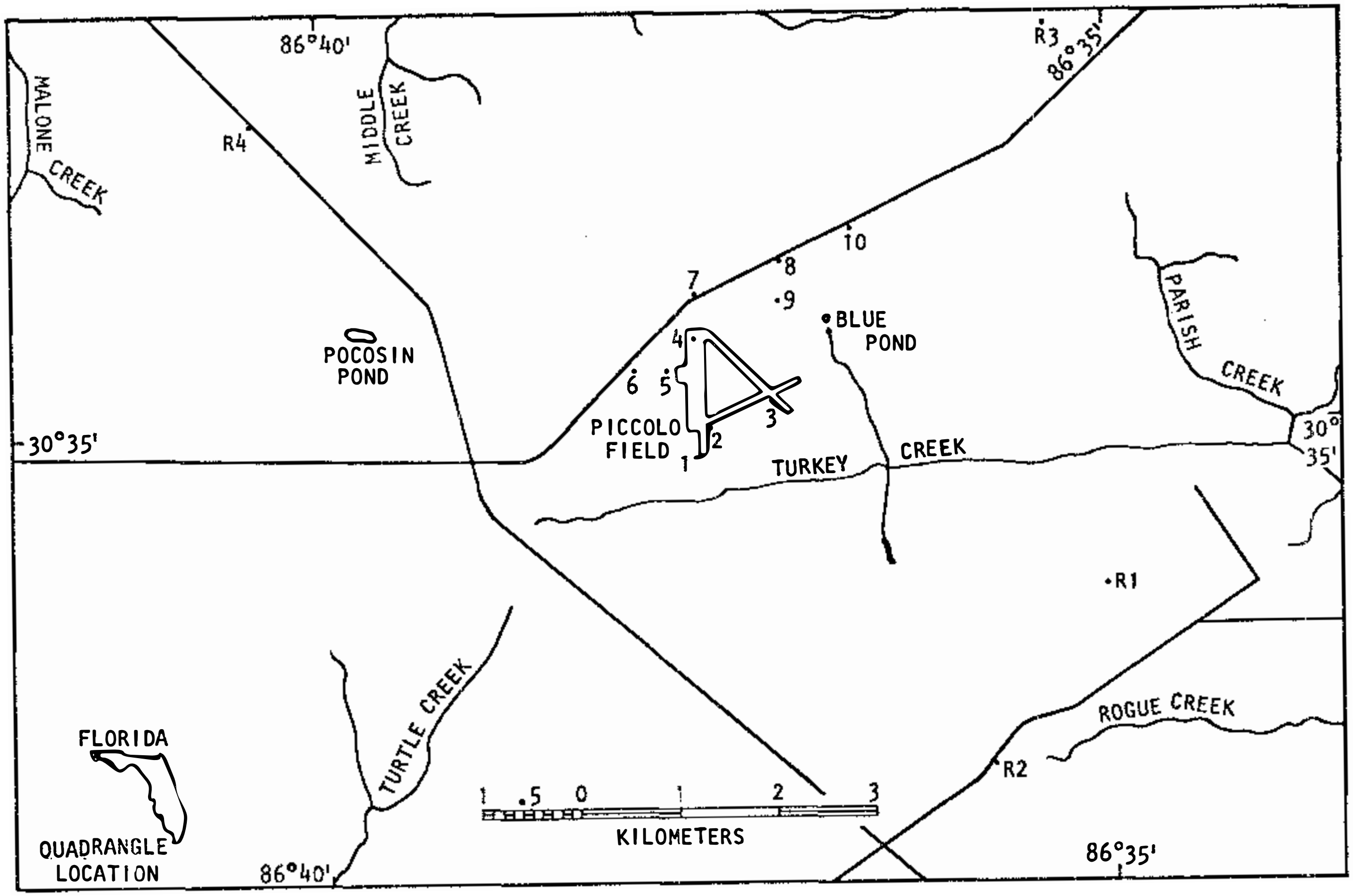

Figure 10. The test area at Eglin AFB, Florida.

If it were not for the presence of trees the terminals for more than half of these paths would be within radio line of sight, even at the 3 m receiving antenna height. Because trees, especially evergreens, are known to cause considerable signal attenuation at VHF and UHF, we estimated the height and density of thick stands of trees and their distance from the antennas. Earlier work has indicated that thick stands of trees may be considered as opaque to radio rays and treated in the same way as a hill or ridge slightly lower than the trees.

Photographs taken at each terminal, and comments on field records were used to estimate the height and location of the trees. While the distribution of heavily forested areas along each path is not specifically known, we may infer that in most instances the intervening terrain is covered with stands of trees of varying height and density. In any event, obstacles nearest the antennas will have more effect on radio propagation along a path than those farther away.

Considering first the receiver sites, we find that R1 is located in a slash area of plowed sandy soil. The ground is flat in the direction of the transmitters and dips downward slightly for about 500 m to a stand of pine and oak trees that range from 2 to 10 m in height. The terrain profiles from R1 to all 10 transmitters show that the 10 and 3 m receiving antennas would be within radio line of sight if there were no intervening trees.

The second receiver location R2 is in a small clearing beside a road. Looking toward the transmitters, the ground is flat for about 20 m across the road to a heavy growth of pine and oak trees that are 3 to 10 m tall. From the terrain profiles we see that, except for intervening trees, the 10 m antenna at R2 would be within radio line of sight for all 10 transmitting antennas, but most of the paths from the two lower antennas would be interrupted by a slight rise in ground elevation about mid-path.

R3, to the northeast, is located in a cultivated area of sandy soil that is covered with rows and clumps of grass. In the direction of the transmitters the ground is flat and clear for 150 m to a pine grove with trees 5 to 10 m tall. The R3 site is on a hill well above terrain toward the transmitters. Except for intervening trees all 10 transmitters would be within radio line of sight at all 3 receiving antenna heights.

Site R4 to the northwest of the transmitters is on sandy soil in a small clearing beside a road. Across the road toward the transmitters the area is clear for about 15 m to a growth of scrub bushes interspersed with medium-sized pine trees. The sky is visible between the trees in several places. Although this site is about 10 m higher than most of the transmitters, several paths are interrupted by terrain near mid-path even with the 10 m receiving antenna. At the lower antenna heights, trees and shrubs near the receiver site will cause additional attenuation.

In considering the various transmitter sites, we note that T1 through T5 are located near the runways of Piccolo Field in a flat open area where the sandy soil is covered with grass. Transmitters T6 through T10 are in small cleared areas along a road. These areas are covered with taller grasses, weeds, and bushes. Since the presence of trees near the transmitters will cause additional signal attenuation, a brief description is given of the conditions at each transmitter in the direction of each receiving site.

From T1	toward	R1 & R2	320 m to 3 to 4 m pines, then a small valley
		R3	250 m to 3 to 5 m pines
		R4	25 m to a dense growth 5 m pines
T2		R1 & R2	at the edge of a dense growth 6 m pines
		R3	35 m to dense growth pines
		R4	165 m to dense growth pines
T3		R1	125 m to dense heavy pines, sparse trees closer
		R2	at the edge of dense pine growth
		R3	45 m to dense growth 6 m pines
		R4	225 m to dense growth 6 m pines
T4		R1	100 m to dense growth 6 m pines
		R2	260 m to dense growth 6 m pines
		R3	15 m to dense growth 5 to 8 m pines
		R4	5 m to dense growth 5 to 8 m pines
T5		R1 & R2	175 m to dense growth pines, with a few closer trees
		R3	200 m to dense growth 5 to 8 m pines
		R4	35 m to dense growth 5 to 8 m pines
T6		R1	75 m to tall pines
		R2	20 m to dense pine grove
		R3	flat area, heavy brush and small trees
		R4	45 m to 6 to 8 m pines
T7		R1	200 m to dense growth 6 m pines
		R2	20 m to dense growth 6 m pines
		R3 & R4	flat area, heavy brush and woods
T8		R1	20 m to a dense pine grove with 5 to 10 m trees
		R2	500 m to a row of oak and pine trees
		R3	15 m to sparse woods and low shrubs
		R4	100 m to sparse woods and low shrubs

From T9 toward	R1 & R2	50 m to scattered trees
	R3	30 m to dense pines 10 m high
	R4	350 m to dense pines 10 m high
T10	R1	350 m to a grove of oak and pine
	R2	500 m to a pine grove
	R3	70 m to dense pines 8 to 10 m high
	R4	30 m to dense pines 6 m high

The field tests included two sets of measurements of the electrical ground constants of the soil at each receiver site. The values of ground conductivity, calculated from these measurements, ranged from nearly zero to about 30 mS/m with the highest values at R1. The relative permittivity ranged from 4 to 11 with an average value of 5. These small values of the electrical constants are typical of so-called "poor ground." An earlier report has described some of the effects of electrical ground constants on propagation. At frequencies above 170 MHz, the effects of changes in the ground constants are small when antennas are more than 5 m above the ground. With lower antennas, changes in relative permittivity or dielectric constant of the ground have much more effect than changes in conductivity. (For propagation over sea, changes in either conductivity or permittivity will affect propagation). When both antennas are less than 1 m above ground an increase in relative permittivity from 5 to 25 may reduce the average transmission loss about 10 dB.

5.2. Summary of Measured Path Loss

The recorded values of received power, converted to basic transmission loss, were grouped for each frequency and receiving antenna height for each of the 40 paths in the Eglin area. This yielded 240 groups with about 70 recorded values in each group. Distributions of basic transmission loss were obtained for each group and are shown in Appendix B of this report. These figures show for each path the cumulative distributions of basic transmission loss at VHF (172 Mhz) and UHF (410 MHz) for the three receiving antenna heights h1, h2, and h3, representing 10, 3, and 0.3 m, respectively. On these plots a normal distribution appears as a straight line. Some of the reasons for marked deviations from normal distributions have been discussed in section 3. For example, the distributions of data obtained over path T1-R1 and plotted in figure 11 show little variability at VHF for all three receiving antenna heights. At the higher frequency the distributions for the two lower antennas appear anything but normal. The data for these November and December records were considered separately and are shown on the right-hand side of the figure. These show that the distribution for each period is fairly normal, but there is much less loss in the December than in the November data. The cause of this differnece in level is not known, but it does not appear consistently for the data obatined from the other transmitters during this same period of time.
The data from T3-R1 show greater losses in December at VHF, but

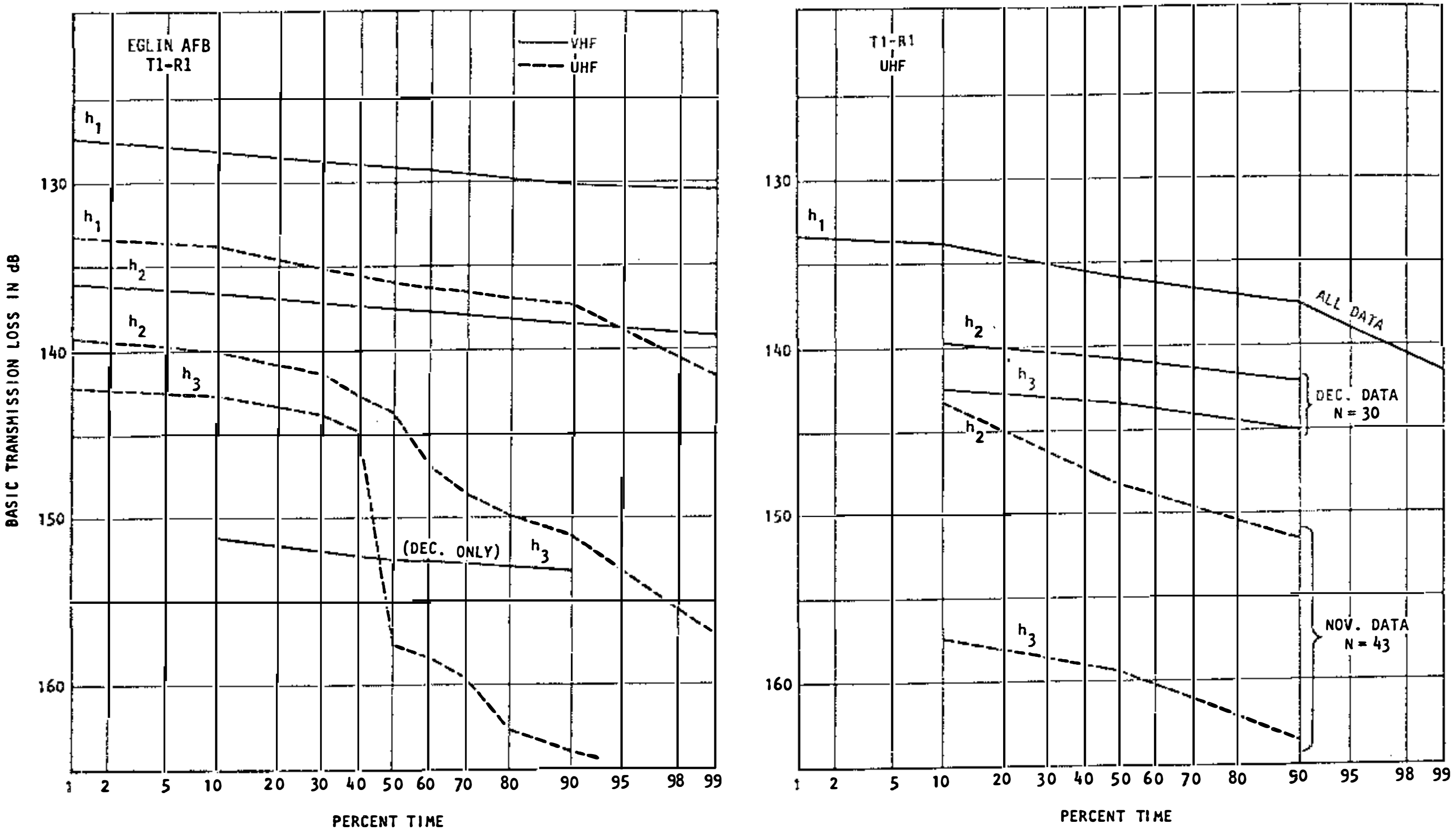

Figure 11. Cumulative distributions of basic transmission loss recorded over path T1-R1, Eglin AFB.

no consistent differences at UHF where the December loss is greater at h1 but less at h3. On path T4-R1 there is a sudden change of some 20 dB at both frequencies, while on T7-R1 such a change is observed only on the lower frequency. No such extreme changes in level are observed in the data from the other receiver sites.

Fortunately, the extreme changes rarely occur at or near the median level, but they must be considered in estimating the long-term variability of the signal. The 10, 50, and 90% values of basic transmission loss from these distributions are listed in table 7. In keeping with the earlier discussion we give greater credence to the 10 and 50% values than to those at 90%. Some of the latter are below threshold while others are much below the median value. Disregarding such questionable values, we find that the long-term variability for these short paths is usually only 2 to 3 dB from the 10% to the 50% level, with slightly larger differences between the medians and the 90% values.

Median values of basic transmission loss for each of the 40 measurement paths are plotted as a function of path length in figures 12 to 14. Each median value is coded as to receiver site. Figure 12 shows the measured loss for each path at 172 MHz with receiving antenna heights of 10 and 3 m. The same information for 410 MHz is plotted in figure 13, while figure 14 shows the data obtained at both frequencies on the 0.3 m antenna. In all cases the antennas of the transmitting sensors are at 0.3 m. The dashed curves are drawn to represent the median losses for all 40 paths at each frequency and antenna height. The solid curves are area predictions which will be described in the next section.

As previously noted, receiver sites R1 and R3 are clear for some distance in the direction of the transmitters, while R2 is located in a small clearing with a heavy growth of trees in the direction of the transmitters. The data plotted on the figures clearly show the greatest losses at R2, with considerably less loss over paths of the same length at R1 and R3. The data at 172 MHz show more than the predicted loss with the two higher receiving antennas, but agree fairly well with predicted values at the lowest antenna height. The data at 410 MHz show more than the predicted loss at all receiver heights. This again suggests an effect of the numerous dense stands of trees which are expected to have more effect at UHF than at VHF.

In addition to variability in time, there is considerable path-to-path or location variability. At these frequencies, in rather smooth terrain, one would not expect much path-to-path variability. With the higher receiving antennas at both frequencies, the total range of values at any distance is 25 to 30 dB, with the central two-thirds of the values falling within a range of 14 to 15 dB. With the lowest antennas, figure 14, a somewhat smaller range of values is observed, with a total range of some 20 dB at any distance.

Table 7. Basic Transmission Loss, All Paths, Eglin AFB, 10, 50, and 90% Values

		VHF									UHF								
		10m			3m			0.3m			10m			3m			0.3m		
Path No.	Dist. km	10	50	90	10	50	90	10	50	90	10	50	90	10	50	90	10	50	90
T R 1 1	4.30	128.3	129.0	130.1	136.6	137.6	138.6	151.4	152.6	153.4	133.9	136.0	137.4	140.2	143.6	151.1*	142.7	157.7*	164.2*
2	4.32	124.2	126.3	128.3	133.4	134.8	135.8	139.4	140.0	144.4	136.6	137.3	140.7	146.6	149.7	152.0	149.2	150.2	153.1
3	3.88	135.6	138.8	153.1*	139.6	140.6	143.2	152.2	153.4	155.6	135.9	136.8	145.1*	141.7	143.6	162.6*	160.8	165.5	169.9*
4	4.82	120.1	122.2	142.0*	129.5	134.5	154.4*	135.8	138.0	159.4*	135.6	136.4	150.5*	142.2	147.0	158.8*	155.1	158.9	161.9*
5	4.99	128.5	130.2	132.2	136.8	138.8	139.8	140.9	141.3	150.3*	136.7	137.4	157.2*	144.9	146.3	154.4*	153.3	155.2	161.8*
6	5.39	130.7	134.5	136.7	139.4	145.5	148.1	140.5	151.1*	152.3*	135.1	135.9	157.0*	142.8	144.6	161.9*	151.3	159.2*	166.5*
7	5.09	123.7	125.2	145.9*	136.6	139.9	158.8*	141.1	142.1	161.8*	136.9	144.6*	147.8*	147.6	152.3	160.1*	161.1	162.6	165.0
8	4.65	127.6	132.4	134.6	140.1	146.7	148.6	151.9	157.9	160.4	136.2	137.2	145.2*	149.4	151.8	167.5*	159.7	165.0	167.5
9	4.40	120.2	122.3	127.6	132.1	135.4	135.9	140.1	140.7	153.2*	134.0	135.2	157.4*	140.6	146.2	-	152.3	155.0	158.9
10	4.45	124.6	127.2	129.2	134.1	137.8	138.8	139.4	140.2	144.9*	137.1	142.1*	153.6*	150.4	155.5	169.5*	160.3	165.5	170.8*
1 2	4.26	134.0	134.9	135.9	142.6	143.6	144.8	143.5	145.1	157.7*	151.7	154.0	156.3	147.7	151.9	156.2	151.5	156.3	158.4
2	4.45	132.8	134.9	136.1	135.6	137.3	138.5	142.9	143.2	144.6	148.1	149.4	151.5	156.6	158.3	160.5	159.4	162.0	162.8
3	4.32	130.5	134.0	135.6	143.2	145.5	147.1	149.0	155.4*	157.5	146.5	150.0	154.0	150.3	156.9	161.8	157.3	162.4	163.8
4	5.28	148.1	152.2	162.4*	145.0	145.5	163.0*	147.1	147.8	164.1*	156.5	157.7	158.9	159.8	161.6	162.5	162.6	163.1	164.2
5	5.28	146.6	149.5	162.4*	148.7	149.9	151.4	149.7	151.3	153.6	148.4	151.6	154.2	157.9	158.8	159.9	160.5	163.1	164.8
6	5.46	136.8	138.1	138.9	146.0	148.7	151.8	150.9	152.6	156.4	156.5	158.8	160.6	157.4	159.9	162.1	160.6	162.0	162.9
7	5.62	150.6	153.5	160.6*	148.3	150.0	162.7*	156.4	157.7	160.5*	150.2	152.3	-	158.2	161.7	-	161.4	163.0	-
8	5.56	133.8	137.8	138.5	146.2	147.0	148.1	153.0	157.5	160.4*	157.2	159.4	-	157.7	159.7	-	158.9	162.3	-
9	5.22	140.6	142.4	145.3	144.0	144.7	146.0	150.0	151.2	156.4	146.0	146.8	148.5	153.3	158.7	-	159.2	163.3	-
10	5.69	137.3	138.0	139.5	149.1	150.9	154.7	151.6	153.3	154.7	157.5	159.1	161.5	158.1	159.7	-	162.2	163.4	-

* Questionable value

Table 7. Basic Transmission Loss, All Paths, Eglin AFB, 10, 50, and 90% Values (Continued)

		VHF									UHF								
		10m			3m			0.3m			10m			3m			0.3m		
Path No.	Dist. km	10	50	90	10	50	90	10	50	90	10	50	90	10	50	90	10	50	90
T R																			
1 3	5.65	134.9	136.2	139.3	149.5	151.3	153.0	148.2	149.5	151.4	141.4	142.4	145.1	141.2	143.8	149.2	159.0	160.1	160.9
2	5.29	128.6	130.4	131.7	143.6	145.1	158.6*	145.6	147.9	152.7	141.1	142.2	144.1	139.2	142.1	144.8	156.1	157.9	159.6
3	4.70	122.1	123.1	124.0	129.0	130.2	132.1	137.5	139.0	140.6	138.6	142.5	145.9	148.1	151.6	158.8*	152.6	154.6	158.5
4	4.69	134.6	136.2	140.4	136.2	138.2	141.5	149.1	151.2	155.9	134.8	136.0	138.3	138.2	139.9	146.1	147.9	150.2	154.2
5	5.19	138.1	140.7	141.4	137.5	139.9	142.0	152.9	155.8	157.3	150.8	154.1	156.0	147.7	148.6	152.5	159.6	161.2	162.1
6	5.60	129.3	130.2	132.1	136.0	136.8	139.8	148.9	150.7	158.1*	135.5	136.7	140.0	141.0	146.2	150.9	150.7	153.7	157.1
7	4.51	127.4	129.7	130.6	135.2	136.7	140.0	152.9	154.6	157.2	146.1	147.6	153.9	150.8	152.7	154.7	154.2	158.3	159.4
8	3.60	124.0	125.3	128.0	129.9	130.9	134.2	139.4	140.4	141.7	132.8	134.1	136.7	137.7	140.1	144.1	142.7	148.1	152.0
9	3.87	128.1	129.4	131.4	131.3	135.4	138.9	145.1	146.5	150.5	143.1	146.2	149.1	144.9	150.9*	157.8*	158.2	159.7	161.3
10	2.79	128.4	130.0	132.7	133.1	134.9	140.7	147.9	149.9	156.6	136.4	140.0	143.5	138.4	142.7	144.8	140.8	144.5	152.1*
1 4	5.69	137.0	139.6	140.5	147.5	148.4	149.8	145.4	147.1	148.5	153.5	155.1	156.7	158.3	159.5	160.1	160.6	161.3	161.9
2	5.58	135.2	136.5	138.9	144.3	147.2	148.7	146.1	147.4	157.3*	142.7	145.4	150.7	153.1	155.2	157.3	156.7	158.5	160.9
3	5.95	137.1	138.3	141.3	142.6	144.2	145.8	146.8	151.5*	154.5*	148.1	149.9	151.9	152.8	155.4	158.5	160.2	160.9	161.7
4	5.00	124.7	126.5	129.6	132.5	136.1	137.8	137.9	144.5*	147.7*	149.6	154.0	155.9	151.0	156.3	158.0	160.2	160.5	161.4
5	4.89	128.9	131.6	132.7	136.6	138.6	147.5*	143.1	145.7	147.4	146.0	147.9	150.8	151.7	153.6	156.4	161.2	161.7	162.3
6	4.51	128.0	130.5	141.1*	133.8	140.8*	143.0*	135.6	137.2	138.7	144.8	148.6	152.9	147.8	151.0	156.3	154.9	159.4	161.8
7	4.80	136.1	138.3	143.0	138.7	142.5	144.5	145.8	148.1	153.8	132.3	134.6	138.1	143.5	146.8	152.2	149.7	153.7	156.7
8	5.54	121.8	123.3	126.0	139.8	143.3	146.8	136.6	137.7	138.9	143.9	146.9	151.7	152.3	154.8	158.9	151.8	156.7	161.4
9	5.62	126.8	128.5	130.7	133.2	134.4	136.8	138.4	144.2	149.0	139.3	141.4	144.6	141.6	144.4	153.2	150.8	157.6	160.1
10	6.21	139.6	142.1	146.0	146.8	152.4	156.1	145.8	152.0	157.9	149.2	151.7	155.3	157.0	158.7	160.6	159.3	160.5	161.8

* Questionable value

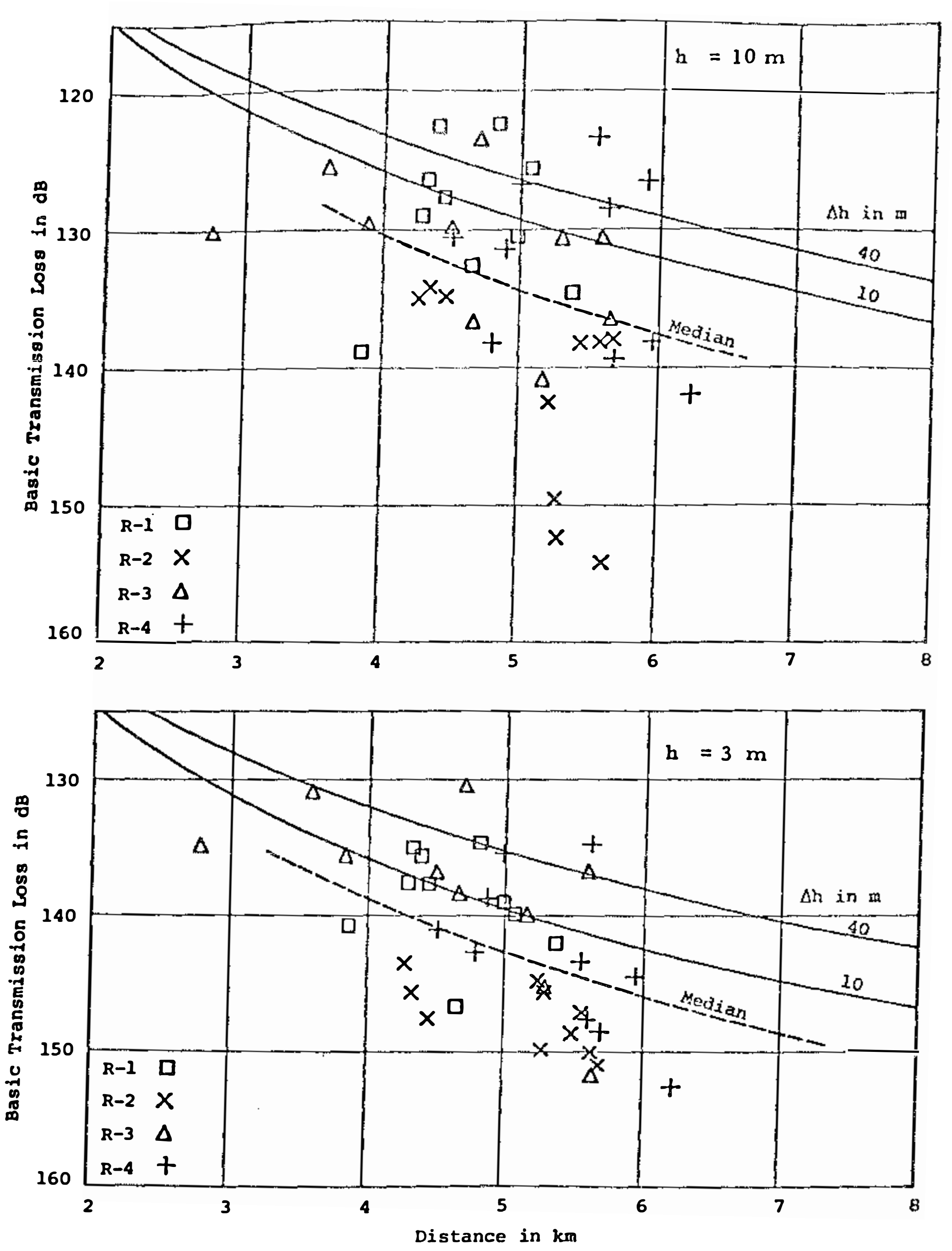

Figure 12. Median values of basic transmission loss at 172 MHz, with 10 and 3 m receiving antennas, Eglin AFB.

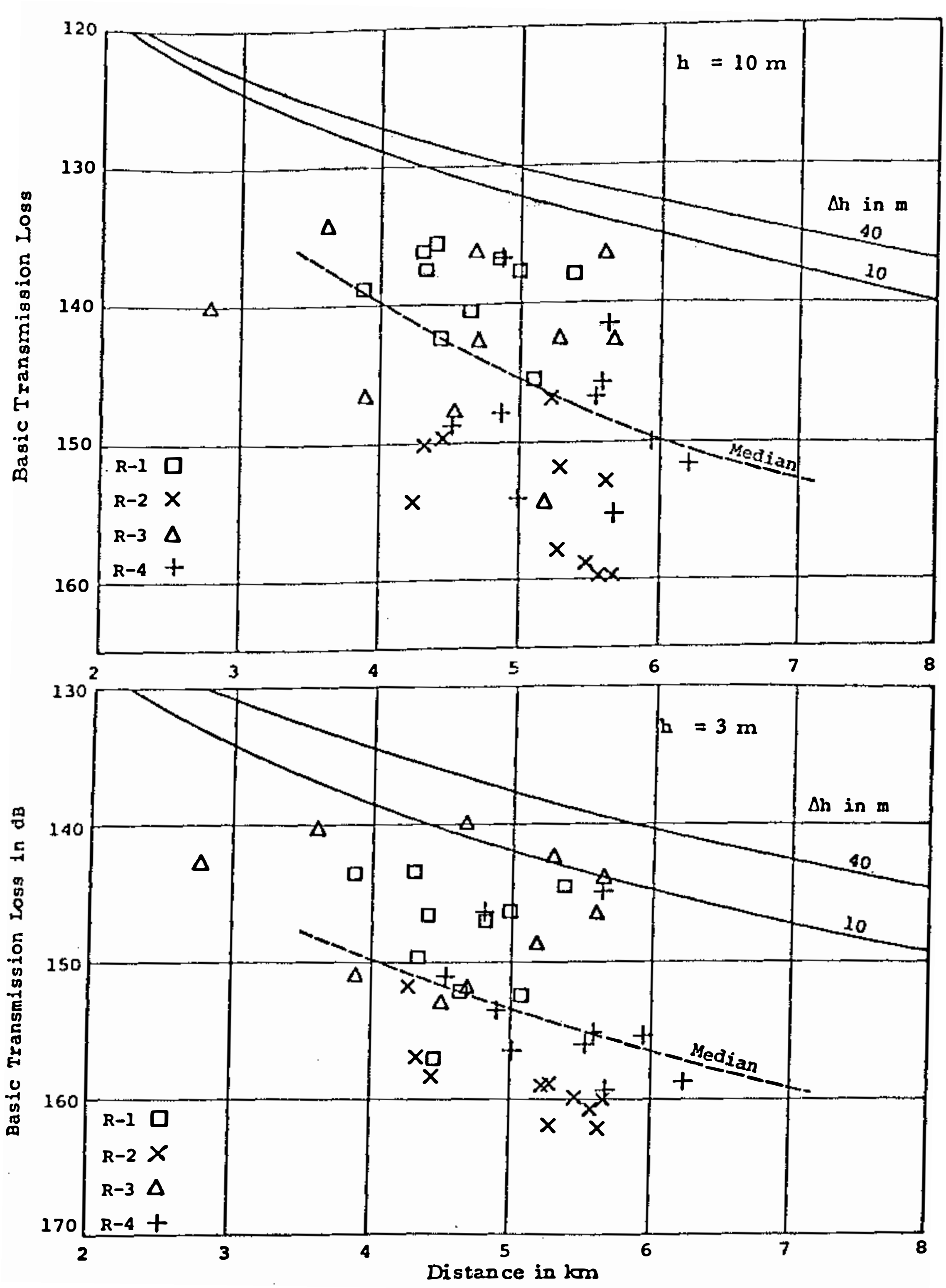

Figure 13. Median values of basic transmission loss at 410 MHz, with 10 and 3 m receiving antennas, Eglin AFB.

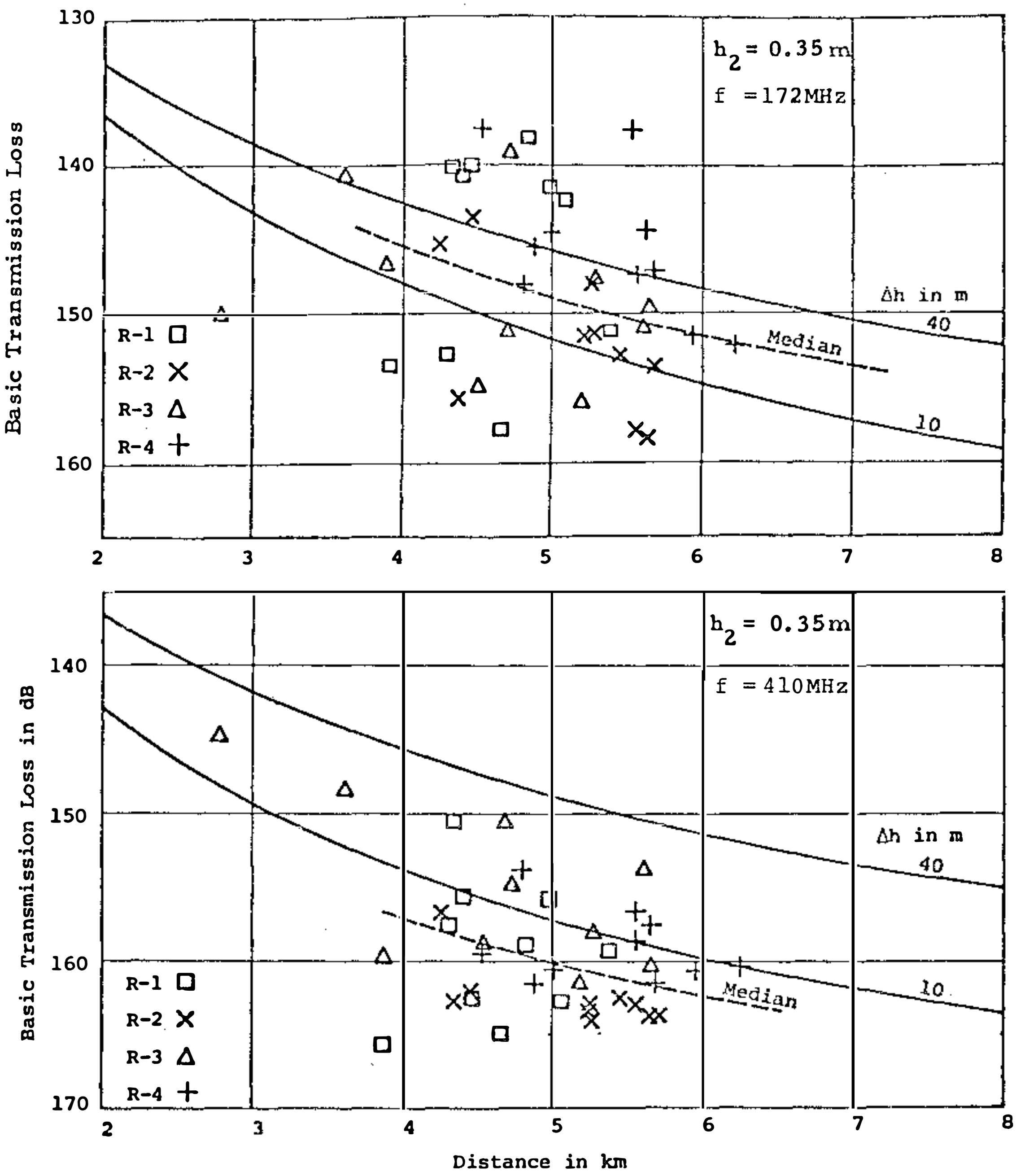

Figure 14. Median values of basic transmission loss at 172 and 410 MHz, with 0.35 m receiving antenna, Eglin AFB.

5.3. Comparison with Predicted Values

Several propagation models have been developed which may be applicable to predict basic transmission loss for comparison with the measurements obtained in this program. Of the many available models, we will consider mainly those that have been developed in the Institute for Telecommunication Sciences (ITS) and its precursors. These models have been reduced to a computer format and can readily be applied for such comparisons. A brief description of the models is given in the next section.

5.3.1. Propagation Models

A propagation model, developed for use with low antennas over irregular terrain, is described by Longley and Rice (1968). The model calculates long-term median transmission loss as a function of path length, and may be used either with detailed terrain profiles for actual paths or with parameters that are representative of median terrain characteristics in a given area.

To estimate terrain irregularity, the interdecile range, $\Delta h(d)$, of terrain above and below a straight line fitted to elevations above sea level is calculated at fixed distances. Median values of $\Delta h(d)$ increase with path distance to an asymptotic value, Δh, which characterizes the statistical aspects of terrain.

In the area prediction model the estimates of median path parameters in terms of Δh are based on an extensive study of terrain. For this model the required input parameters to calculate basic transmission loss as a function of distance are only the radio frequency, the antenna heights, an estimate of the terrain parameter, Δh, some information as to the choice of antenna sites, and estimates of the electrical ground constants. For paths overland, at frequencies above 100 MHz, the latter are important only for very low antennas, less than 3 m above ground. Previous comparisons of predicted with measured values for a large amount of data (Longley and Reasoner, 1970), show that the area model tends to overestimate the loss over paths with a single isolated obstacle, and for paths whose terminals are within radio line of sight. The model gives good results for transhorizon paths, including short diffraction paths, which are rather difficult to predict.

This model may also be used when detailed path profiles are available. In this application, path parameters are obtained from the profile, and the actual horizon elevations, distances, and calculated effective antenna heights are used in computing basic transmission loss. These values represent the expected long-term median, with an allowance for variation in time, and for prediction error. Certain limitations in application to specific paths are imposed in this model. The angle of elevation from each antenna to its horizon should not exceed 200 mr, and the distance to each horizon should not be less than one-tenth nor more than three times the corresponding smooth earth horizon. For paths with large elevation angles, calculated losses are larger than corresponding measured values, while with horizons very close to the antenna the reverse is usually the case.

For paths with known profiles a third propagation model may be used. This model, referred to as a point-to-point model, determines the path characteristics as to whether the terminals are within radio line of sight, whether there is a single obstacle isolated from terrain, and so on. When the type of path is known, applicable methods from Rice et al. (1967), as modified for computer use, calculate transmission loss over the path. While generally applicable in most situations, this model calculates too much loss for very short diffraction paths over smooth terrain.

None of the three models described above includes an explicit allowance for the effects of man-made and natural surface objects such as buildings and trees. It is usually assumed that a large building in a radio path is opaque to radio rays, and has the same effect as a hill or ridge, with the radio energy diffracted over and around it.

Much attention has been given to the effects of trees, particularly in jungle areas, both in terms of theory and measurements. Large measurement programs were carried out in tropical jungles by several investigators, notably by the Atlantic Research Corporation and by Stanford Research Institute, and are reported by Sturgill et al. (1966 and 1967), Hagn and Barker (1970), and Taylor et al. (1966).

The theoretical approach taken by Pounds and La Grone (1963), Tamir (1967), Sachs and Wyatt (1968), and others, represents forest vegetation as an imperfect dielectric slab. This so-called "slab model" represents the inhomogeneous, anisotropic real jungle by a homogeneous isotropic, lossy dielectric. As the frequency is increased above 100 MHz, the trees tend to act more and more as individual scatterers. One of the important features of this model is the lateral wave. Radio rays that leave the source near the critical angle of internal reflection, θ_c, excite a trapped or lateral wave just along the tree tops. The attenuation in the lateral wave increases as the square of the distance. The critical angle θ_c is defined in terms of the effective dielectric constant ε, as

$$\sin \theta_c = \varepsilon^{-\frac{1}{2}} .$$

An apparently reasonable range of values of conductivity and effective dielectric constant is from $\sigma = 10^{-5}$ S/m, $\varepsilon = 1.01$ for thin forests to much larger values of $\sigma = 10^{-3}$ S/m, $\varepsilon = 1.5$ for very dense forests. If we assume $\varepsilon = 1.012$ as for a rather open forest, we find the critical angle $\theta_c = 1.461$ r from the normal, or 110 mr from the horizontal, about 6° elevation.

Some of the early observations on the effects of trees are summarized by Rice (1971). He quotes some suggested values of attenuation rate, γ in dB/m, through deciduous trees in full leaf, assuming $\varepsilon = 1.012$ and $\sigma = 0.012$ mS/m. Values with vertical polarization at 172 and 410 MHz are about 0.1 and 0.2 dB/m, respectively. Through pine forests the rate of attenuation would be greater, especially when the trees are wet. These suggested rates of attenuation apply to situations where both antennas are in the woods.

In many situations we are not dealing with propagation in a tropical jungle or rain forest, but rather with the effects of trees or thickets of trees on an otherwise open radio path. Typical dense, and rather extensive woods are practically opaque at UHF and higher frequencies. When woods are near the receiving antenna the signal appears to be principally that diffracted over the trees. But with less dense woods the signal transmitted through may be greater than that diffracted over or around them. Head (1960) studied propagation at 500 MHz between a high and a lower antenna located a short distance behind a thick stand of trees. He considered the attenuation to be a function of clearing depth, which is the distance from the lower antenna to the edge of the woods. This empirical relation is defined as

$$A_c = 52 - 12 \log_{10} d_c \quad \text{dB},$$

where A_c is the attenuation below the smooth earth value and d_c is the clearing depth in meters.

Many investigators assume that when a thick belt of trees is between the terminals of a radio path, the energy transmitted through the trees is negligible compared with the diffracted field. The propagation loss is then calculated by assuming diffraction over an obstacle slightly lower than the trees.

5.3.2. Comparison with Area Predictions

The area prediction is based on an estimate of terrain irregularity as defined by the parameter Δh. Profiles of the 40 paths in the Eglin area were examined to obtain estimates of Δh. These values range from about 10 to 120 m with a median Δh = 40 m representing quite smooth terrain. The smoothest paths are those to receiver site R3, with a median value of 20 m, while the least smooth are those to R1 with a median value of about 100 m. These estimates of Δh are based on terrain only and do not include the heights of trees in the forests.

Predicted basic transmission loss as a function of distance assuming random antenna siting is shown with measured values in figures 12, 13, and 14. Curves for Δh = 10 and 40 m are drawn. For these short paths the curve for Δh = 100 m is practically identical with that at 40 m for f = 172 MHz. At the higher frequency the curve for Δh = 100 m shows about 3 dB more loss than that for Δh = 40 m with the 10 m antenna, but shows about 4 dB less with the lowest antenna.

The dashed lines on these figures show medians of measured values over these 40 paths. These medians show more loss than predicted in all cases. The deviation of predicted median values, with Δh = 40 m, from those observed with the 10, 3, and 0.3 m receiving heights is about 7, 7, and 3 dB at 172 MHz, and 15, 15, and 11 dB at 410 MHz. In the area prediction model, a location variability with σ = 8 and 10 dB for the two frequencies is included to allow for the expected path-to-path range in loss. Even with this additional loss allowed, the data show much more loss than predicted. This additional attenuation is caused not only by the presence of thick stands of pine trees, but also by their proximity to one or both path terminals.

5.3.3. Comparison with Point-to-Point Predictions

As previously noted, the area prediction may be used in a point-to-point mode where the parameters for each path are obtained from path profiles. These specific parameters are then used in calculating basic transmission loss for the path. If profiles based only on terrain information were used, many paths in the Eglin area would have terminals within line of sight. Since for these paths trees obstruct the direct line of sight, the calculated losses would be too small.

The trees were, therefore, considered as opaque to radio energy and computations of diffraction over them were made. For this purpose we estimated the distance from each terminal to a thick stand of trees, and a horizon elevation slightly lower than the tops of the trees. These estimates resulted in many horizon elevation angles that were beyond the limits of the model, with corresponding excessively high computed transmission loss values.

Since some energy can find its way between the trees, especially near their narrower tops, we decided to modify this approach. Instead of considering the trees as completely opaque and calculating only diffraction over them at steep angles, we allowed for possible transmission through the trees above the critical angle of internal reflection, which would allow for some transmission by means of the lateral wave discussed in subsection 5.3.1. Assuming an effective dielectric constant $\varepsilon = 1.012$ for the woods gives a critical elevation angle of 110 mr (about 6°), which was chosen as the maximum allowable elevation angle.* This substitution in the computation allows for what is probably a very real effect, and also brings the calculated elevation angles within the capability of the model.

Values of basic transmission loss calculated with this allowance for trees are compared with measured values. Distributions of the difference ΔL between each pair of values are shown in figure 15. Positive values of ΔL indicate more loss predicted than measured while negative values show the reverse situation. Cumulative distributions of ΔL for all 40 paths and all 3 receiving antenna heights at VHF show the median difference is zero, $\Delta L = 0$dB. However, a small percentage of paths show measured losses exceeding predicted values by 10 dB or more. At UHF the median difference shows about 3 dB more measured than predicted loss, and a small percentage of paths show some 15 dB more loss than predicted.

These negative values may result either from the fact that trees are very near the terminals, and the limit of the model with respect to horizon distance is exceeded and/or that no allowance has been made for absorption of the signal by trees. Because negative values of ΔL are more

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* Some estimates of conductivity and effective dielectric constant in evergreen forests are much larger than this with σ from 0.002 to 0.05 mS/m. If we assume $\sigma = 0.04$ mS/m then $\varepsilon = 1.04$ and the critical elevation angle would be nearly 200 mr.

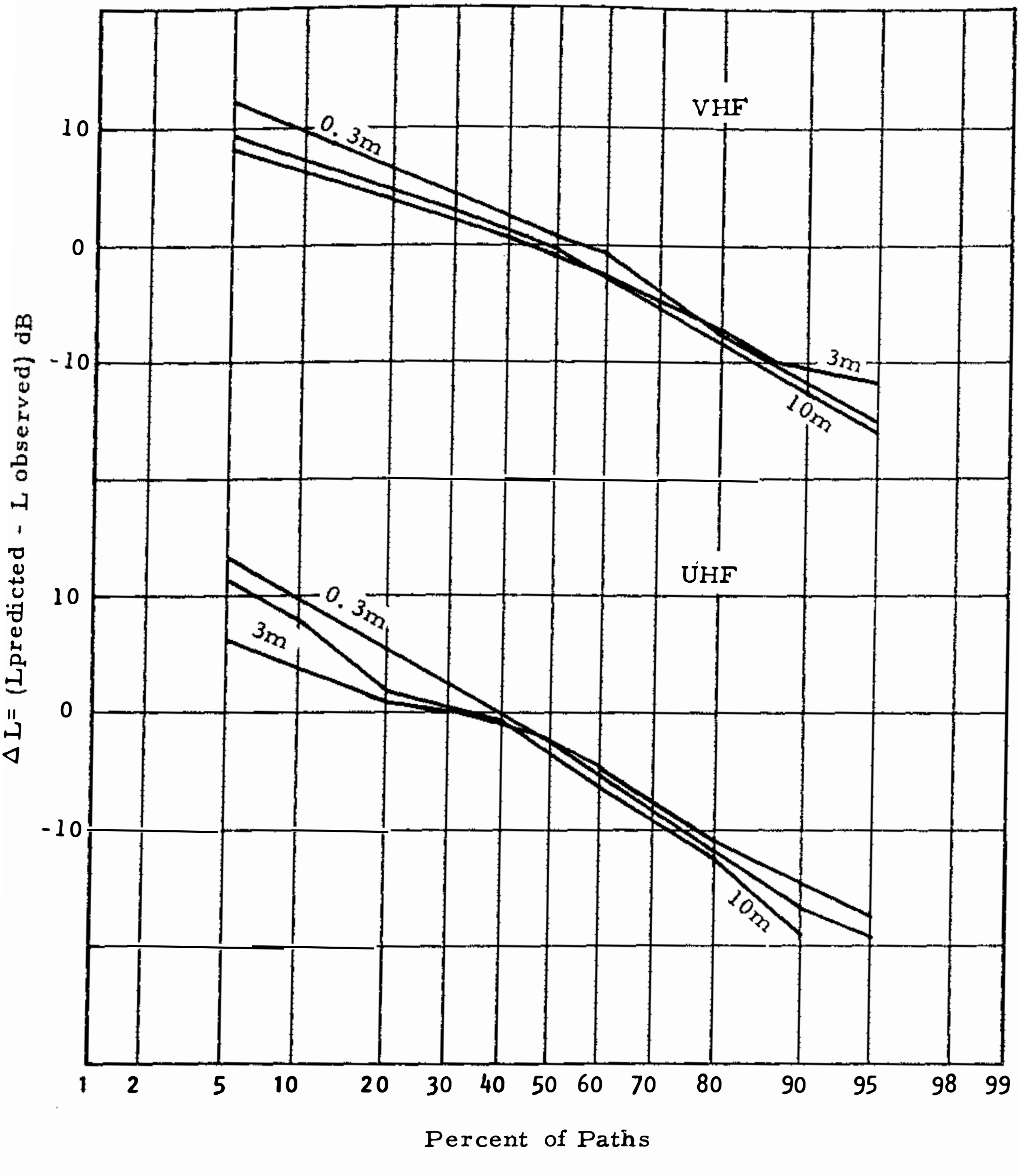

Figure 15. Cumulative distributions of ΔL = (L predicted - L measured) in dB, Eglin AFB.

common at 410 than at 172 MHz we can assume that failure to allow for absorption by the trees may be a factor. (The attenuation rates through woods at 410 and 172 MHz are 0.2 and 0.1 dB/m, respectively, for deciduous trees in full leaf). An allowance for absorption is difficult to estimate because we have no knowledge of the extent of pine woods along the transmission paths. If we assume rates of 0.2 and 0.1 dB/m then passing through 50 m of woods would cause attenuations of 10 and 5 dB. Since calculated elevation angles of more than 300 mr have been replaced by a maximum of 110 mr, this assumes passage through the woods for considerable distances. Thus the additional attenuation by woods could easily account for the greater measured losses.

Earlier work with very low antennas has indicated that an empirical correction may be used to allow for the additional transmission losses when horizon distances d_L are very small, i.e., less than one-third of the smooth earth distance d_{Ls}. This empirical correction $\Delta L_c = 10 \log_{10} (d_{Ls}/d_L)$ is added to the predicted loss. If we apply this correction to the paths in this study it could increase predicted losses by a maximum of 20 dB. This particular empirical correction was developed for use where the nearby obstacles were actual changes in terrain elevation. The correction does not appear to be applicable in this situation where the "obstacles" are heavy pine woods.

The point-to-point model, based on methods described by Rice et al. (1967) was used to predict transmission loss for these paths. The large elevation angles again are beyond the applicable range of the model. Even when a maximum value of 110 mr was imposed the model predicted less than the measured loss by 5 to 7 dB. The range of differences ΔL is very nearly the same as for the modified area model.

The empirical estimate of attenuation by trees in terms of clearing depth, reported by Head (1960), does not appear to be applicable to this particular situation. For one thing, no allowance is made for differences in antenna height. The data show that there are greater losses at the lower receiver heights even when the same woods form the obstacle for all heights.

For this area, then, the best agreement with data is obtained when we assume that the trees are practically opaque to radio energy, but that when the woods are close to the terminals some energy is transmitted through rather than over the tree tops.

6. THE GRAHAM MOUNTAIN AREA

An area in the Pinaleno Mountain range, south of Graham Mountain, Arizona, was selected for measurements in mountainous terrain. During the first measurement period in September and October much of the attempted recording was below receiver sensitivity, especially at 410 MHz, and with the lowest receiving antenna height at both frequencies. Measurements were made over the same paths during a two week period in April, after the equipment had been modified so that records were obtained most of the time for all paths.

We had planned the two measurement periods to cover the extremes of wet and dry seasons, to determine possible seasonal variations in this desert area. However, the weather failed to cooperate, and was warm and very dry during both measurement periods.

In the Graham Mountain area the terrain is quite irregular with values of the terrain parameter Δh ranging from 50 to 950 m. The median value for all paths at the test site is Δh = 180 m, which is representative of mountainous terrain, but not of extremely rugged mountains. The soil is dry and granular, with rather sparse vegetation, which includes coarse grasses, cactus and mesquite, with a few small trees in some places. Rocky hills and rock outcrops are a common feature of the area.

6.1. Description of the Test Site

The test site is located in the southeast part of Arizona, just south of Gillespie Mountain. Most of the measurements were made from the group of 10 transmitters which are located along a trail to the left of center in figure 16. The first four receiver sites, located to the northeast, northwest, east and southeast of the transmitters, are shown on the figure as R1, R2, R3, and R4.

Because difficulties were experienced in obtaining data at R3 and R4 the transmitters were moved to new locations along a trail through Oak Draw, shown in the southeast corner of figure 16, and measurements were recorded on Oct 16 and 17 at R5, which is near R1. These locations were not used during the April measurements.

Terrain profiles for the 50 measurement paths in this area were plotted from information regarding distance and terrain elevation read from a detailed topographic map of the area. These profiles are included in the appendix to this report.

The paths in this area represent a wide variety of conditions ranging from hilly to very rugged terrain. The 10 paths to each receiver site show wide differences within each group. Those to receiver site R2 show the least irregularity with a range of Δh values from 70 to 160 m, and a median Δh = 100m. The paths to R4 are over much more rugged terrain with a range of Δh from 180 to 950 m and a median value Δh = 600 m. Values of Δh for paths to R3 range from 100 to 420 m with a median value Δh = 330 m. The paths to R1 and R5 are over moderately rough terrain with a range of Δh from 50 to 250 m and a median value of 150 m.

Because of the wide range of terrain irregularity in the paths to each receiver site these measurements are grouped by terrain type rather than by receiver location. Also, because of the great differences in type of terrain, we would expect a wide range in path loss recorded over paths of the same length.

An examination of the path profiles shows that many paths pass over a single isolated hill, or more commonly over two hilltops, which are isolated from the rest of the terrain. Some 35 of the paths are of this type where small obstacles in the immediate foreground of the antenna will

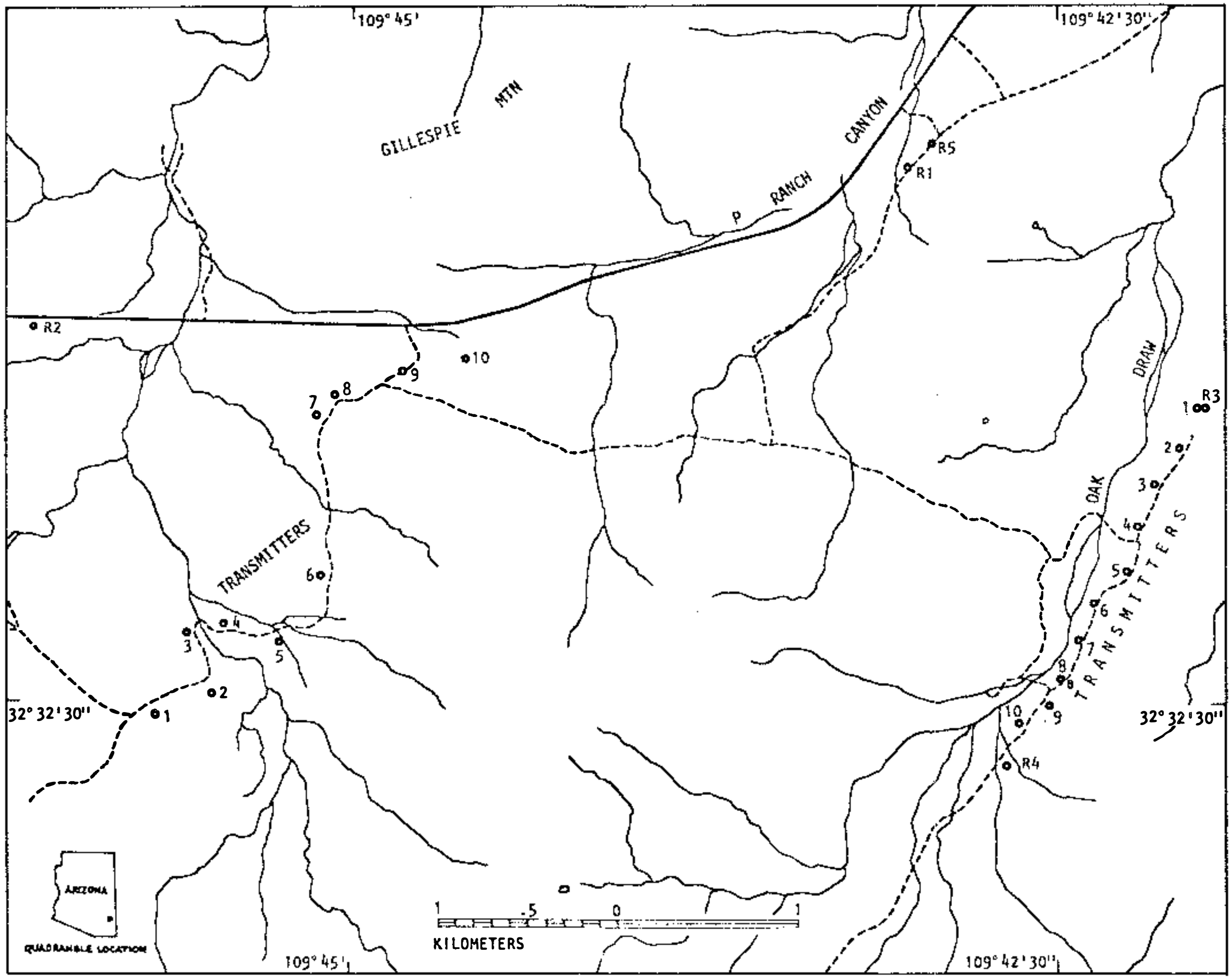

Figure 16. The test site, Graham Mountain Area, Arizona.

have little effect. For four of the paths to R2 the terminals are within radio line of sight. The remaining paths are two-horizon diffraction paths.

During the April tests, measurements were made of the electrical ground constants at three of the receiver sites. The soil at these sites was crushed granite rock with sparse vegetation. There was no measurable rain during the period and the humidity was about 15%. The data yielded highly variable results for ground conductivity, but the range for relative permittivity is from 4 to 15. Values of $\sigma = 10$ mS/m and $\varepsilon = 5$ were selected as representing the ground constants in this area.

6.2. Summary of Measured Path Loss

Recorded values of received power, converted to basic transmission loss, were grouped by frequency and receiving antenna height for each of the 50 paths in this mountainous area. Because we wished to observe any differences that might occur between the fall and spring values, they were handled separately. Cumulative distributions of basic transmission loss were obtained for each path, frequency, receiving antenna height, and period of time. These distributions are plotted in a series of figures in Appendix B of this report.

These figures illustrate some of the problems in determining the validity of the data that were previously discussed. For example, the data for path T1-R1 show a sudden drop of 20 dB at VHF on the 10 m receiving antenna, but no similar change on the other two antennas. The data for path T2-R1 show a drop of 10 dB at the 3 m height for the lower frequency and of more than 15 dB at the 0.3 m height for the higher frequency. Again for path T6-R2 there is a drop in signal of some 20 dB in the April data. For some paths there is practically no difference in level between the spring and fall values, while for other paths differences in level of 10 to 15 dB occur, with the spring loss being greater.

Because of these sudden changes in level the two periods were considered separately in calculating the cumulative distributions of all measured values. Tables 8 and 9 list the 10, 50, and 90% values of basic transmission loss from these distributions. In keeping with the earlier discussion of validity, we place greater confidence in the 10 and 50% values than in those at 90%. Table 8 lists the values from data obtained in September and October. These are from distributions of 63 and 58 measured means at R1 and R2, but from only about 25 to 30 measurements at the other receiver sites. The table clearly shows that most of the attempted measurements were below receiver threshold at R3 and R4.

Table 9 lists values from distributions of more than 50 measured means at each of the first four receiver sites in April. In the meantime, the equipment had been modified so that most of the attempted measurements were well above threshold. In general, these values show rather small variations in level of the data during each measurement period and differences of 2 to 5 dB from one period to the other. The few wide differences probably do not represent real changes in propagation conditions.

Table 8. Basic Transmission Loss, 10, 50, and 90% Values, All Paths, Graham Mountain Area, Sept., Oct. 73

Path No.		Dist. km	VHF									UHF								
			10m			3m			0.3m			10m			3m			0.3m		
T	R		10	50	90	10	50	90	10	50	90	10	50	90	10	50	90	10	50	90
1	1	5.10	124.8	127.1	129.9	125.8	128.1	130.5	137.7	139.9	141.8	132.8	135.4	139.6	130.0	131.8	134.6	136.5	139.9	143.7
2		4.78	123.6	125.9	127.9	128.4	129.8	131.4	140.4	141.8	146.3	132.4	135.9	139.9	133.5	135.0	138.1	142.4	143.9	>145.0
3		4.71	129.9	132.0	134.2	135.9	138.8	143.7	139.0	141.1	143.4	>143.2	-	-	>143.2	-	-	>145.1	>146.0	-
4		4.49	137.8	140.7	-	133.0	136.7	-	142.5	147.7	-	139.4	143.0	-	139.4	141.3	-	145.0	150.0	>152.9
5		4.30	136.8	138.7	143.4	137.4	139.3	142.9	142.2	147.3	150.1	132.9	135.9	139.7	133.6	136.2	141.8	137.9	143.3	>145.9
6		3.99	141.4	143.0	144.8	136.0	138.4	142.2	137.9	139.8	141.7	142.5	-	-	142.9	-	-	145.6	>152.7	-
7		3.52	124.7	127.1	129.2	130.6	132.2	134.3	140.1	141.4	145.6	133.4	136.2	141.9	137.8	143.6	145.9	139.1	144.9	147.4
8		3.38	120.7	121.9	124.6	137.5	142.3	147.8	138.6	140.2	143.0	127.0	130.8	-	136.9	-	-	141.8	>143.9	-
9		2.99	128.0	129.8	132.8	126.5	129.3	131.1	140.2	142.1	145.8	126.6	130.8	134.8	135.5	139.2	142.8	135.8	139.0	142.8
10		2.66	121.7	124.9	130.8	125.7	127.2	128.6	137.7	140.8	146.0	119.9	122.3	127.0	122.3	125.1	130.2	135.8	140.9	143.6
1	2	2.21	115.8	116.5	120.6	119.9	121.4	124.1	122.7	123.9	126.4	124.7	127.5	132.1	130.2	132.5	138.7	137.3	137.8	142.8
2		2.22	112.2	113.0	116.5	105.5	106.3	109.7	116.8	117.8	120.4	124.7	127.9	129.6	129.2	130.8	133.5	132.4	136.0	137.7
3		1.89	113.2	114.8	117.9	113.6	114.3	117.8	125.5	133.7	136.4	119.2	121.1	132.8	120.7	122.8	134.0	132.5	133.6	142.2
4		1.95	113.6	118.2	-	112.9	117.1	-	126.2	132.0	-	110.2	111.5	117.3	114.8	115.7	119.9	126.3	129.3	>135.1
5		2.19	119.8	121.2	123.8	119.0	119.7	123.6	123.7	124.8	127.7	128.6	130.5	135.4	131.0	137.8	143.3	135.8	137.3	143.4
6		2.10	121.1	124.5	132.4	119.8	122.8	129.6	127.7	131.1	137.2	126.7	130.2	136.2*	125.2*	130.0*	134.6*	132.5	136.2	141.2
7		1.64	99.8	100.5	104.1	107.6	108.0	112.2	118.8	119.8	122.9	113.9	117.3	125.4	114.7	117.4	124.2	128.4	130.4	138.2
8		1.72	109.1	109.8	113.0	117.1	120.0	122.7	129.1	131.4	135.7	115.0	119.0	122.8	118.2	120.4	128.3	132.0	134.5	140.0
9		2.07	100.5	101.9	104.9	114.5	116.0	119.1	127.4	128.6	132.8	108.3	109.5	113.5	112.1	112.9	117.2	126.8	127.8	135.0
10		2.38	103.8	105.2	108.1	115.8	117.5	120.1	130.5	132.8	135.5	113.1	113.9	121.6	115.0	115.7	124.0	131.5	132.9	141.6

*** Questionable value**

Table 8. Basic Transmission Loss, 10, 50, and 90% Values, All Paths, Graham Mountain Area, Sept., Oct. 73 (Continued)

		VHF									UHF								
		10m			3m			0.3m			10m			3m			0.3m		
Path No.	Dist. km	10	50	90	10	50	90	10	50	90	10	50	90	10	50	90	10	50	90
T R																			
1 3	6.04	135.1	135.8	>137.3	141.5	142.3	-	137.2	-	-	141.2	-	-	142.5	-	-	143.5	-	-
2	5.72	133.7	134.7	-	138.6	140.2	146.3	144.3	147.5	>149.2	141.5	-	-	>141.6	-	-	143.6	-	-
3	5.75	142.5	144.8	>150.0	144.7	145.9	>152.2	147.0	152.2	>156.2	144.0	-	-	149.2	-	-	150.8		
4	5.55	148.9*	151.4	>155.2	145.3	147.3	>155.8	154.7	155.7	>157.6	147.1	-	-	145.8	-	-	151.0	-	-
5	5.28	138.6	141.0	>146.4	146.1	>149.0	-	144.6	>149.0	-	142.7	>145.0	-	143.7	-	-	144.5	-	-
6	4.97	143.8	146.5	-	151.8	153.4	-	148.3	154.4	>157.0	>149.0	-	-	>150.0	-	-	>151.0		
7	4.92	142.4	143.0	-	141.2	142.5	-	145.5	>147.0	-	>143.0	-	-	>144.0	-	-	145.0	-	-
8	4.80	143.3*	144.5*	-	140.1	142.2	-	146.3	>147.0	-	>136.0	-	-	140.1	-	-	>144.0	-	-
9	4.43	134.3	136.5	>142.1	137.1	138.3	>144.3	145.2	145.7	148.6	137.7	140.8	-	135.5	141.4	-	144.1	-	-
10	4.12	135.7	136.8	-	139.0	141.1	>146.5	146.2	>147.0	-	140.0*	142.0*	-	142.7*	-	-	143.9*	-	-
1 4	4.70	137.6	138.1	>139.5	136.0	138.1	>139.0	142.4	>144.0	-	138.4	-	-	138.2	-	-	140.3	-	-
2	4.44	138.6	139.5	>142.0	139.7	141.2	>143.0	143.2	>144.0	-	>138.0	-	-	>139.0	-	-	>140.0	-	-
3	4.58	142.3	144.1	>148.0	137.8	140.8	>147.0	150.0	151.8	>152.0	142.9	-	-	144.2	>146.0	-	146.6	-	-
4	4.39	144.1	-	-	144.3	>151.0	-	150.3	>152.0	-	143.0	144.0	-	139.1	143.4	144.6	144.9	-	-
5	4.10	140.1	>142.0	-	141.4	>143.0	-	143.6	>144.0	-	138.4	-	-	138.7	-	-	140.2	-	-
6	3.93	135.3	137.5	-	138.3	140.5	>142.8	141.4	141.8	>145.3	137.6	-	-	138.2	-	-	140.0	-	-
7	4.27	138.5	139.7	-	142.0	>143.0	-	>142.8	-	-	>138.0	-	-	>138.9	-	-	>139.8	-	-
8	4.22	138.6	140.8	-	135.2	136.4	>140.0	141.6	>142.8	-	>137.8	-	-	>137.4	-	-	>140.4	-	-
9	3.95	139.8	140.6	>144.0	137.0	141.3	>144.0	142.0	142.5	>145.0	138.6	-	-	>138.0	-	-	>140.3	-	-
10	3.73	131.8	132.9	>136.0	132.9	133.8	>137.0	140.8	141.2	>143.0	138.4	-	-	137.3	-	-	140.5	-	-

* Questionable value

Table 8. Basic Transmission Loss, 10, 50, and 90% Values, All Paths, Graham Mountain Area, Sept., Oct. 73 (Continued)

		VHF									UHF								
		10m			3m			0.3m			10m			3m			0.3 m		
Path No.	Dist. km	10	50	90	10	50	90	10	50	90	10	50	90	10	50	90	10	50	90
T R																			
1 5	2.06	124.6	125.2	128.5	129.8	130.9	133.5	133.7	134.7	137.3	134.6	136.8	139.6	137.7	139.4	142.1	148.9	>153.1	-
2	2.14	120.7	121.5	123.2	128.6	130.0	131.5	141.8	>142.2	-	133.1	134.1	135.5	134.0	135.3	136.7	>145.7	-	-
3	2.20	134.3	137.6	>140.0	133.1	134.6	137.0	140.5	141.0	-	132.8	134.3	136.0	>145.0	-	-	>146.0	-	-
4	2.36	130.8	132.1	133.7	144.8	>148.0	-	>149.0	-	-	134.5	135.3	136.0	135.0	135.9	136.8	137.9	-	-
5	2.54	124.1	125.4	128.0	135.2	137.0	>138.0	141.0	>142.0	-	132.5	133.5	134.8	>145.3	-	-	137.5	138.1	>139.0
6	2.64	130.0	131.0	133.0	135.5	136.5	138.8	137.8	138.9	140.2	141.6	-	-	-	-	-	143.5	-	-
7	2.79	120.1	121.4	123.7	120.0	121.4	123.8	127.1	128.4	130.8	127.0	128.4	130.5	129.2	131.8	135.4	135.1	136.3	138.5
8	2.97	119.4	120.5	122.9	123.7	125.0	126.8	137.3	138.5	139.6	134.4	135.3	136.6	136.5	137.1	138.0	>146.0	-	-
9	3.10	124.8	125.7	128.0	124.3	125.7	127.6	131.7	133.1	135.5	122.6	124.0	126.3	126.5	128.3	130.3	135.3	136.6	137.7
10	3.17	136.3	137.7	140.6	143.9	145.2	147.1	149.5	150.0	150.4	141.9	142.6	-	-	-	-	-	-	-

Table 9. Basic Transmission Loss, 10, 50, and 90% Values, All Paths, Graham Mountain Area, April 74

			VHF									UHF								
			10m			3m			0.3m			10m			3m			0.3m		
Path No.		Dist. km	10	50	90	10	50	90	10	50	90	10	50	90	10	50	90	10	50	90
T	R																			
1	1	5.10	127.1	128.1	149.1*	129.7	130.5	139.3	140.1	141.5	145.1	131.7	132.7	134.1	127.1	128.3	142.2*	138.6	142.3	149.2
2		4.78	126.8	128.3	129.7	130.5	131.6	144.1*	139.8	146.4	149.9	136.2	139.3	141.3	133.4	134.3	143.3*	144.4	146.0	157.6*
3		4.71	132.6	137.5	139.4	136.6	141.2	143.2	147.1	149.9	153.4	141.5	143.7	147.6	135.4	137.7	147.1	151.0	152.9	158.3
4		4.49	131.5	132.8	146.5*	139.7	140.7	148.8	143.8	144.5	152.6*	137.8	139.4	151.3*	138.3	139.6	143.9	148.5	150.7	157.3
5		4.30	135.5	137.3	139.5	138.6	139.9	141.2	143.6	148.2	152.4	137.9	142.0	155.0*	132.5	134.2	137.7	144.1	147.5	148.8
6		3.99	130.2	146.4*	150.8*	135.4	149.0*	157.5*	142.6	147.4	161.4*	137.2	141.4	143.2	136.2	137.1	137.8	147.8	156.1	158.4
7		3.52	126.0	126.8	127.3	130.4	137.0	137.7	136.3	144.6	145.7	131.5	132.8	134.1	141.0	144.6	150.6	143.3	146.6	154.7
8		3.38	124.6	125.5	134.3	132.0	133.6	137.6	142.8	143.5	147.0	127.8	129.1	130.3	134.5	137.3	139.0	141.0	143.8	146.1
9		2.99	124.6	125.4	133.4	124.2	131.6	132.5	135.1	139.9	141.2	133.6	138.7	151.8*	134.1	137.8	141.6	135.6	138.5	146.1
10		2.66	116.4	117.3	118.7	125.5	126.3	144.1	132.0	135.6	136.2	122.5	130.5	134.2	122.9	124.1	125.1	136.2	138.9	147.2
1	2	2.21	120.5	120.7	121.7	122.9	127.8	128.5	124.2	128.4	129.1	126.2	129.1	129.8	128.1	130.4	135.2	139.8	140.2	141.8
2		2.22	115.5	117.5	118.3	107.7	108.7	111.7	117.8	118.8	120.0	133.5*	137.8*	140.8*	122.6	125.1	132.4	133.5	137.5	138.3
3		1.89	115.7	116.2	116.8	115.5	116.2	116.9	125.5	129.5	130.3	116.7	117.9	119.0	120.5	126.2	127.4	127.3	129.3	130.5
4		1.95	107.4	108.4	109.1	108.2	108.7	110.1	117.6	119.2	119.6	112.9	114.0	115.1	114.6	117.0	118.0	125.7	128.6	129.7
5		2.19	122.1	123.0	123.9	123.4	125.0	126.1	125.3	126.9	127.4	128.0	130.6	131.5	133.1	137.7	143.0	135.3	135.9	136.9
6		2.10	114.1	135.5*	141.7*	115.4	135.5*	145.1*	126.0	147.9*	151.6*	120.3	123.0	124.2	118.0	119.0	120.9	129.8	132.3	133.4
7		1.64	103.4	103.7	104.2	111.4	111.6	112.2	121.4	123.4	123.9	117.0	117.8	119.2	114.5	116.3	116.8	127.5	130.7	131.4
8		1.72	111.8	118.6	119.3	121.5	122.5	124.4	133.3	134.0	134.8	116.1	118.6	120.3	114.2	115.2	117.5	134.4	138.5	140.1
9		2.07	105.6	106.0	106.6	116.4	116.7	118.7	128.3	129.7	130.4	112.8	113.7	115.0	112.4	113.1	116.7	127.0	127.9	130.0
10		2.38	103.6	103.9	104.5	112.6	112.9	113.9	128.0	128.4	129.5	117.7	118.4	119.6	117.9	118.9	120.9	128.2	129.8	130.6

* Questionable value

Table 9. Basic Transmission Loss, 10, 50, and 90% Values, All Paths, Graham Mountain Area, April 74 (Continued)

		UHF									UHF								
		10m			3m			0.3m			10m			3m			0.3m		
Path No	Dist. km	10	50	90	10	50	90	10	50	90	10	50	90	10	50	90	10	50	90
T R																			
1 3	6.04	137.7	138.4	141.0	154.3	156.7	160.8	156.1	157.9	162.4	142.8	146.2	150.3	139.6	143.2	146.0	152.8	156.0	157.3
2	5.72	133.6	137.6	138.3	142.8	145.1	146.8	152.1	153.0	154.1	143.8	145.0	147.7	146.2	147.5	151.6	158.3	>159.2	>160.1
3	5.75	144.1	146.7	149.8	150.4	151.8	154.5	158.4	159.7	161.8	146.5	148.6	152.1	144.2	147.5	150.0	158.3	159.4	>160.0
4	5.55	139.2	140.3	141.0	150.3	151.2	159.0	156.5	157.6	158.7	154.4*	156.2	157.1	148.5	151.2	157.4	158.5	159.4	>160.0
5	5.28	141.5	144.4	150.3	149.5	151.0	161.3	157.2	157.8	159.4	144.8	149.6	152.6	146.1	148.1	153.1	157.7	159.2	>160.0
6	4.97	137.0	146.6*	157.9*	140.6	142.0	143.9	151.2	153.4	157.6	153.1	154.3	156.3	146.1	148.5	154.3	154.7	159.0	>160.0
7	4.92	146.4	151.3	153.1	150.6	152.0	157.3	162.1*	-	-	143.9	151.3	157.6	147.9	156.7	160.0	158.3	161.0	>161.0
8	4.80	135.0	135.9	137.3	136.0	136.9	138.0	144.2	145.0	145.8	135.1	141.4	149.7	136.1	138.3	139.2	148.2	154.5	>160.0
9	4.43	132.3	136.7	140.2	138.6	140.3	141.1	148.2	151.9	154.9	134.5	135.9	138.1	132.3	133.1	141.6	154.0	156.4	158.9
10	4.12	133.6	134.9	141.7	135.9	136.4	137.8	149.9	155.1	157.0	131.0	132.0	134.6	136.3	137.1	141.0	151.3	152.7	155.6
1 4	4.70	139.8	140.3	141.2	141.1	142.5	143.4	150.8	154.0	155.6	141.8	143.5	145.3	140.3	144.1	148.4	154.5	156.3	159.2
2	4.44	153.8*	158.4*	161.1*	137.2	138.6	140.2	148.2	154.6	160.6	140.6	146.8	158.0	146.5	151.4	158.0	153.5	157.0	>160.0
3	4.58	142.6	145.5	149.0	144.1	152.0	159.2	153.4	156.8	159.7	145.0	147.4	154.8	142.7	149.6	155.1	153.7	155.9	157.6
4	4.39	142.1	144.5	146.1	145.0	146.2	147.6	149.2	152.4	156.9	145.6	147.7	150.6	137.4	139.2	142.0	149.2	155.1	159.2
5	4.10	139.3	139.8	140.8	144.9	145.6	146.3	153.3	154.6	156.7	147.6	152.3	157.3	139.4	143.6	148.6	151.8	155.7	160.1
6	3.93	146.6*	148.5*	150.7*	136.0	137.4	138.7	144.7	146.6	149.9	142.7	153.7	158.5	140.0	143.6	147.0	157.1	158.8	>160.0
7	4.27	155.9*	158.4*	160.9*	147.6	148.5	151.9	160.3	160.8	162.2	145.8	150.4	158.6	148.4	150.2	153.0	158.8	160.6	161.6
8	4.22	153.9*	159.3*	162.6*	145.6	147.0	149.6	145.9	149.5	152.4	147.7	152.5	156.7	146.4	148.7	153.9	156.6	158.6	161.5
9	3.95	144.6	145.9	148.3	148.6	149.7	153.7	145.6	146.9	148.7	140.6	144.2	150.0	138.0	139.8	145.6	151.3	157.7	159.8
10	3.73	133.4	134.0	134.8	137.6	138.5	139.7	139.8	140.6	141.7	144.6	153.1	155.9	139.7	142.3	148.0	149.6	158.1	160.4

* Questionable value

In an attempt to study diurnal and seasonal changes the measured means were plotted for each hour of the day and for each continuous recording session as was done for the Eglin data in figures 3 through 7. Usually, there is little change in level from one hour to another throughout the 14 to 16 hr measurement day, especially at the lower frequency. Often during an entire 16 hr day there is not more than a dB change in level. Changes from one day to another are greater, but frequently the total range of values for 60 hrs of recording does not exceed 5 dB. For some paths the September losses are greater than those measured in October, but for other paths the two periods are indistinguishable. The same is true of the April data. There are no clear and consistent differences between records taken in the fall and in the spring. These hour-to-hour, day-to-day, and season-to-season changes are not sufficiently consistent to define diurnal or seasonal changes.

It is quite apparent that there are questionable values in both the distributions plotted in a number of figures in the appendix and in the 10, 50, and 90% values listed in tables 8 and 9. In order to identify questionable values, the median basic transmission loss for each continuous recording period was obtained for each path at each frequency and receiving antenna height. At R1 for example, we listed medians of measurements for all records obtained Sept 20, 26, 27, Oct 11, 12, Apr 8, 9, 18, and 19, a total of 9 recording periods encompassing 120 hrs. These listings clearly show the periods when the data appear to be questionable.

Unusually large losses are recorded at R1 on April 18 and 19 for some antenna heights at 172 MHz over paths from T1, 2, 3, 4, 8, and 10, and at 410 MHz over paths from T1, 2, 4, and 5. These values are 10 to 20 dB below those in the other seven continuous recording periods, and occur with any one or more of the receiving antennas. Unusually large losses were also obtained on Apr 8 and 9 from T2 and 6 at the lower frequency and T5 and 9 at the higher one. One striking example occurred on Apr 8 where the loss from T2 with the 10 m receiving antenna was recorded as more than 154 dB. This is 15 dB more than any of the losses recorded with this antenna during the 8 other periods, and 20 dB more than the loss recorded during this same day on the 3 m antenna.

At R2 very large losses were recorded in all the April measurements at 410 MHz from T2 and received on the 10 m antenna. These showed 10 dB more loss than that recorded on the 3 m antenna, and were also some 10 dB more than the losses recorded in the fall. A few questionable values were also noted in the smaller amounts of data recorded at R3, 4, and 5. Records that are considered questionable on the basis of this analysis are indicated in tables 8 and 9.

These lists of median values for all continuous recording periods were used in estimating the median of all measurements recorded during fall and spring at each receiver site. In these estimates, obviously erroneous values were excluded, resulting in a 10 to 90% range of values of 5 to 6 dB in most cases. These median values of basic transmission loss are plotted versus path length in figures 17, 18, and 19. The median for each path is coded as to terrain type ranging from irregular to

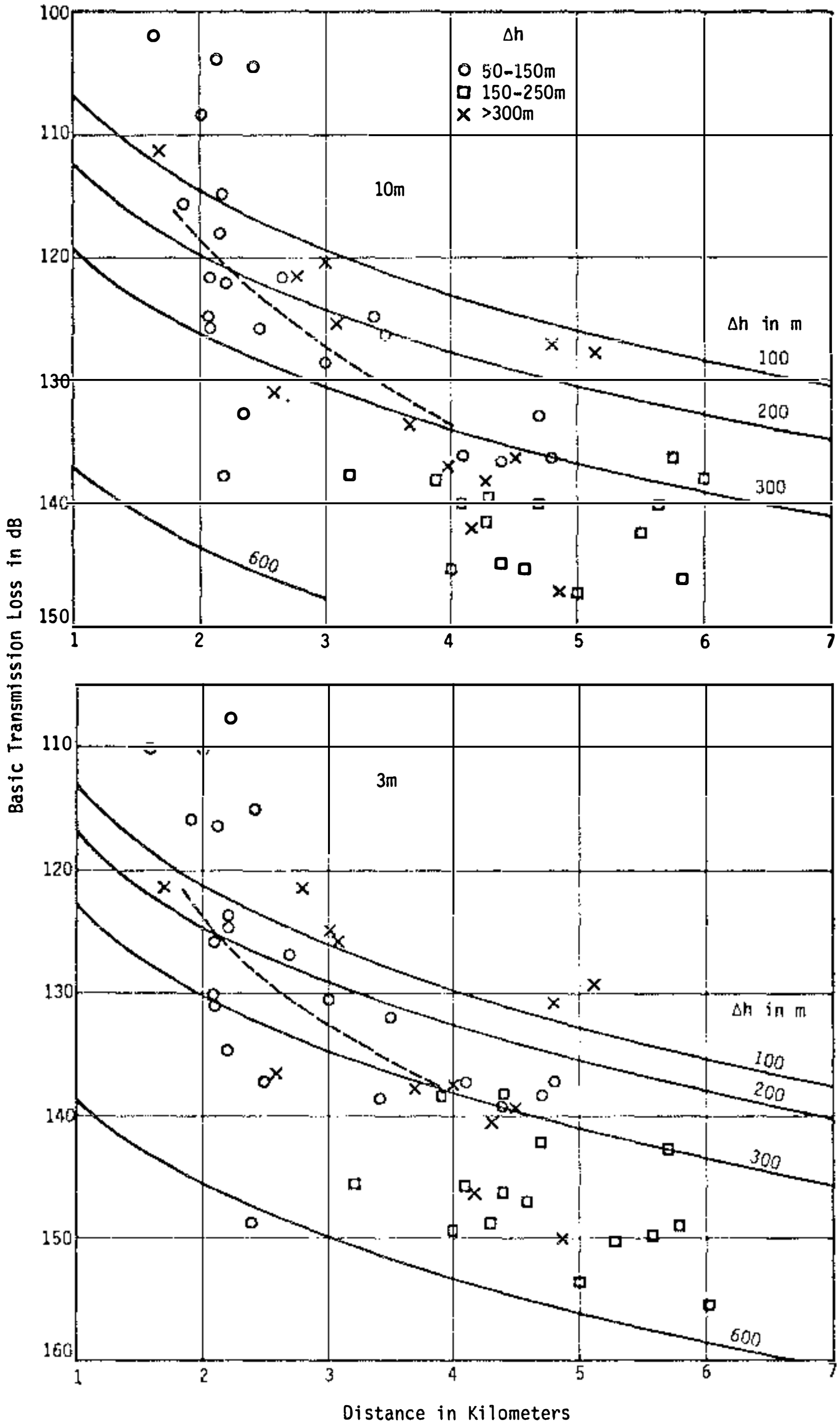

Figure 17. Median values of basic transmission loss versus path length, Graham Mountains, 172 MHz, 10 m and 3 m recieving hts.

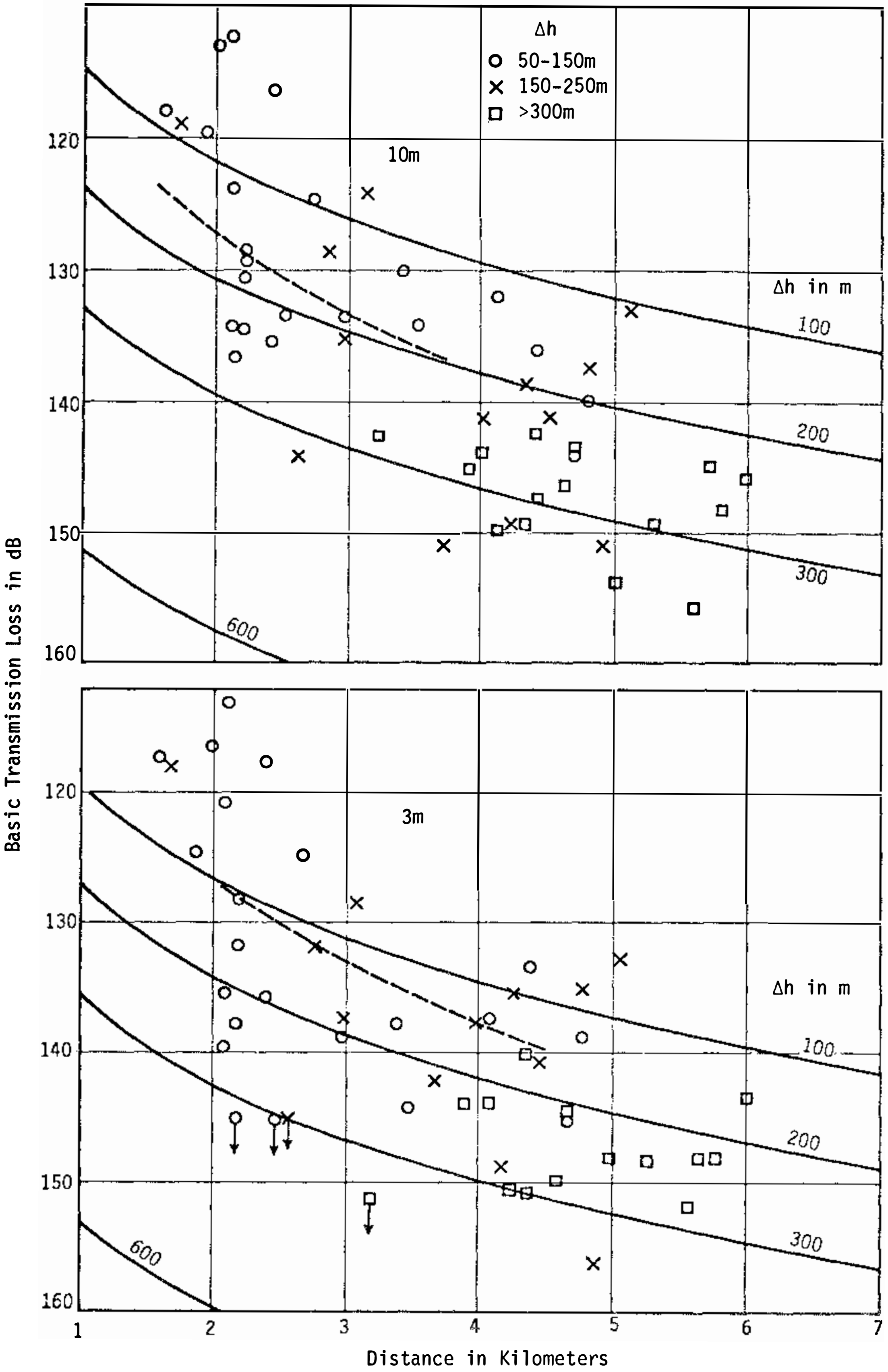

Figure 18. Median values of basic transmission loss versus path length, Graham Mountains, 410 MHz, 10 m and 3 m antennas.

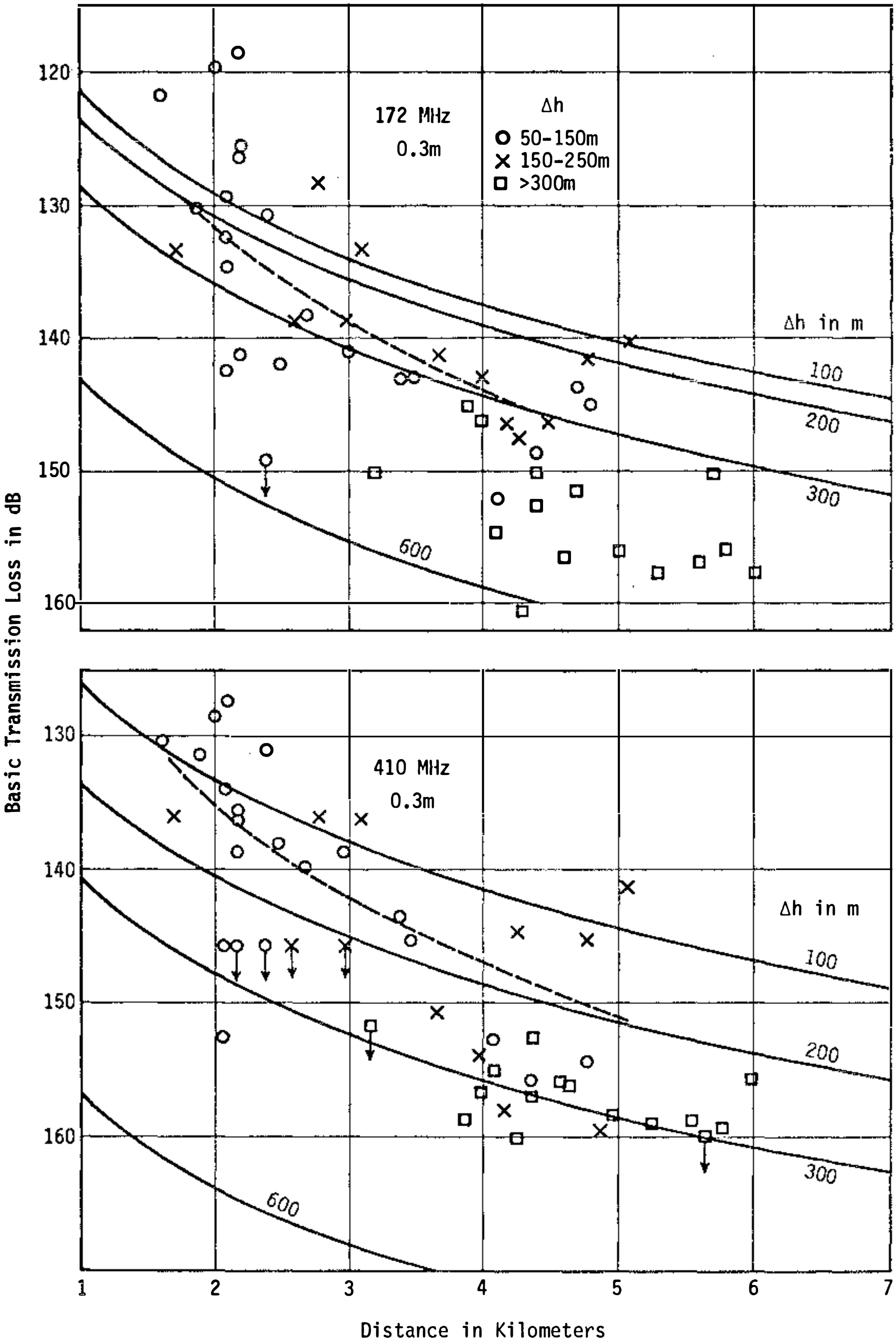

Figure 19. Median values of basic transmission loss versus path length, Graham Mountains, 172 and 410 MHz, with 0.3 m antennas.

mountainous. For all paths the transmitting antenna is 0.3 m above ground. The data show a wide range of some 25 to 30 dB at each distance for each frequency and antenna height. The four short paths, which show the smallest transmission losses, have their terminals within radio line of sight at all but the lowest receiving antenna. The smooth curves of the figures show predicted loss as a function of distance for several types of terrain, as described in the next section.

6.3. Comparison with Predicted Values

The data from the Graham Mountain area are compared with both area type and point-to-point prediction models, which have been described in section 5.3. In this area, vegetation is so sparse that it is practically negligible compared to the large differences in terrain elevation, and no consideration is given to vegetation effects.

The smooth curves drawn on figures 17, 18, and 19, are area predictions for several estimates of terrain irregularity, $\Delta h = 100$, 200, 300, and 600 m. These curves are calculated assuming that the antennas are randomly sited, and with electrical ground constants $\sigma = 5$ mS/m, $\varepsilon = 5$. The median values of transmission loss for each path are coded to indicate terrain type, grouped in ranges of Δh from 50 - 100 m, 100 - 250 m, and >300 m.

A line drawn through the medians of all data at 172 MHz with Δh from 50 to 250 m at the 10 and 3 m antennas would agree with the $\Delta h = 200$ m curves at the shorter distances, but shows more loss at distances greater than 4 km. At the 0.3 m receiving antenna such a line would lie between the curves for $\Delta h = 200$ and 300 m. The median values of data over paths with Δh >300 m lie between the prediction curves for 300 and 600 m.

A line through the medians of data at 410 MHz for paths with Δh from 50 to 250 m lies between the 100 and 200 m prediction curves, as shown in figures 18 and 19. The data for the more rugged terrain are near the curve for $\Delta h = 300$ m. This is probably because for most of the paths in this group transmission is over an isolated obstacle rather than a two-horizon path.

This model predicts basic transmission loss for an average path in each type of terrain, with a path-to-path or location variability that has a standard deviation of 8 to 10 dB at these frequencies. When an allowance for location variability is included, the medians for the 50 paths in this area are well within the predicted limits.

Path parameters obtained from terrain profile information were used as input to the area prediction model, in order to calculate point-to-point predictions for each of the 50 paths at each frequency and antenna height. The predicted values were then compared with the medians of measured values over each path. Cumulative distributions of the differences ΔL = (L predicted -L observed) were obtained and are plotted in figure 20. As previously noted, this model predicts much too great a loss for paths whose terminals are within radio line of sight. Large predicted losses yield positive values of ΔL, while large measured losses yield negative values of ΔL.

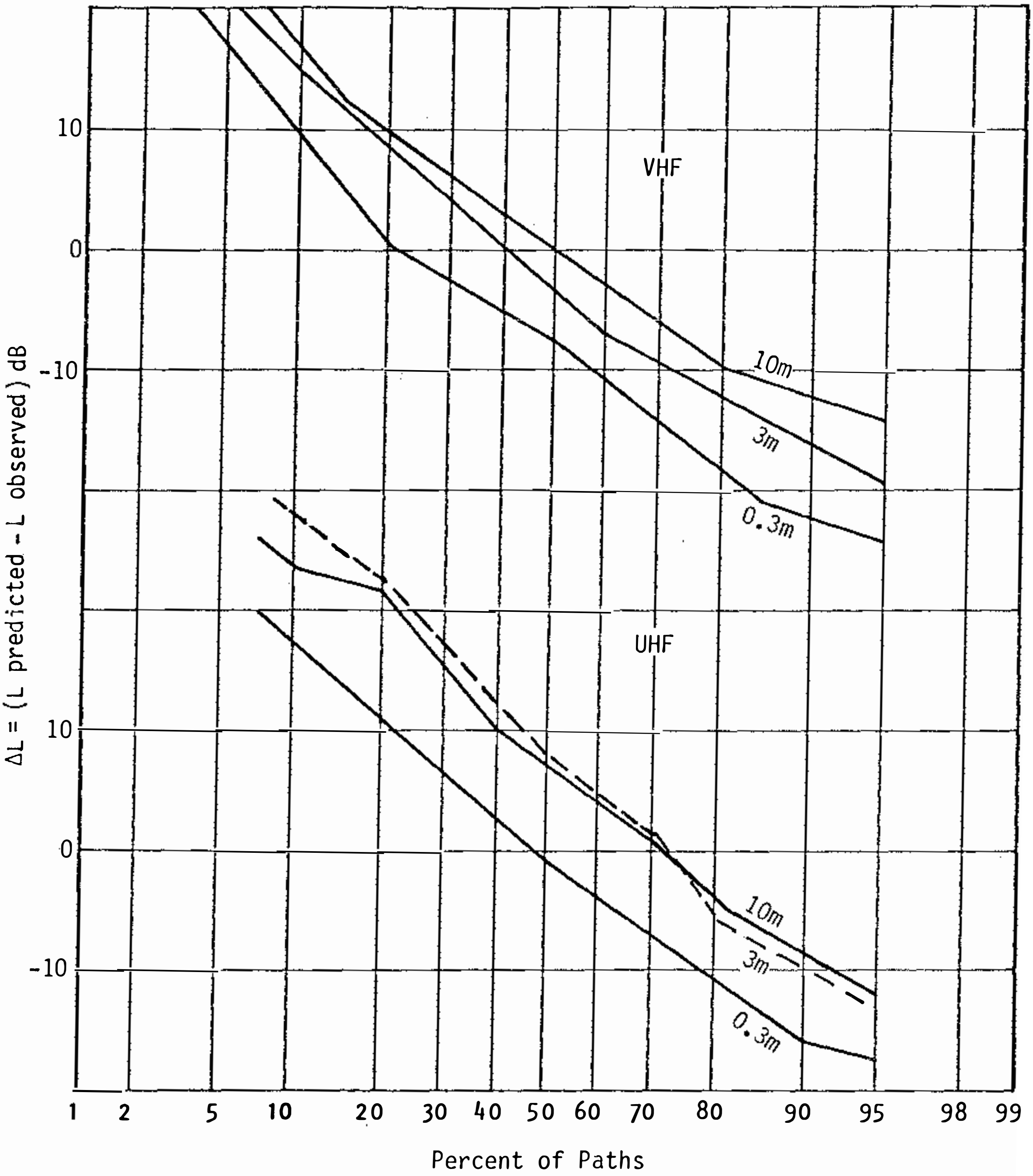

Figure 20. Cumulative distributions of differences ΔL between predicted and measured medians, 50 paths, Graham Mountains, area predictions using path parameters.

The cumulative distributions of ΔL show that at 172 MHz with the 10 m antenna the predicted values agree with measurements at the median, but we tend to predict too little loss when both antennas are near ground level. At 410 MHz, on the other hand, the predictions agree with measurements when both antennas are near the ground, but we tend to predict too much loss when one antenna is elevated 3 or 10m. For this group of paths in mountainous terrain the model computes too great a difference in loss between the lowest and highest receiving antenna heights. This is partly due to the preponderance of single obstacle paths in this set of measurements.

Point-to-point predictions were also calculated based on the methods described by Rice et al. (1967). The differences between measured medians and calculated values were again obtained. Cumulative distributions of the differences are plotted in figure 21. Here we see good agreement between measured and predicted values with both antennas near the ground, but we predict somewhat too much loss with the 10 m receiving antenna. Using this model we predict too much loss for the six two-horizon paths where a model for calculating diffraction over irregular terrain is used. For these short paths the parameters are outside the range of applicability of this model. An empirical approximation was used to estimate the loss for the four paths whose terminals are within line of sight. This approximation tends to underestimate the loss, especially when both antennas are practically at ground level.

The calculations of diffraction over a single or double obstacle are highly sensitive to changes in estimates of effective antenna heights. In earlier applications a subjective estimate of the height of each antenna above a reflecting plane has been used. For this project we devised a computer estimate of effective antenna heights, which is intended specifically for use with low antennas, 10 m or less above ground. For trans-horizon paths a curve is fitted by least squares to the terrain from the antenna for 90% of the distance to the horizon, excluding the 10% nearest the horizon. If the height, h, of the antenna above this curve is greater than its height above ground let the effective height $h_e = h$, otherwise the effective height is equal to the height above ground, $h_e = hg$. For line-of-sight paths we assume $h_e = hg$ because with low antennas we expect some interference from the immediate foreground. Undoubtedly, these automated estimates of effective height are too large or too small for some of the paths, but are quite adequate overall.

7. THE HUNTER LIGGETT AREA

The area selected to represent hilly terrain, with some vegetation, is located in the Hunter Liggett Military Reservation, California. This area is in the coastal range, south of San Francisco. Topographic maps show a good deal of vegetation on the hills, with wide shallow valleys that support little growth.

Two measurement periods were chosen to represent extremes of climatic conditions in this area; a period in January and February, expected to be

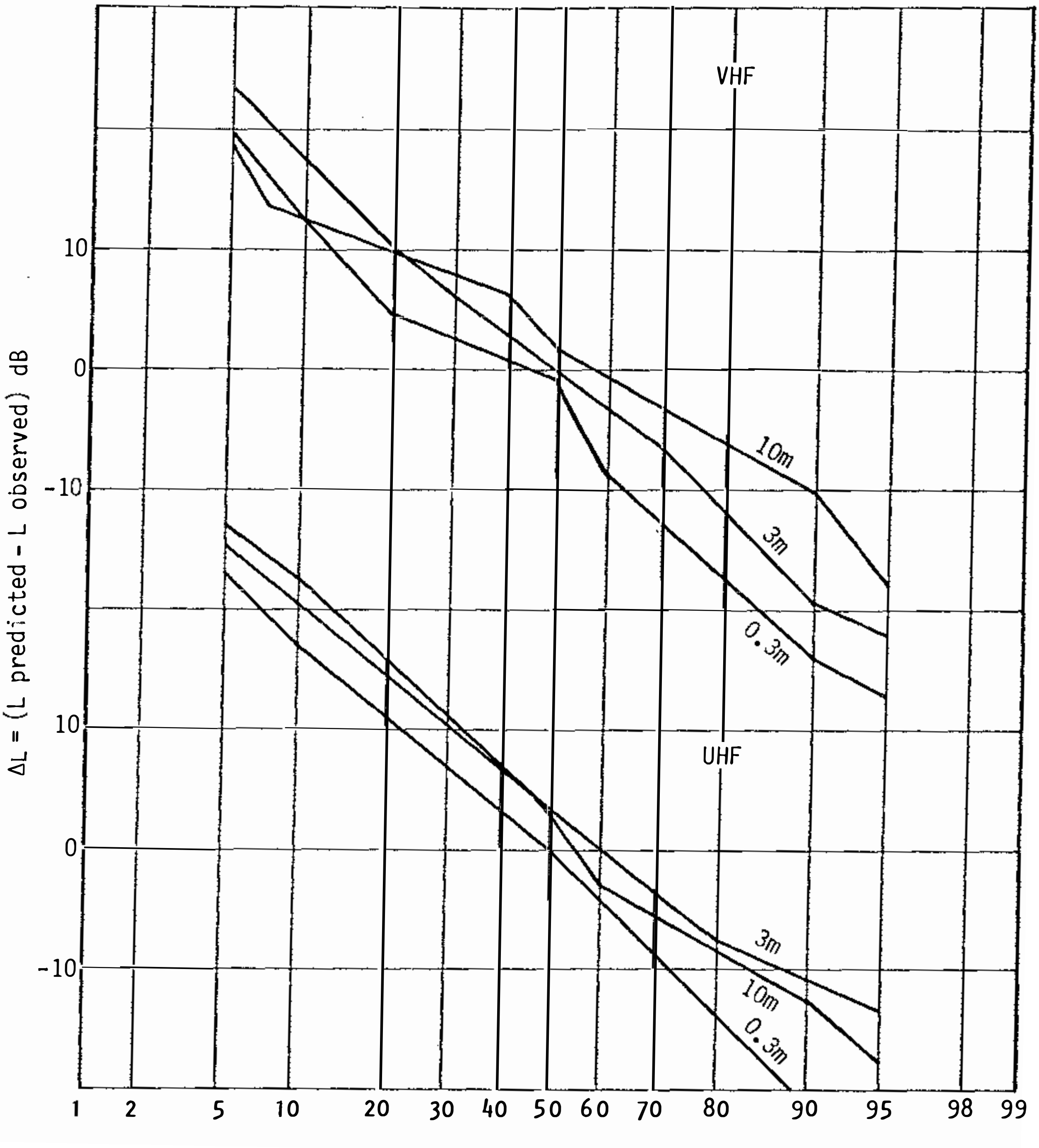

Figure 21. Cumulative distributions of differences ΔL between predicted and measured medians, 50 paths, Graham Mountains, point-to-point predictions based on Rice et al. (1967).

the typical rainy season, and one in May and June which was expected to be the beginning of the dry summer season. During the first period the weather was quite cool, with temperatures dropping to freezing during the night. At night the weather was typically calm, cold, and quite humid, with a relative humidity of 90% or more. In the daytime the weather was much warmer, with temperatures rising above 20°C (about 70°F), light winds and much less humidity. The second period in May and June found the nights still cool, calm and humid, with the days considerably warmer, up to 35°C, light breezes and less humidity. However, both periods were characterized by high humidity at night, little cloudiness, and practically no rain.

The test area is from 350 to 400 m above sea level with a few of the larger hills rising to 450 m. It appears to be rather uniformly hilly with no large differences in terrain type from one location to another. The terrain is described by a median value of Δh about 200 m, which is representative of hilly to mountainous terrain.

The soil is a loose, gravelly loam in most places. This supports a rather sparse growth of coarse grass weeds and small shrubs. In places there are a few deciduous and evergreen trees, with occasional small thickets.

7.1. Description of the Test Site

The test site is located southeast of Hunter Liggett headquarters. The 10 transmitters were placed in a hilly area along a trail through Ruby Canyon. The four receiving sites, located southwest, south, northeast, and north-northeast of the transmitters are shown on figure 22 and labeled R1 through R4. Transmitter 7 was moved after the first measurements to R1 and R2, and is shown twice on the figure - one location for paths to R1 and R2, the other for paths to R3 and R4.

Terrain profiles for the 40 measurement paths in this area were plotted from information regarding distance and terrain elevation read from detailed topographic maps. The profiles are to be found in the appendix to this report.

The four receiver sites are all in rather open terrain with an unobstructed view for some distance in the direction of the transmitters. R1 is on the top of a small hill, in a grassy area with a clear view over a small valley in the direction of the transmitters. All of the paths to this receiver site are over a single isolated obstacle, about two-thirds of the distance along the path. R2 is located in a flat open area. The terrain is level for about 300 m and then rises sharply to a ridge some 80 m high. The foreground is covered with low dense brush, with some pine and oak trees. R3 is located on the edge of a slight depression. The terrain gradually rises to a low ridge about 1 km away. R4 is located in a wide flat pasture from which the ground rises slowly to a low tree-covered hill. The transmitters are, in general, located at higher elevations than the receiver sites, but the paths are interrupted by intervening hills. The general area where the transmitters are located is rolling terrain, covered with grass, low brush, and scattered small oak and evergreen trees.

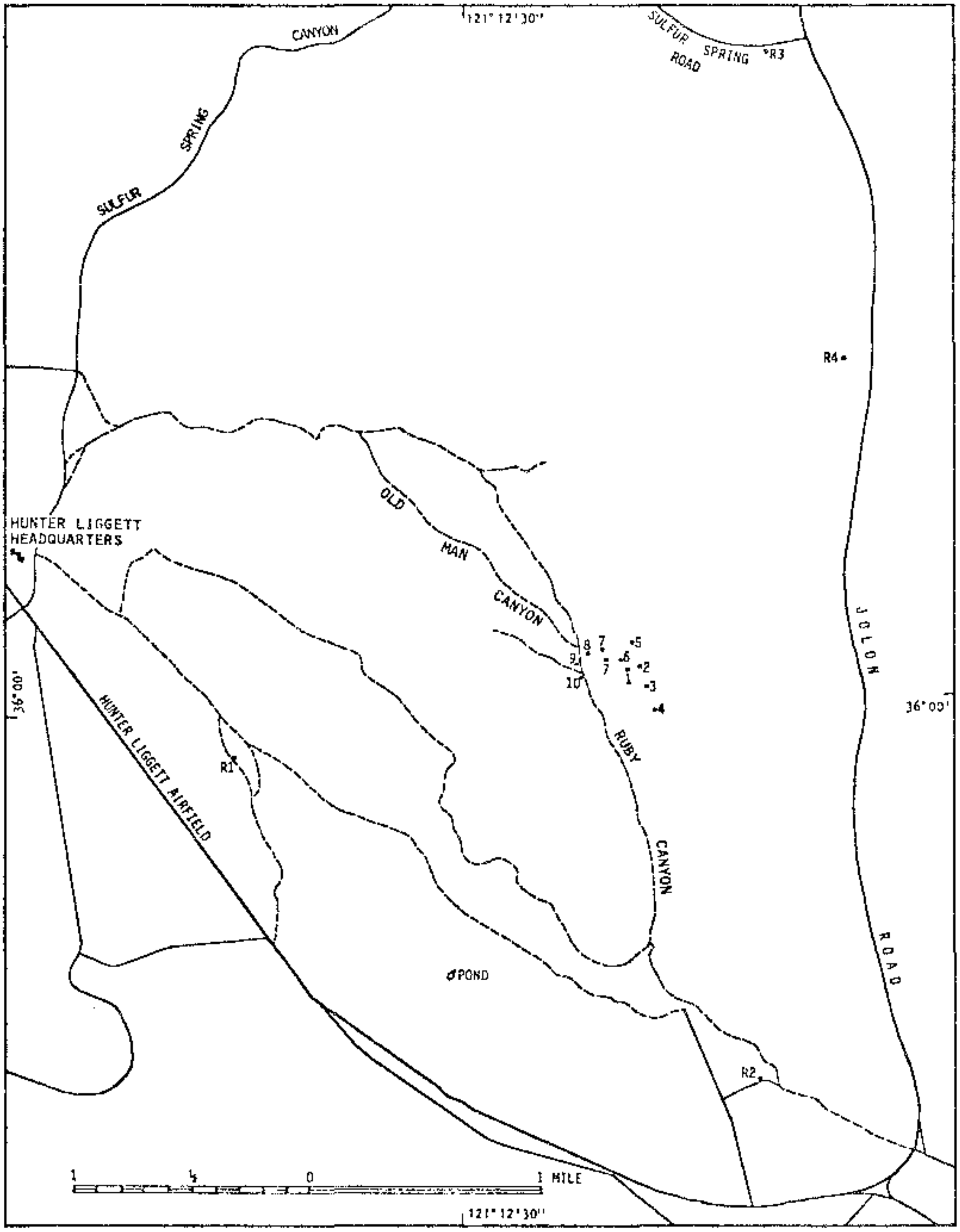

Figure 22. The Hunter Liggett test site showing the placement of the transmitters and receivers.

The terrain at the test site is quite consistent from path to path. Estimates of the parameter Δh for the 40 paths range from 134 to 282 m, with a median value of 216 m. Considering the 10 paths to each of the four receiver sites, we find median values of Δh = 240, 185, 215, and 220 m. We therefore assume Δh = 200 m as characteristic of the area. The 40 paths are all rather short, from 2.5 to about 4.5 km in length, and many of them pass over a single isolated obstacle. None are line-of-sight paths and several have two horizons.

During both testing periods measurements were made of the electrical ground constants at all four receiver sites. These were recorded each hour for some 18 consecutive hours at each site, in January and February, and for about 10 consecutive hours in June. The lowest and most consistent values were obtained at R1 where the conductivity is typically 9 or 10 mS/m with a range of relative permittivity from 3.3 to 4.8, and a median value $\varepsilon = 4$. At the other receiver sites the relative permittivity ε is greater in February, with median values of $\varepsilon = 17$, 11, and 16 in February, and $\varepsilon = 10$, 8, and 11 in June for R2, R3, and R4, respectively. Values of conductivity at these sites are large and quite variable ranging from 10 to >200 mS/m with median values of 100, 30, and 60 mS/m for the three sites, respectively.

7.2. Summary of Measured Path Loss

The recorded values of received power were converted to basic transmission loss, and grouped for each of the 40 paths in the Hunter Liggett area by frequency and receiving antenna height. In order to identify possible seasonal differences betwen the February and June data, the two groups were kept separate in this analysis. Cumulative distributions of all values for each path in each period were obtained and are shown in Appendix B of this report. These figures show distributions of basic transmission loss at 172 and 410 MHz for each of the three receiving antenna heights. The 10, 50, and 90% values from these distributions are listed in tables 10 and 11.

An examination of the distributions plotted in the figures and the values listed in the tables show no consistent differences between the winter and spring values, but does show large inconsistencies in the data. In checking for validity we observed frequent failures of the peak tuning routine with large changes in frequency from one tuning to the next. Such failures were particularly common in the Hunter Liggett data. However, for all of the values shown here tests for internal or within-the-hour consistency have been made and each recorded value in the distributions represents edited data. No automated tests were used to determine the validity of values in successive records, and these sometimes show large changes. Because the changes from one hour to the next and from one recording period to the next are usually quite small, such sudden changes in level are regarded as questionable. Questionable values are indicated in the listings in tables 10 and 11.

Table 10. Basic Transmission Loss, 10, 50, and 90% Values, All Paths, Hunter Liggett Area, Jan., Feb. 74

		VHF									UHF								
		10m			3m			0.3m			10m			3m			0.3m		
Path No.	Dist. km	10	50	90	10	50	90	10	50	90	10	50	90	10	50	90	10	50	90
T R																			
1 1	2.8	115.7	116.6	116.8	116.1	118.2	118.7	119.8	120.2	121.1	127.5	133.3	137.2	131.4	139.2	142.3	137.9	143.3	146.1
2	2.9	123.4	123.8	124.5	128.9	133.0	133.7	127.5	127.8	128.4	135.5	140.5	141.0	145.7	148.3	151.5	146.8	151.2	152.8
3	2.9	129.5	130.9	132.2	125.4	125.9	126.5	136.1	140.3	141.7	131.5	134.2	136.1	134.5	137.8	138.7	139.7	140.9	142.3
4	2.9	116.3	119.2	120.0	115.2	116.6	117.1	121.1	125.6	127.0	126.3	132.1	133.5	123.7	125.8	127.0	135.6	146.9*	153.6*
5	2.9	118.9	122.8	124.0	121.5	124.2	126.1	119.3	120.1	120.4	127.8	129.6	130.8	123.9	127.5	128.4	132.0	133.5	135.0
6	2.8	115.5	116.2	116.8	116.3	118.8	120.4	117.0	117.4	119.2	120.2	121.5	122.7	127.6	129.7	131.6	131.5	136.9*	138.5*
7	2.7	118.4	119.5	120.6	127.5	128.6	131.9	123.3	124.3	126.2	129.1	130.1	135.9	124.1	126.6	128.1	132.3	133.7	136.6
8	2.6	126.3	127.1	128.3	124.3	132.9*	134.7*	124.7	125.3	128.8	131.9	137.7	140.2	134.2	137.3	141.1*	135.4	137.6	138.8
9	2.5	116.9	117.6	118.9	129.3	136.0*	139.0*	120.1	121.0	121.5	128.5	130.9	132.5	135.6	138.0	141.7	139.0	140.0	141.5
10	2.5	126.7	127.7	129.7	127.4	129.5	131.3	129.4	134.1	135.4	130.0	133.4	134.0	136.5	142.5*	143.9	137.3	139.6	140.7
1 2	3.0	136.6	139.3	143.1	141.2	141.9	143.3	142.2	147.5	149.3	140.2	142.2	145.1	136.5	138.0	140.6	148.5	150.2	153.1
2	3.0	138.7	143.3	-	142.8	147.5	-	152.9	155.8	-	150.8	153.2	-	155.6	158.8	-	>163.0	-	-
3	2.8	139.8	143.7	-	148.2	151.5	153.3	151.7	153.8	157.2	155.1	159.8	-	156.3	160.7	-	>163.0	-	-
4	2.6	121.8	122.5	126.4*	127.8	128.6	139.8*	131.5	132.1	132.6	126.2	139.9*	144.1*	133.3	137.0	141.4	142.1	143.9	146.5
5	3.1	129.3	130.1	132.5	124.5	128.8	130.1	134.7	135.2	136.7	132.8	135.4	138.0	134.4	139.8	144.1	139.6	143.0	144.5
6	3.1	127.8	143.5*	150.2*	125.5	134.4	135.4	130.7	133.1	133.9	131.1	136.1	142.1	132.9	135.0	141.4	134.5	139.2	141.3
7	3.1	133.9	147.5*	158.3*	131.1	132.3	133.4	139.6	140.9	142.0	132.8	135.0	148.2	130.4	138.5	140.4	138.1	138.8	139.8
8	3.2	127.9	128.7	133.2	123.9	124.4	130.8	133.0	133.8	136.9	134.8	138.4	139.2	139.1	151.7*	157.4*	157.3	160.4	163.0
9	3.1	134.7	135.6	137.5	137.2	139.6	141.1	148.0	150.5	152.2	137.4	139.7	141.5	138.5	139.3	141.8	145.5	146.7	152.5
10	3.0	128.8	129.2	130.7	129.0	129.6	131.2	137.9	138.3	140.3	138.8	140.4	141.9	143.2	146.2	150.1	147.8	149.0	152.8

* Questionable value

Table 10. Basic Transmission Loss, 10, 50, and 90% Values, All Paths, Hunter Liggett Area, Jan., Feb. 74 (Continued)

		VUF									UHF								
		10m			3m			0.3m			10m			3m			0.3m		
Path No.	Dist. km	10	50	90	10	50	90	10	50	90	10	50	90	10	50	90	10	50	90
T R																			
1 3	4.4.	145.8	147.1	150.3	159.3	161.4	162.6	160.0	161.3	162.5	157.2	158.6	160.5.	159.5	160.3	162.5	>163.0	-	-
2	4.4	142.8	143.6	145.4	149.1	150.0	151.7	155.0	155.9	157.1	148.9	152.6	155.5	156.4	158.1	-	>163.0	-	-
3	4.5	124.3	125.7	126.3	140.4	142.0	143.1	137.6	145.1	146.7	129.2	130.7	134.0	149.3	154.3*	162.*	145.6	146.7	152.9
4	4.7	123.7	125.4	126.1	133.4	138.3	139.3	141.7	144.9	145.7	126.4	129.3	131.1	136.3	138.1	140.0	146.0	148.7	156.0
5	4.2	129.9	132.1	133.5	135.9	138.4	139.7	137.4	139.0	140.0	130.6	132.1	135.0	143.8	146.2	149.0	150.9	152.8	156.1
6	4.4	157.4	160.8	-	163.0*	-	-	161.8	163.0	-	156.1	158.8	-	160.2	161.7	-	>164.0	-	-
7	4.3	140.4	141.5	154.3*	157.6	-	-	154.6	167.2	-	152.9	155.0	160.6	162.6	-	-	>164.0	-	-
8	4.4	144.0	147.7	151.4	155.4	157.2	159.6	158.6	162.4	164.0	158.1	159.5	161.4	160.5	161.0	163.0	>164.0	-	-
9	4.4	145.9	147.1	-	161.8	163.4	-	159.6	-	-	150.4	151.1	153.1	>163.0	-	-	161.7	162.5	-
10	4.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1 4	2.6	142.8	144.8	146.3	156.6	162.4*	163.5	157.4	158.3	160.0	151.5	152.8	156.6	158.8	160.3	-	>163.0	-	-
2	2.6	135.3	138.0	-	142.6	144.7	-	151.3	156.1	-	143.5	147.6	155.8	144.2	151.2*	159.1*	156.9	159.1	160.4
3	2.7	120.3	121.0	122.2	132.2	133.1	136.4	135.4	136.6	137.7	131.8	134.3	143.5*	129.5	130.9	132.5	150.1*	151.9*	159.5*
4	2.8	121.7	123.1	124.2	128.8	129.3	130.4	129.0	130.7	131.2	132.4	130.2*	143.9*	131.3	133.0	134.5	136.9	138.8	141.3
5	2.5	125.6	126.0	126.5	122.8	124.2	124.5	132.6	133.5	134.2	128.5	129.6	131.4	123.8	128.0	131.8	147.2	149.0	154.8
6	2.6	149.6	153.8	157.1	154.8	156.6	159.2	154.9	155.8	157.5	150.8	154.4	156.1	156.9	159.4	161.9	>164.0	-	-
7	2.6	148.2*	152.9*	156.7*	154.6	159.2	161.3	161.7	164.4	165.7	150.3	153.5	160.9	157.9	160.4	162.4	163.3	-	-
8	2.7	149.7	150.8	152.3	150.6	152.5	153.6	160.9	162.7	163.7	156.2	157.8	159.3	154.5	157.3	159.3	>164.0	-	-
9	2.8	135.4	136.8	138.4	139.3	139.8	140.5	144.0	146.5	148.6	145.2	146.1	147.2	147.6	149.9	152.1	160.6	162.4	-
10	2.8	143.6	144.6	150.6	158.6	159.6	-	158.0	163.6	-	157.8	159.5	162.3	153.5	155.8	159.0	>164.0	-	-

* Questionable value

Table 11. Basic Transmission Loss, All Paths, Hunter Liggett Area, 10, 50, and 90% Values, May-June 1974

		VHF									UHF								
		10m			3m			0.3m			10m			3m			0.3m		
Path No.	Dist. km	10	50	90	10	50	90	10	50	90	10	50	90	10	50	90	10	50	90
T R																			
1 1	2.8	115.5	117.6	118.6	116.7	117.1	117.5	119.4	121.4	122.1	124.5	126.3	133.2	128.0	143.8*	150.5*	134.3	135.6	139.7
2	2.9	123.2	123.8	124.7	128.6	129.4	130.1	125.8	127.8	128.5	138.6	140.0	142.0	148.2	154.9*	-	144.9	146.1	150.0
3	2.9	139.0*	140.3*	142.9*	127.2	128.1	129.0	134.7	136.0	137.1	134.5	135.5	136.8	135.7	138.0	139.4	142.0	143.5	144.8
4	2.9	120.9	121.4	122.1	114.8	115.5	116.3	128.7	130.2	131.0	131.4	135.9	139.7	127.4	131.4	132.7	140.5	145.4	147.7
5	2.9	120.8	121.3	123.1	129.4	130.5	133.2	124.4	125.5	126.1	126.2	128.4	130.8	127.6	131.2	133.7	134.1	135.9	137.9
6	2.8	114.4	115.0	115.9	119.0	120.2	120.9	117.8	119.0	119.5	123.0	123.9	125.3	126.1	129.1	132.4	125.6	126.2	126.8
7	2.7	120.3	121.0	122.7	128.5	129.6	137.0	123.5	123.9	124.7	130.0	132.2	133.3	129.5	130.5	132.1	133.6	137.9	138.8
8	2.6	126.6	127.3	127.9	142.9*	147.8*	152.4*	128.4	130.4	131.2	134.5	136.5	138.2	134.4	135.8	137.1	133.1	135.3	136.4
9	2.5	117.6	119.2	119.8	127.2	128.3	129.2	122.7	126.0	127.0	129.4	130.3	131.7	134.3	135.5	137.0	138.1	139.0	140.0
10	2.5	127.7	128.8	129.6	128.9	129.5	130.1	130.4	133.3	134.0	136.9	137.7	138.6	139.8	140.7	143.2	144.0	145.5	146.7
1 2	3.0	138.2	140.4	144.6	145.7	147.5*	152.4*	142.4	145.4	146.9	135.1	137.8	140.2	134.9	136.9	138.8	152.1*	155.7*	158.0*
2	3.0	139.7	140.2	141.2	144.6	148.1	151.6	155.0	157.3	158.8	157.9*	-	-	152.6	155.4	158.3	>162.0	-	-
3	2.8	147.7	152.4	155.4	150.1	153.8	159.3	152.0	152.8	154.9	154.5	157.7	-	158.1	-	-	>162.0	-	-
4	2.6	125.6	128.4	130.1	127.9	131.2	135.4	133.5	135.8	137.1	127.5	129.9	133.8	134.9	138.8	143.0	143.9	146.2	148.1
5	3.1	131.8	133.1	134.6	127.4	130.5	133.1	139.4	141.4	142.7	134.8	137.0	141.2	136.3	141.7	146.2	142.7	144.6	148.0
6	3.1	129.0	135.4	138.6	130.5	132.9	134.0	132.9	136.0	136.9	131.3	133.7	136.9	128.4	129.8	131.9	138.7	140.2	143.8
7	3.1	122.4	124.5	126.1	123.7	129.1	131.5	131.7	136.7	137.5	139.5	142.5	153.3*	136.7	140.0	154.8*	142.7	144.7	159.3*
8	3.2	136.7	138.5	139.7	133.4	134.4	135.7	142.6	143.4	145.3	138.0	140.7	147.7	145.8	150.7	154.6	148.4	151.9	155.2
9	3.1	135.1	139.5	141.7	144.0	147.6	151.3	150.0	154.7	157.5	145.6	149.1	151.1	145.4	149.6	153.2	155.5	>160.0	-
10	3.0	127.8	129.8	131.3	128.2	130.0	135.2	139.2	140.0	143.4	144.8	145.9	148.2	146.5	149.0	153.6	148.0	149.6	151.7

* Questionable value

Table 11. Basic Transmission Loss, All Paths, Hunter Liggett Area, 10, 50, and 90% Values, May-June 1974 (Continued)

		VHF									UHF								
		10m			3m			0.3m			10m			3m			0.3m		
Path No.	Dist. km	10	50	90	10	50	90	10	50	90	10	50	90	10	50	90	10	50	90
T R																			
1 3	4.4	150.6	152.5	154.3	159.6	>163.0	-	162.3	-	-	158.6	-	-	160.3	-	-	>163.0	-	-
2	4.4	143.0	143.9	145.4	149.4	150.8	152.6	156.1	158.0	161.5	150.0	154.2	158.0	154.6	156.3	159.2	>163.0	-	-
3	4.5	126.2	126.9	127.9	139.9	140.9	142.0	150.3*	156.2*	159.8*	129.9	131.7	133.3	148.2	150.4	157.6	146.8	147.8	149.1
4	4.7	125.8	126.8	129.1	135.6	136.6	138.2	147.1	148.8	151.5	129.8	131.1	132.6	136.3	139.3	141.0	149.1	150.3	153.2
5	4.2	131.8	133.0	136.3	144.3	147.7	149.9	142.5	143.6	144.9	132.5	134.9	140.8	148.2	150.4	155.6	155.4	157.8	160.0
6	4.4	153.3	155.4	160.0	161.2	163.5	-	163.2	164.6	-	157.2	158.6	>162.0	>163.0	-	-	>163.0	-	-
7	4.3	150.0	154.0	158.0	156.3	157.9	159.6	162.5	163.2	163.8	152.1	154.4	>162.0	163.4	-	-	>164.0	-	-
8	4.4	148.7	149.3	153.4	157.5	158.7	161.9	>165.0	-	-	155.7	158.5	>160.0	159.2	>160.0	-	>163.0	-	-
9	4.4	150.2	152.9	156.2	162.2	-	-	>165.0	-	-	156.4	158.3	>160.0	159.0	>160.4	-	>163.0	-	-
10	4.5	153.4	158.6	162.5	156.9	160.6	>163.0	>165.0	-	-	156.2	158.6	>159.0	>163.0	-	-	>164.0	-	-
1 4	2.6	150.1*	157.7*	158.0*	157.4	161.5	-	160.4	>162.4	-	153.1	158.3	>159.0	157.5	>160.0	-	>163.0	-	-
2	2.6	135.3	140.3	143.4	141.5	143.7	145.1	155.2	157.3	160.7	143.3	150.8*	154.1*	141.9	146.1	149.1	156.3	158.7	159.9
3	2.7	123.1	123.8	124.6	134.2	136.7	140.1	137.4	141.1	142.4	131.9	134.3	136.2	130.5	131.7	132.8	143.5	144.9	146.9
4	2.8	121.1	122.4	123.7	128.6	129.3	130.1	132.3	133.0	134.2	137.9	141.1	142.8	131.1	132.0	134.6	139.4	141.0	142.3
5	2.5	125.8	128.6	129.8	123.6	124.4	125.1	135.4	136.1	137.0	127.0	128.0	130.1	126.0	127.9	131.3	141.6	143.6	146.2
6	2.6	151.1	153.4	156.9	150.1	151.7	153.4	159.0	160.7	161.8	151.3	153.2	155.3	157.5	158.6	159.4	>163.0	-	-
7	2.6	138.6	139.5	141.0	149.3	152.2	157.4	161.8	-	-	149.0	156.6	161.0	151.4	154.2	157.1	160.5	163.3	-
8	2.7	154.1	158.8	163.2	158.4	159.9	161.7	>165.0	-	=	154.9	158.2	-	154.4	156.3	159.6	>164.0	-	-
9	2.8	136.2	137.0	138.5	140.1	141.0	141.9	148.2	149.0	150.1	152.8	155.5	158.2	150.4	152.2	154.0	>164.0	-	-
10	2.8	145.9	147.2	149.0	155.2	156.9	162.6	162.6	163.1	164.6	157.1	158.6	-	156.0	158.0	160.3	>164.0	-	-

* Questionable value

Median values of all the data, some 120 values in each group, for each path at each frequency and antenna height are plotted versus path length in figures 23, 24, and 25. The smooth curves on the figures are area predictions, which will be discussed in the next section, and the dashed curves represent the medians of plotted points. The most striking feature of these plots is the extreme path-to-path variability. For paths from 2.5 to 3 km in length the range of measured medians is 40 to 45 dB, with many values of basic transmission loss much greater than would be expected for these short paths.

Considering each receiver site, we note that the paths to R1 show the least loss, those to R4 show considerably more loss than those to R2, while the paths to R3 show a very wide range in path loss. An examination of the path profiles gives some idea of the reasons for these differences. The profiles to receiver site R1 show that for all 10 transmitters the paths pass over a single isolated ridge or hill. At R1 and at most of the transmitter sites the terrain falls off into a depression, so that radio rays are well clear of terrain throughout most of the distance from the transmitter and receiver to their horizons. At R2 the terrain is level for a short distance then rises to a ridge more than 0.5 km away, so that the radio ray to the horizon is well clear of intervening terrain. At about half of the transmitters the paths to R2 are over flat or rising terrain, so rocks, shrubs, or trees in the immediate foreground will cause additional path loss. At R4 the terrain rises gradually to a small nearby ridge, with a higher ridge about half a km away, but from the transmitters the situation is quite different. For most paths the transmitters are immediately behind a hill in the direction of R4. Considering the somewhat longer paths to R3, we note that R3 is on an irregular slope that rises gently to a small ridge. There is little clearance above terrain, and any small obstacles in the near foreground would cause additional path loss. From the transmitters toward R3 there is a small ridge immediately in front of most of them.

7.3. Comparison with Predicted Values

The area prediction model developed by Longley and Rice (1968) was used to calculate median basic transmission loss as a function of path length for this area, and the resulting curves are shown with the medians of measured values on figures 23, 24, and 25. The predictions assume random antenna siting, with $\Delta h = 200$ m, and no specific allowance for vegetation. In all cases the median of all measured losses is greater than the predicted loss for this Hunter Liggett area. At both 410 and 172 MHz the medians of all measured values show about 7 dB more loss than we predict.

The area prediction includes an allowance for path-to-path variability with a standard deviation of 8 and 10 dB at these frequencies. Thus, a band represented by the predicted median ± 8 dB should encompass two-thirds of the measured values at 172 MHz. In this area almost half of the paths show greater losses at both frequencies and all three antenna heights. This is partly due to the extreme spread of the measured values, where the

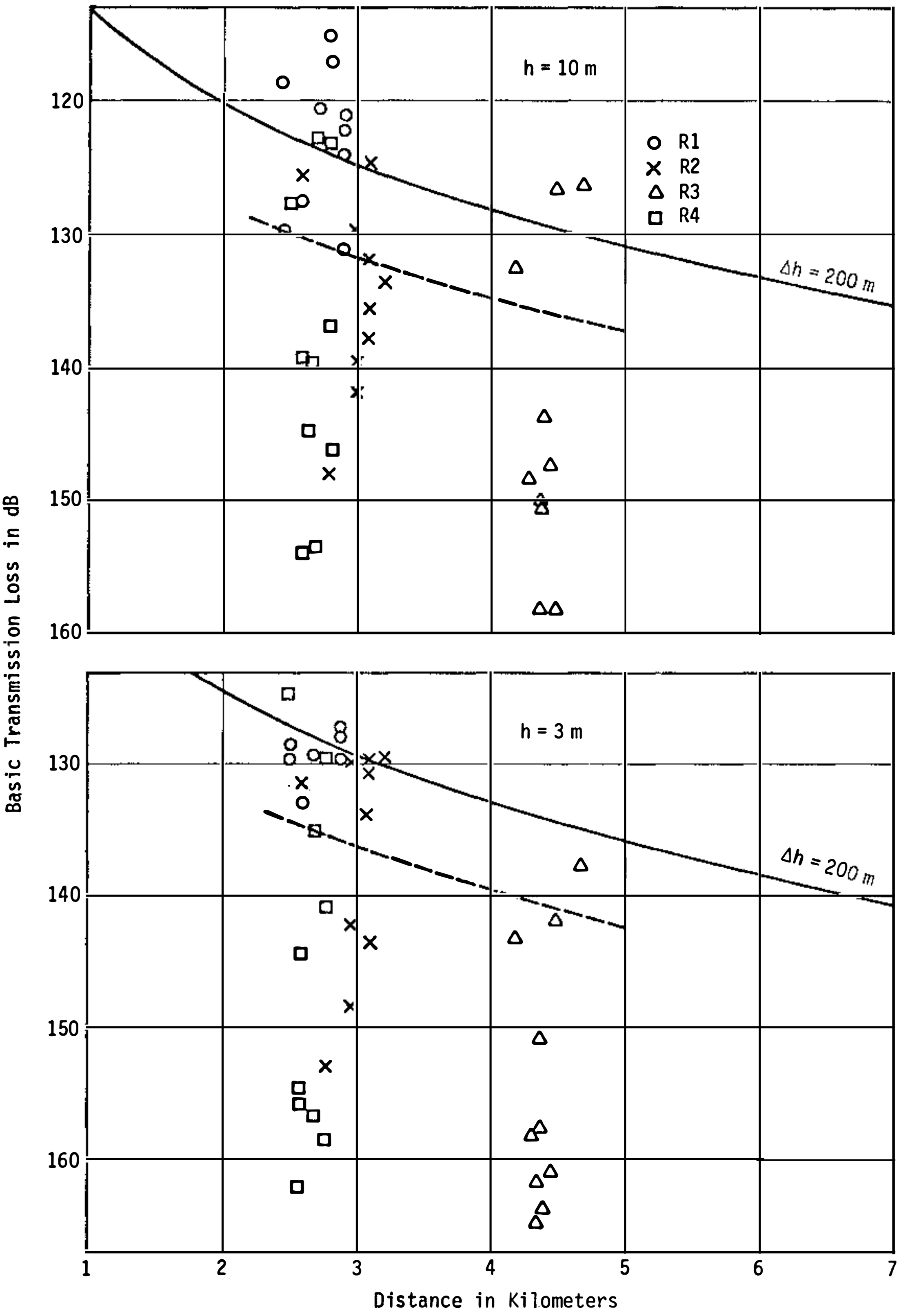

Figure 23. Median values of basic transmission loss at 172 MHz with 10 m and 3 m recieving antenna, Hunter Liggett area.

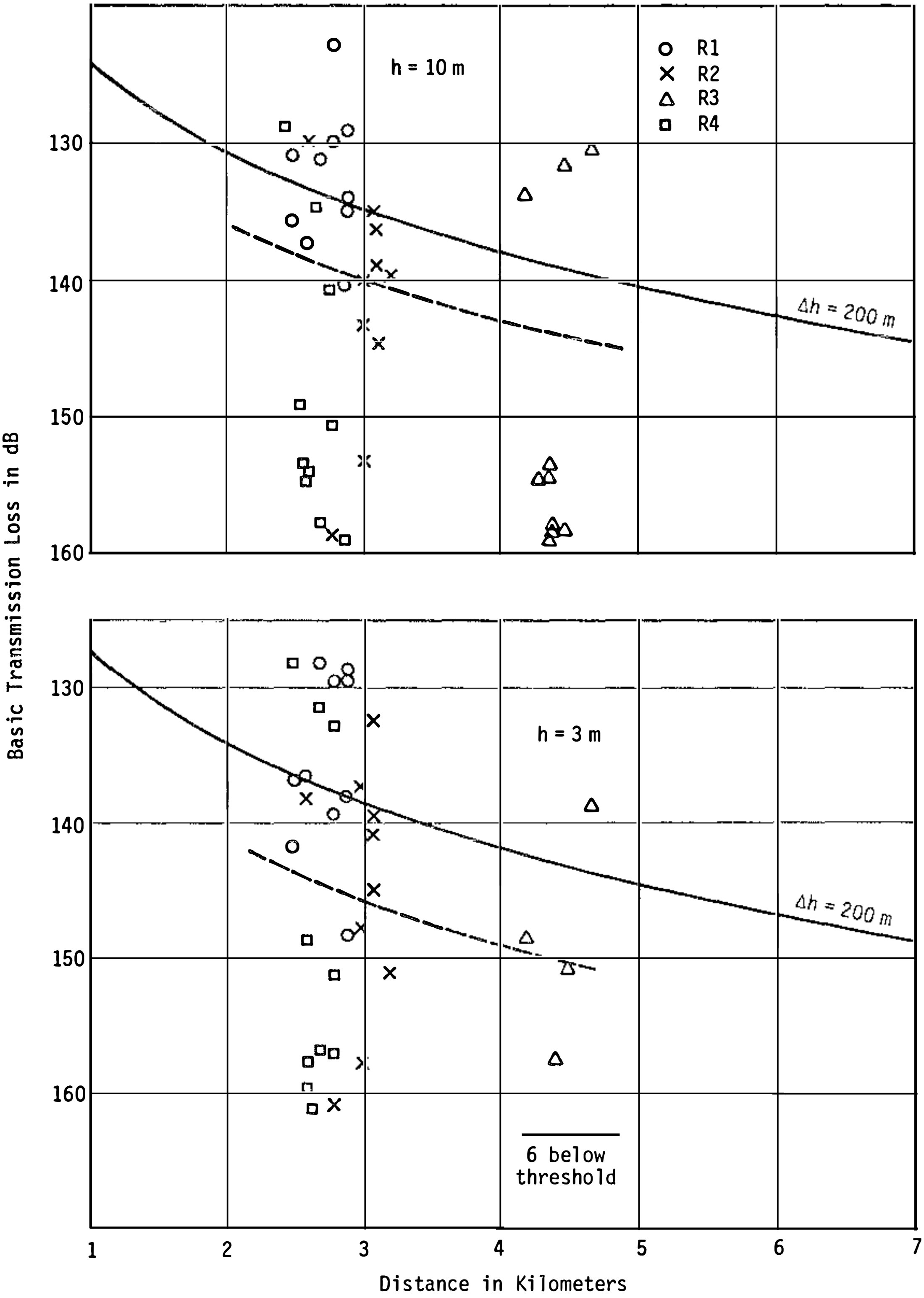

Figure 24. Median values for basic transmission loss at 410 MHz with 10 m and 3 m recieving antennas, Hunter Liggett area.

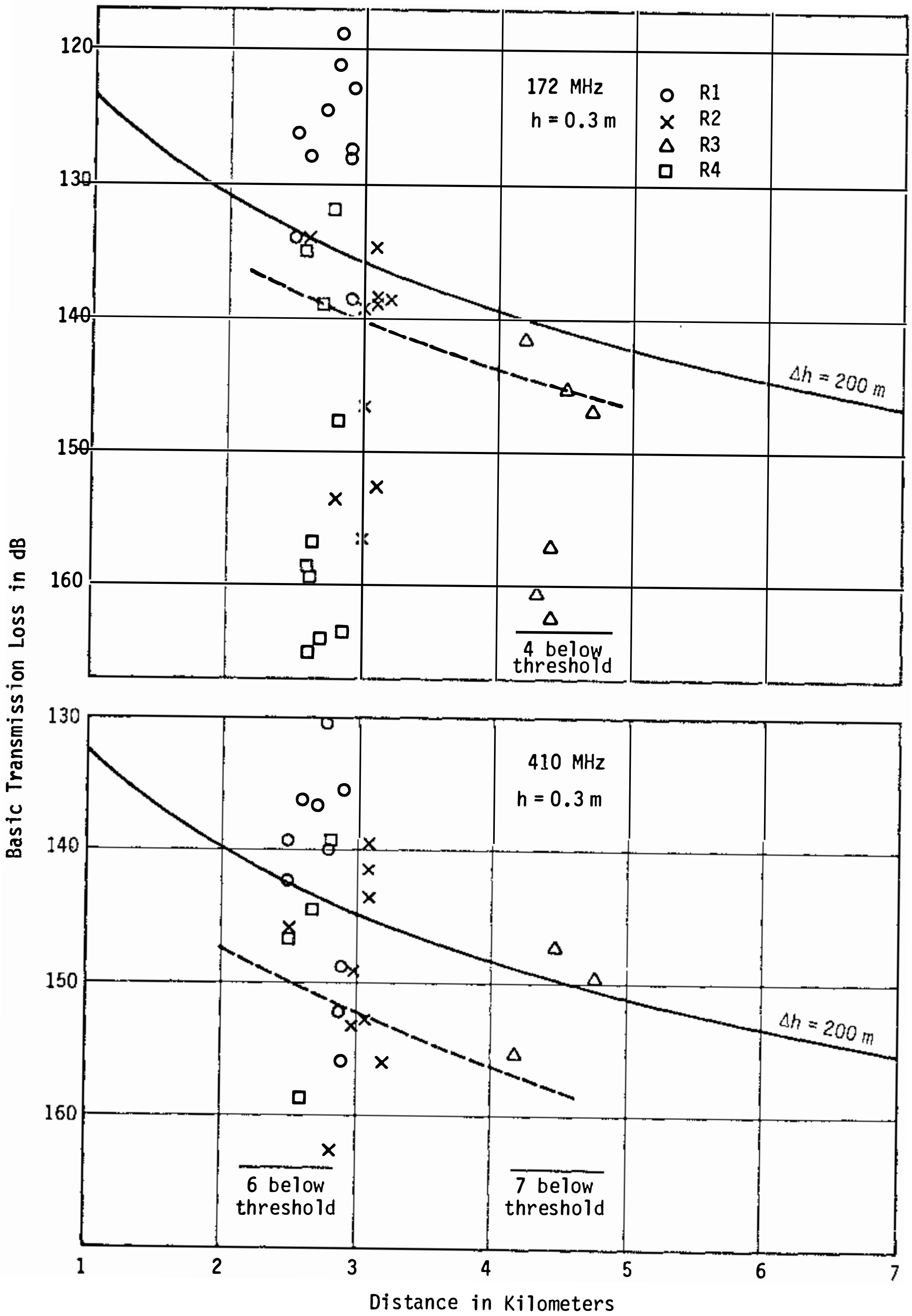

Figure 25. Median values of basic transmission loss at 172 and 410 MHz, with the 0.3 m recieving antenna, Hunter Liggett area.

central two-thirds of the medians of data cover a range of some 35 dB, rather than the predicted 16 dB. However, the only suggested explanation for the unusually large losses over these paths is that the sites are somewhat poorer than a truly random selection would yield.

Transmission loss for each path, at each frequency and antenna height, was predicted using actual parameters from each path profile in the area prediction model. The differences between predicted and observed loss were calculated. Distributions of these differences, ΔL, are shown in figure 26. Positive values of ΔL show that we have predicted more than the measured loss, while negative values show greater loss than predicted. The figure shows that at the median we predict 4 to 7 dB less than the measured loss at 172 MHz, but very nearly the same value at 410 MHz. In both cases the difference between measured and predicted loss is more than 10 dB for a small percentage of these 40 paths.

At both frequencies we predict less than the measured loss with the 0.3 m antenna. There are several possible explanations for this. One is the apparent changes in the electrical ground constants with location, and from one period of time to another. Reported values calculated from measurements show a range in conductivity σ from 10 to more than 200 mS/m, with relative permittivity ε from 3 to 47. Median values of ε at the 4 receiver sites range from 4 to 16, with σ from 10 to 100 mS/m. The predictions for all paths were computed assuming $\varepsilon = 10$, $\sigma = 60$ mS/m.

Reference to an earlier report (Longley, 1972) shows that such changes in permittivity have more effect with the lowest than with the two higher receiving antennas. Over a smooth earth with zero height antennas at 170 MHz, a change in ε from 4 to 24 reduces basic transmission loss about 15 dB. With one antenna at 1 m and the other at zero, the difference is still more than 10 dB. At the higher frequency, the sensitivity to electrical ground constants is considerably reduced. This effect could account for the differences shown in figure 26. Sensitivity to changes in electrical ground constants should be more apparent in this area where the radio ray travels close to the ground throughout its entire length for many paths than in the Graham Mountain area where the rays are farther from terrain.

The methods based on those of Rice et al. (1967) are not applicable for this area, because many of the tests are over short diffraction paths where the methods tend to estimate too great a loss.

8. SUMMARY AND CONCLUSIONS

This extensive measurement program has provided a large body of data at VHF and UHF with very low antennas in irregular terrain. The effects of terrain irregularity and of forest cover are clearly demonstrated in the different test areas. Receiving antenna heights of 10, 3, and 0.3 m were chosen to provide a transition from known effects with the higher antennas to the relatively unknown situation with antennas at or very near ground level.

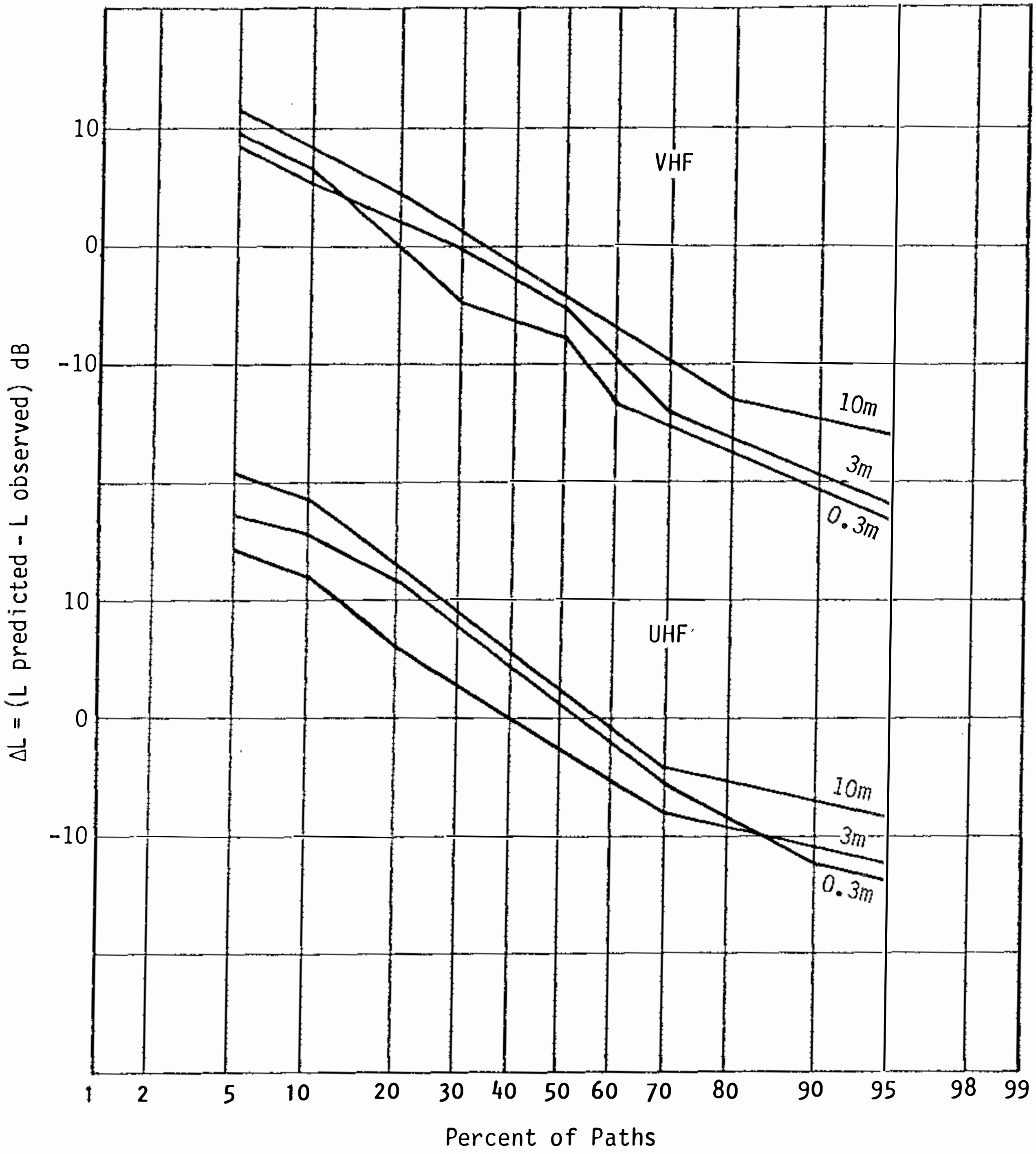

Figure 26. Cumulative distributions of differences ΔL between predicted and measured medians, 40 paths, Hunter Liggett, area predictions using path parameters.

The data from these three test areas clearly show that at VHF the power received over a short path tends to remain at a constant level from one hour to the next for periods of 16 to 18 hrs, and that the change from one day to another or even from week to week does not usually exceed 5 or 6 dB. The somewhat greater variability observed at UHF may result from a frequency instability or the measurement techniques rather than a true difference in propagation. The short-term or within-the-hour variability is usually small with a variance much less than a dB.

Although the variation in time is small, there is a large path-to-path or location variability. For these short paths, differences in path loss of 40 to 45 dB for paths of the same length are common. This large location variability is associated with the low antenna heights, where small obstacles in the immediate foreground may partially block both the launching and reception of the radio signal.

In predicting the transmission loss to be expected between very low antennas the area prediction model reported by Longley and Rice (1968) proves to be useful. This is particularly valuable for short diffraction paths where terrain may range from practically smooth to almost ideal knife-edge conditions, and where for many paths the receiver is just beyond line of sight. This is a particularly difficult range for most propagation models. The area model calculates attenuation at greater distances and within line of sight and interpolates between these values to obtain calculated diffraction attenuation at distances just beyond the horizon. For short paths this model gives generally good results with very low antennas in all terrain types, but makes no specific allowance for the effects of trees. In a heavily forested area an additional allowance is required for the attenuation by the forest, especially when antennas are located near or among the trees. For the Eglin area we found these additional attenuations to be about 7 and 3 dB for the two higher and the lowest receiving antennas at 172 MHz, and about 15 and 11 dB at 410 MHz. In this area many of the terminals were close to thick stands of evergreens. When the terminals are actually in a jungle, the attenuation is extreme, as noted earlier. The additional attenuation by vegetation depends on the density of the forest, how high it is, and how close to the path terminals. The attenuation is also frequency dependent, increasing with increasing frequency.

For predicting loss over individual paths between low antennas the area model with the actual path profile, or parameters derived from the profile, again yields good results. In estimating path parameters it is important to consider local features such as rocks, stands of trees, and low hills, which become important when antennas are at ground level. Solid objects, such as buildings or rock walls, are treated in the same way as hills or ridges in the terrain.

In allowing for the effects of nearby thick stands of trees, we assume that some radio energy passes between the trees rather than over them. If such thickets are very close to an antenna, we limit the elevation angle to a value equal to the critical angle of internal reflection. This keeps the elevation angle within the limits of the model, and assumes some transmission by means of the lateral wave.

We conclude then, that the area prediction model is adequate, even with antennas at or near ground level, when an allownace is made for the effects of forests. This model may also be used to predict losses over individual paths with antennas at or near ground level.

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APPENDIX A. THE MEASUREMENT EQUIPMENT AND ITS OPERATION

The measurement system, designed and assembled by Sandia Laboratories, consisted of 10 commandable transmitter packages and an automated recording system. Each transmitter package consisted of a battery pack, a command receiver, VHF and UHF transmitters, and associated antennas. The transmitters were tuned to nominal frequencies of 172.5 and 410.5 MHz. Each package could be commanded independently by means of coded addresses. The power output for each transmitter was about 2 W.

The transmitting antennas were quarter-wave monopoles above a conical ground "plane" of four rigid wires whose ends rested on the ground and raised the antenna feedpoint about 35 cm above ground level. The command receive antenna, of the same type, was mounted on a wooden pole. All three antennas were connected to the transmitter package by low-loss coaxial cables, as shown in figure A1.

The automated receiving system consisted of a spectrum analyzer interfaced with a mini-computer, a command transmitter, also interfaced to the computer, a low-noise pre-amplifier, and instruments for recording wind speed and direction, temperature, and humidity. The electronic equipment was installed in an air-conditioned shelter, mounted on a flatbed truck. Power was supplied by two gasoline generators, one for the air-conditioning alone.

The six receiving antennas were of the same type as the transmitting antennas, with one for each frequency mounted at heights of 10m, 3m, and on the ground. The command transmit antenna was a yagi-uda type, oriented vertically and mounted at a height of 10 m. Figure A2 shows a typical deployment at a receiving site. The seven antennas are some distance from the truck in the direction of the transmitter sites to minimize any effects the truck might have had on the received signals.

The method of switching to receive the six diffenent signals should be noted. The spectrum analyzer had four input ports which used electronic switches of the PIN diode type. To accomplish the additional switching, cables from the middle and low antennas for each frequency were led to an electrically driven mechanical coaxial switch, and thence to an input port.

Calibrations were performed in the semi-automatic way prescribed for the spectrum analyzer, using a signal generator attached manually to one of the ports. Bandwiths, originally set at 1 kHz, were variable, and noise was chiefly from man-made sources, hence highly variable. Initially the path loss tolerance was about 140 dB, but with the pre-amplifier installed it was about 160 dB.

Each recording day began with a checkout of all equipment and a calibration of the spectrum analyzer. The remainder of the day was divided into recording periods of about an hour each. Figrue A3 is a schematic illustration of the procedure followed during each recording period. First meteorological data were taken and entered into the computer along with identifying information such as date, time, etc. Then the computer went into and automatic mode of 20 measurement cycles, interrupted every fifthe cycle by a "returning cycle." The latter was instituted to follow any frequency drift in the individual transmitters. Each measurement cycle was divided into three parts. The 10 transmitter packages were commanded in succession with the spectrum analyzer switched to the two high receiving antennas. This sequence was then repeated with the medium and the low antennas.

For each record the computer followed a six-step routine which might be described as follows:

1. For each channel, test for excessive noise or an interfering signal and set corresponding by-pass switches. If both channels are noisey, skip to step 6.

2. Command the proper transmitter package.

3. For each channel, test for a received signal and set the corresponding by-pass switches.

4. If not by-passed, measure the received VHF signal strength.

5. If not by-passed, measure the received UHF signal strength.

6. Accumulate and store statistics and print a warning message if any failures have occurred.

Of importance in this process was a value called the "threshold" which could be entered manually into the computer. Ideally, it was set to be slightly larger than the noise power in the pass band of the spectrum analyzer. Excessive noise in step 1 and a received signal in step 3 were defined to be readings larger than this threshold. In steps 4 and 5 the algorithm used to determine the value of signal strength (analogous to a decoding technique) was to make several measurements in rapid sequence and then to average only those which fell above this same threshold.

The failures recorded in step 6 were of three types:

1. Excessive noise in the channel, so that no measurement was attempted. If this occurred regularly, perhaps the threshold was set too low.

2. No received signal at step 3. If this occurred regularly, either the threshold was set too high or there was some trouble with the transmitter or its command receiver.

3. No measured signal at steps 4 or 5. If this occurred regularly, the transmitter was probably terminating its pulse prematurely. Therefore the batteries were low or there was some other trouble at the transmitter.

Normally, a recording period experienced very few of these failures.

The measured values, the accumulated statistics, and a record of the failures were all stored in computer memory. The 20 cycles required about 40 minutes at the conclusion of which the stored values could, at the operator's option, be preserved on 7-track magnetic tape and also printed out locally.

Each visit to a test area produced three or four reels of magnetic tape. These were sent to USAEPG headquarters where they underwent some slight editing for an occasional tape format error or the addition of comments to selected records. The converted tapes were then sent to ITS for the analyses contained in this report.

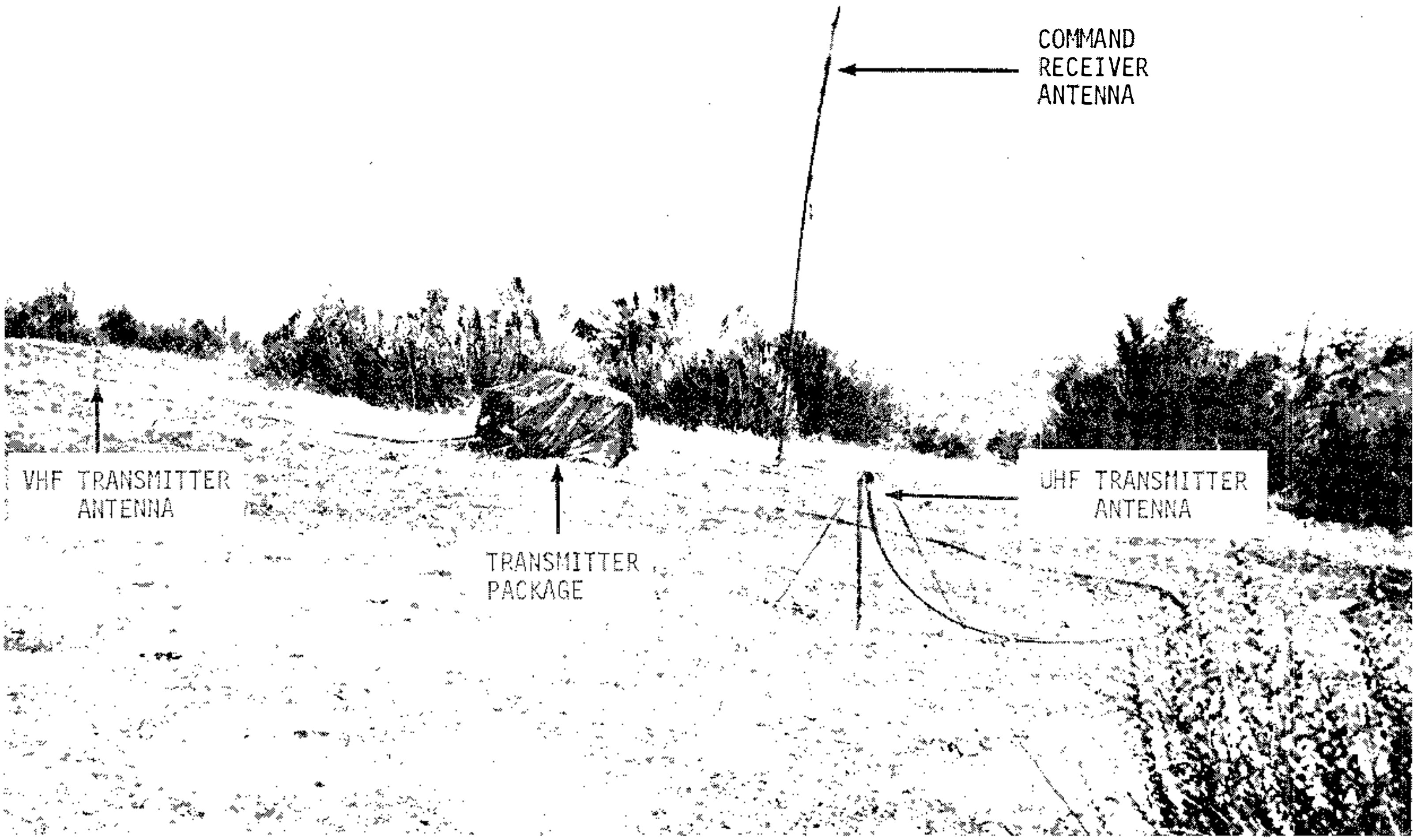

Figure A1. A typical deployment of a transmitter package and its associated antennas.

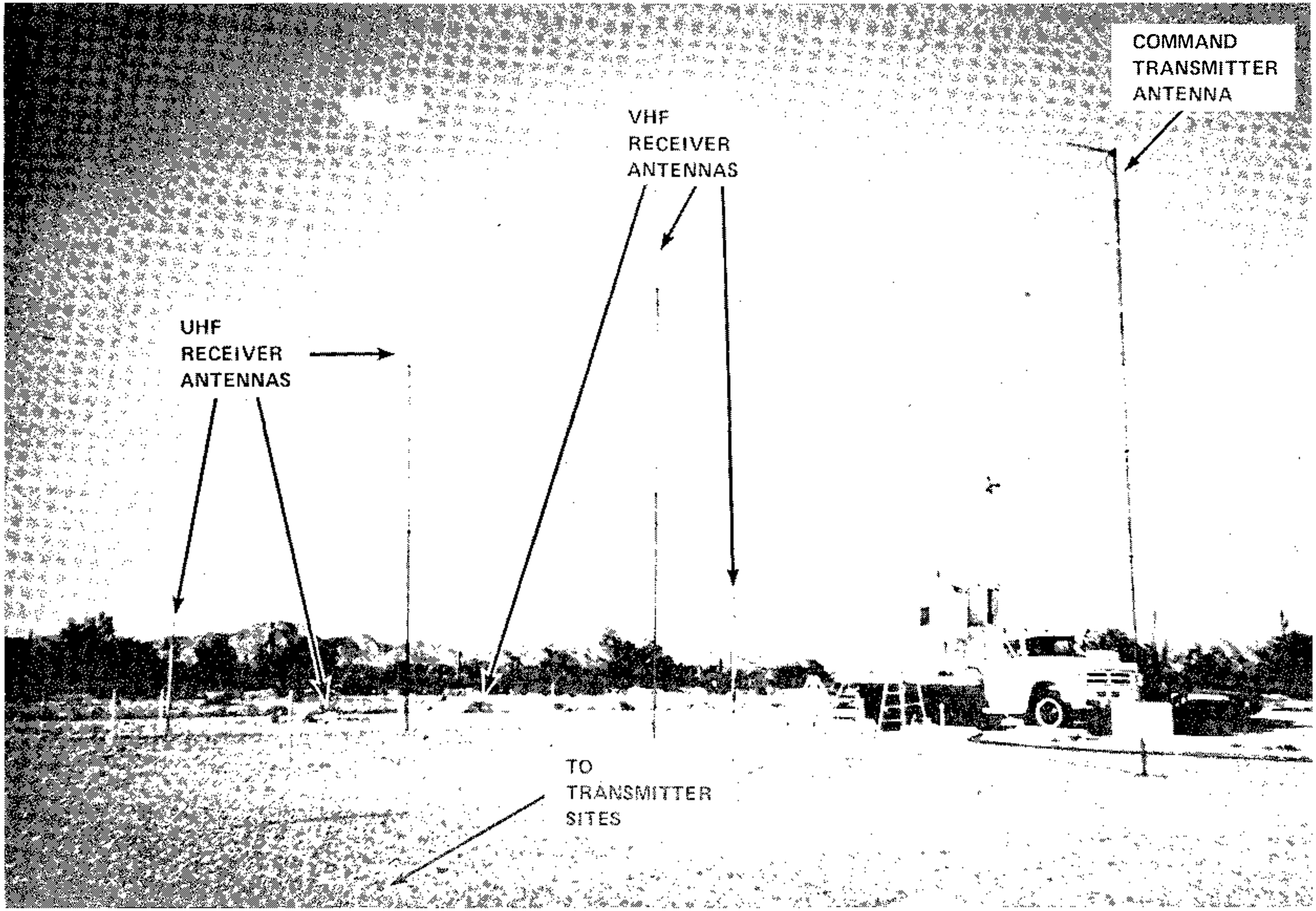

Figure A2. A typical deployment of the Automatic Path Loss Measurement System.

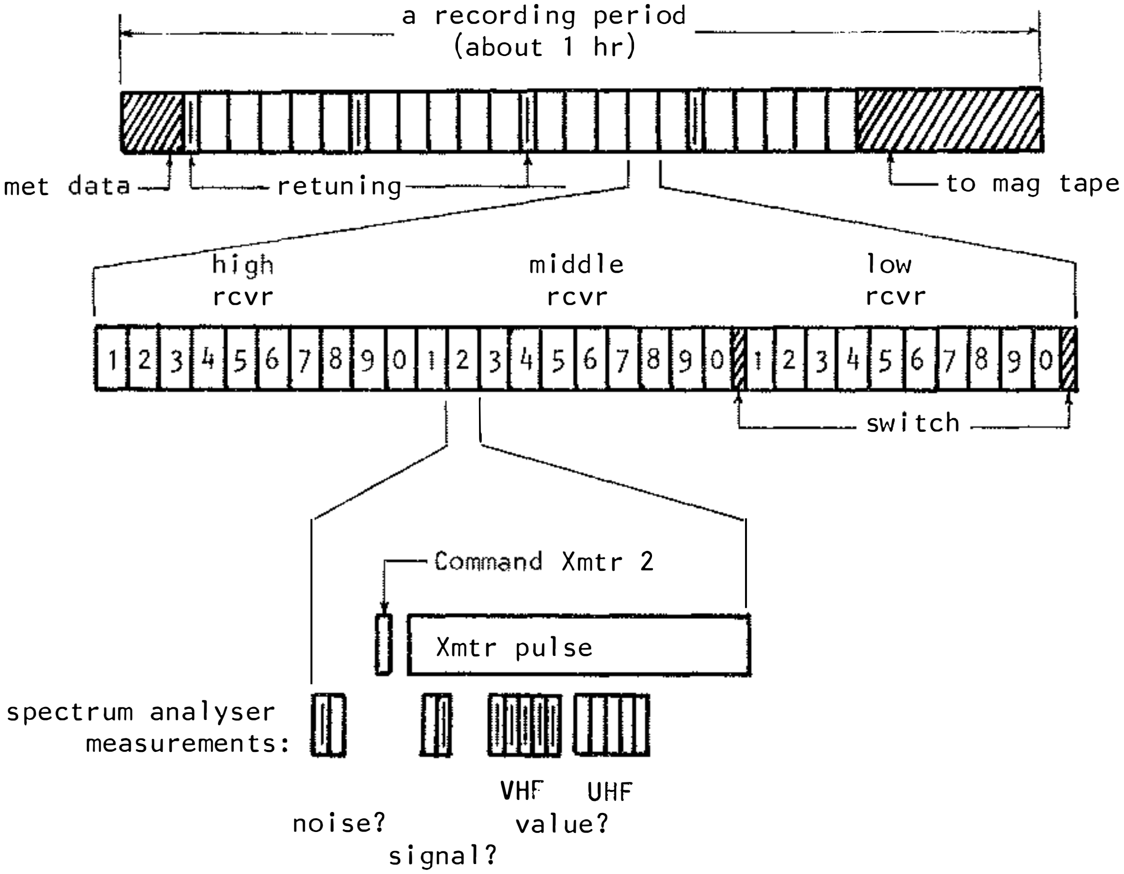

Figure A3. A schematic illustration of APLMS computer operations during a recording period. Time intervals are not to scale.

APPENDIX B. PATH PROFILES AND DATA DISTRIBUTIONS

This appendix contains detailed terrain profiles for all paths over which measurements were made, and cumulative distributions of basic transmission loss at each frequency and receiving antenna height for each path. The figures are grouped, coded, and numbered in sequence for each geographic area. For instance, figures E1 through E10 show terrain profiles for the 40 paths at Eglin AFB, and figures E11 through E30 show cumulative distributions of the data obtained over these paths at each frequency and receiver height. Similarly, figures GM1 through GM13 show terrain profiles for the 50 paths in the Graham Mountain area, and figures GM14 through GM38 show distributions of all data from this area. For the Hunter Liggett area the path profiles are plotted in figures HL1 to HL10, and the corresponding data are shown in figures HL11 to HL30.

Four terrain profiles are shown in each figure. The computer plots show terrain elevation in meters above mean sea level versus distance in kilometers along the measurement path. Figure E1, for example, shows profiles to receiver site R1 from transmitters 1, 2, 3, and 4. These profiles are plotted so that they are all the same length, regardless of actual path lengths of 4.30, 4.32, 3.88, and 4.82 km. The vertical scales are adjusted to retain a constant vertical exaggeration in each set of profiles. The vertical exaggeration is 50 to 1 for the Eglin AFB profiles and 10 to 1 for paths in the Graham Mountain and Hunter Liggett areas. Although these are quite short paths, the plots allow for a radius of curvature which is 1.3 times the actual earth's radius. Only major features of terrain are shown, with no estimates of overburden such as forests, or local obstructions such as isolated trees, rocks, or small hills.

The cumulative distributions of basic transmission loss for Eglin AFB are coded for frequency, VHF(172 MHz) and UHF(410 MHz), and identified by h_1, h_2, and h_3 corresponding to receiving antenna heights of 10, 3, and 0.3 m, respectively. All recorded values are included in these figures, which sometimes show rather erratic behavior as discussed in the report. The data from Graham Mountain receiver sites R1 and R2 and from the Hunter Liggett area are presented separately for the two recording periods. These are coded on each figure, and the VHF and UHF data are presented separately to avoid confusion between the 12 cumulative distributions plotted for each path.

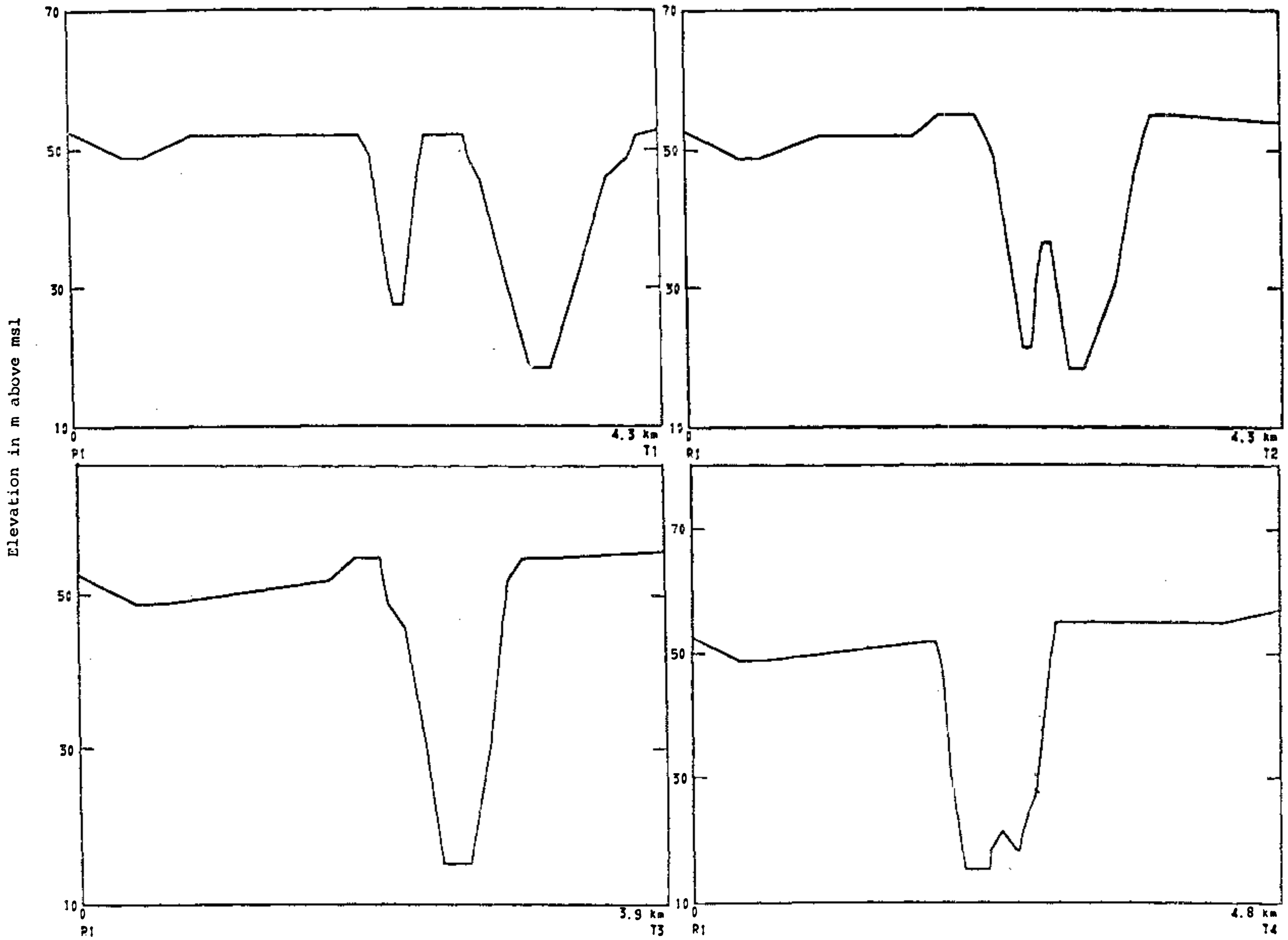

Figure E1. Terrain profiles from transmitter sites T1, T2, T3, and T4 to receiver site R1, Eglin AFB.

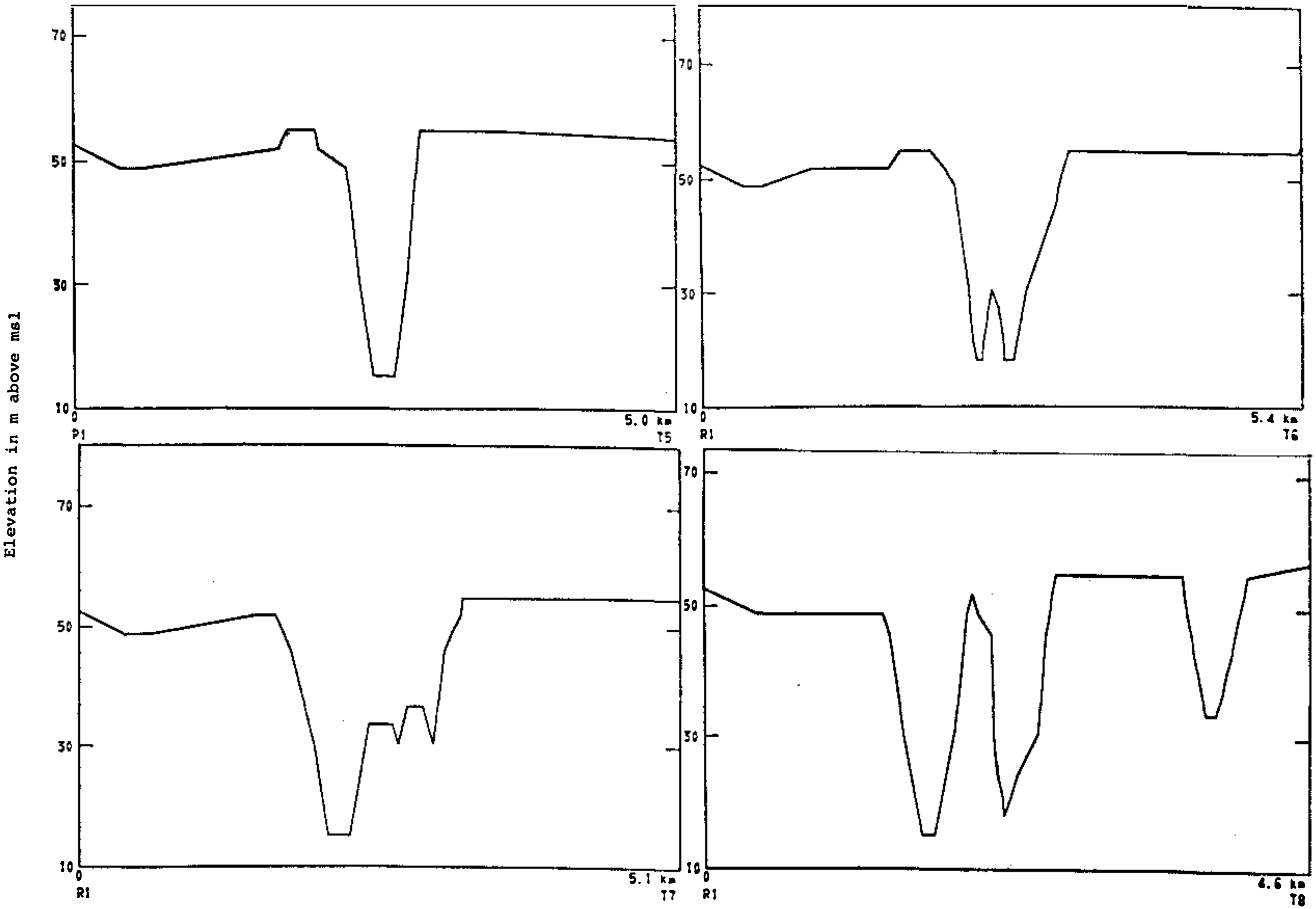

Figure E2. Terrain profiles from transmitter sites T5, T6, T7, and T8 to receiver site R1, Eglin AFB.

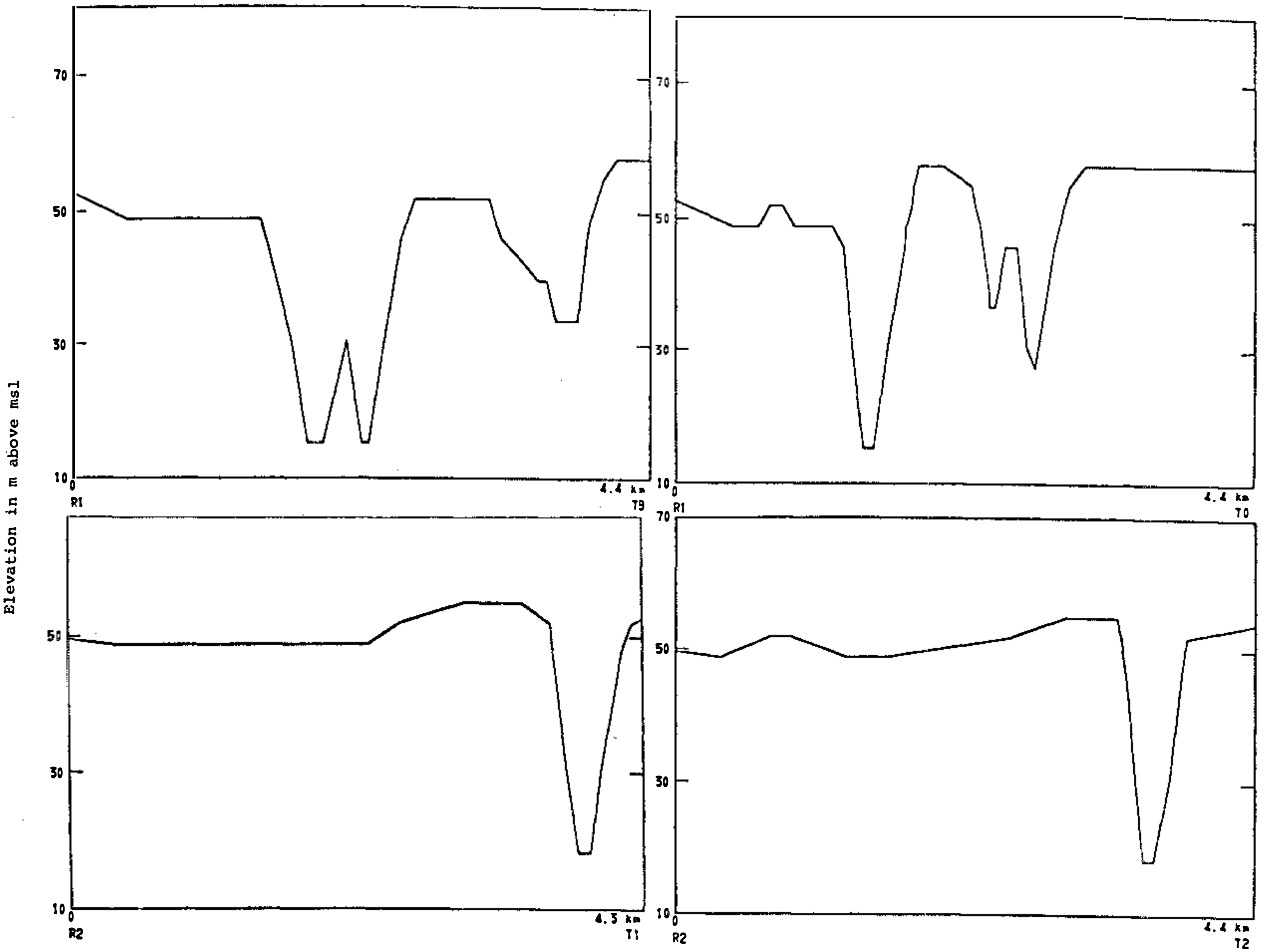

Figure E3. Terrain profiles from T9 and T10 to R1, and from T1 and T2 to R2, Eglin AFB.

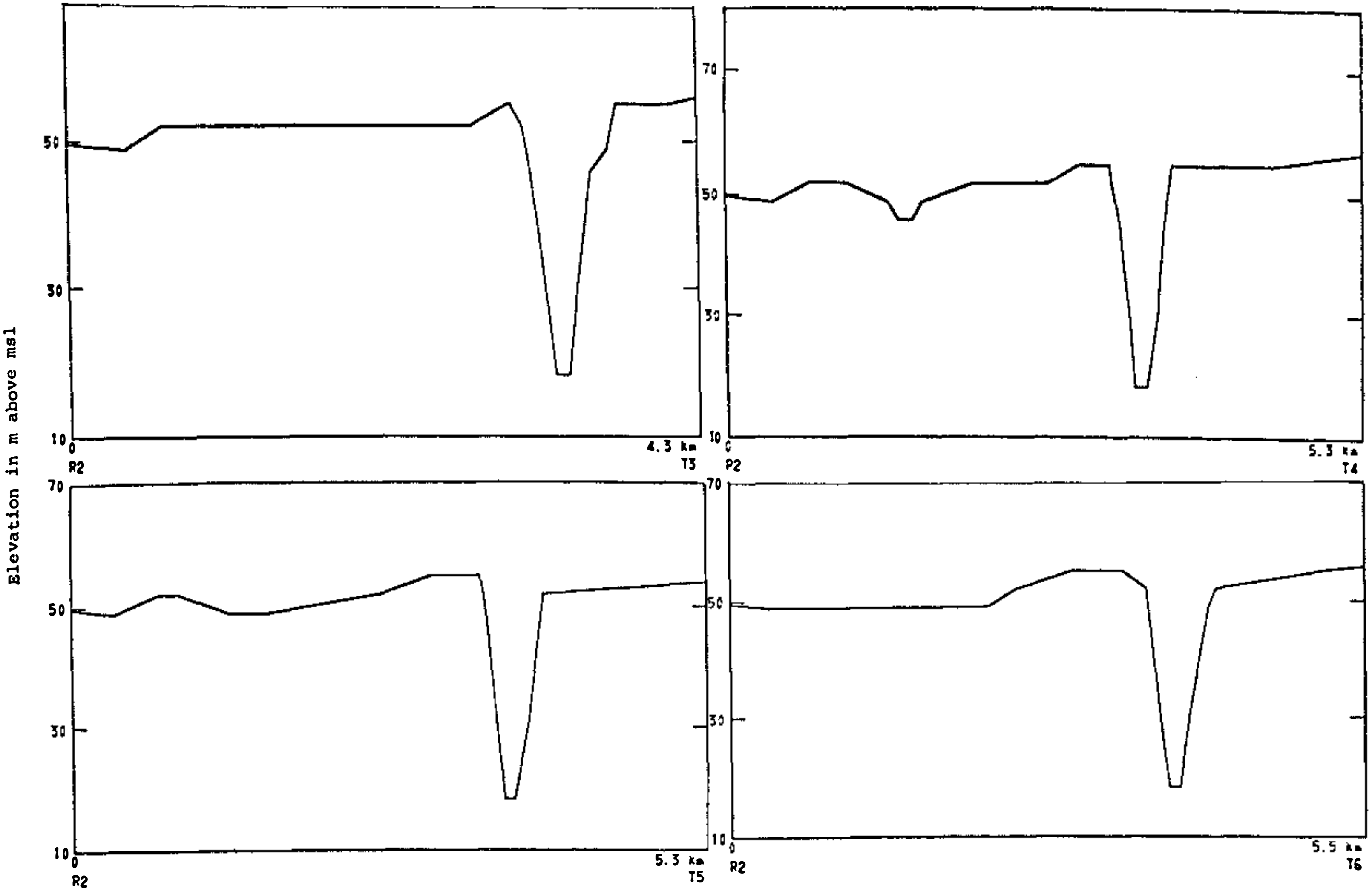

Figure E4. Terrain profiles from transmitter sites T3, T4, T5, and T6 to receiver site R2, Eglin AFB.

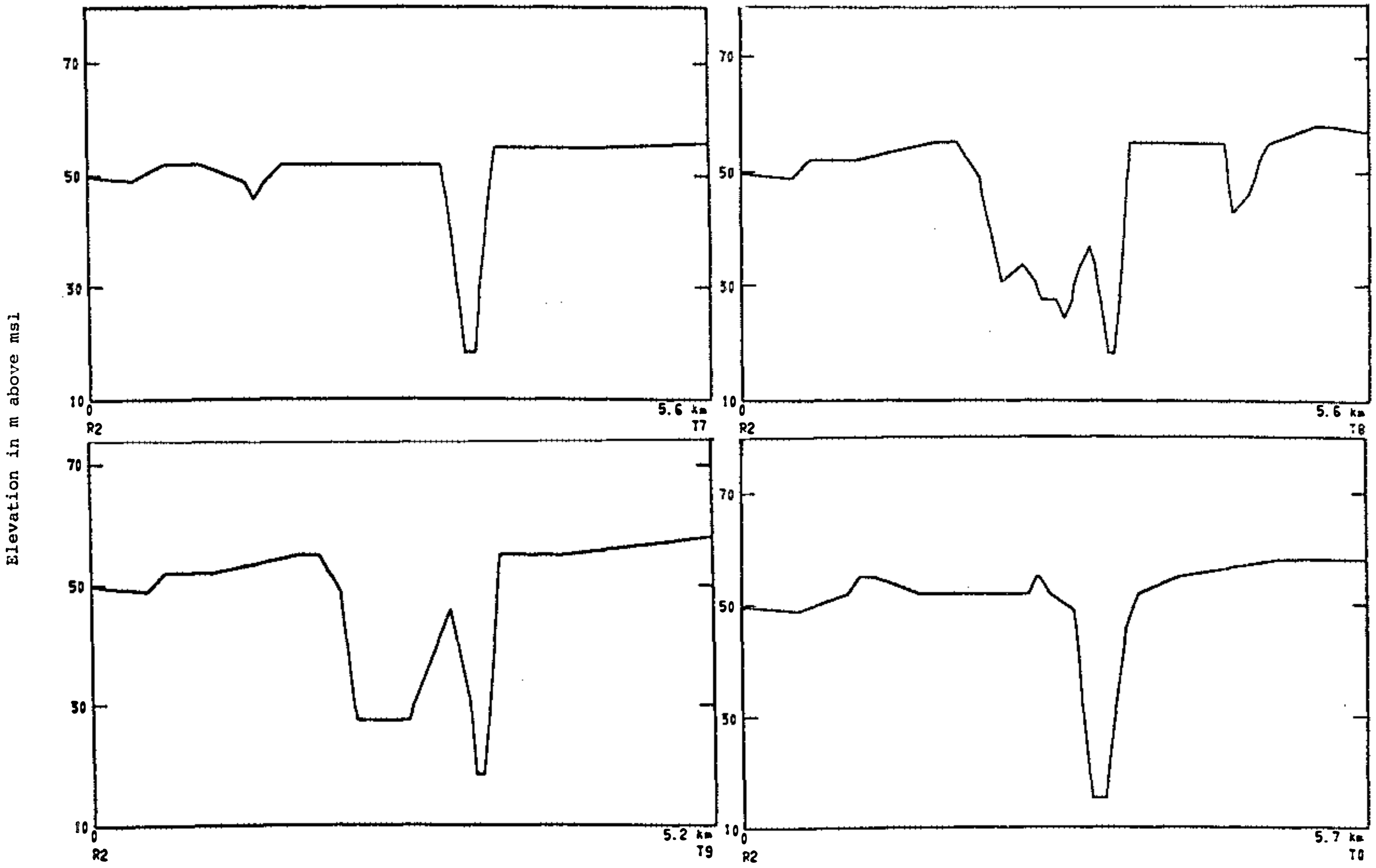

Figure E5. Terrain profiles from transmitter sites T7, T8, T9, and T10 to receiver site R2, Eglin AFB.

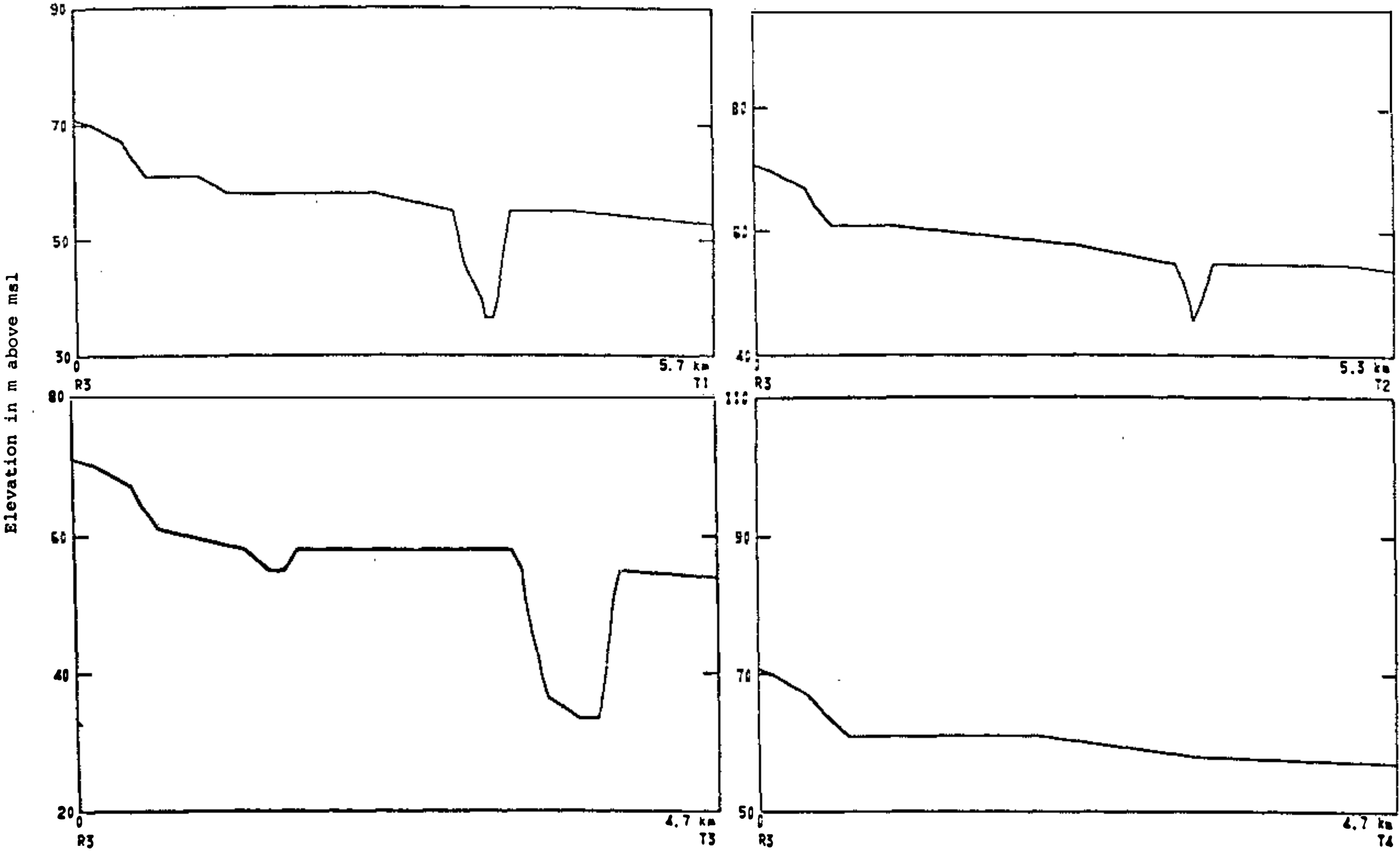

Figure E6. Terrain profiles from transmitter sites T1, T2, T3, and T4 to receiver site R3, Eglin AFB.

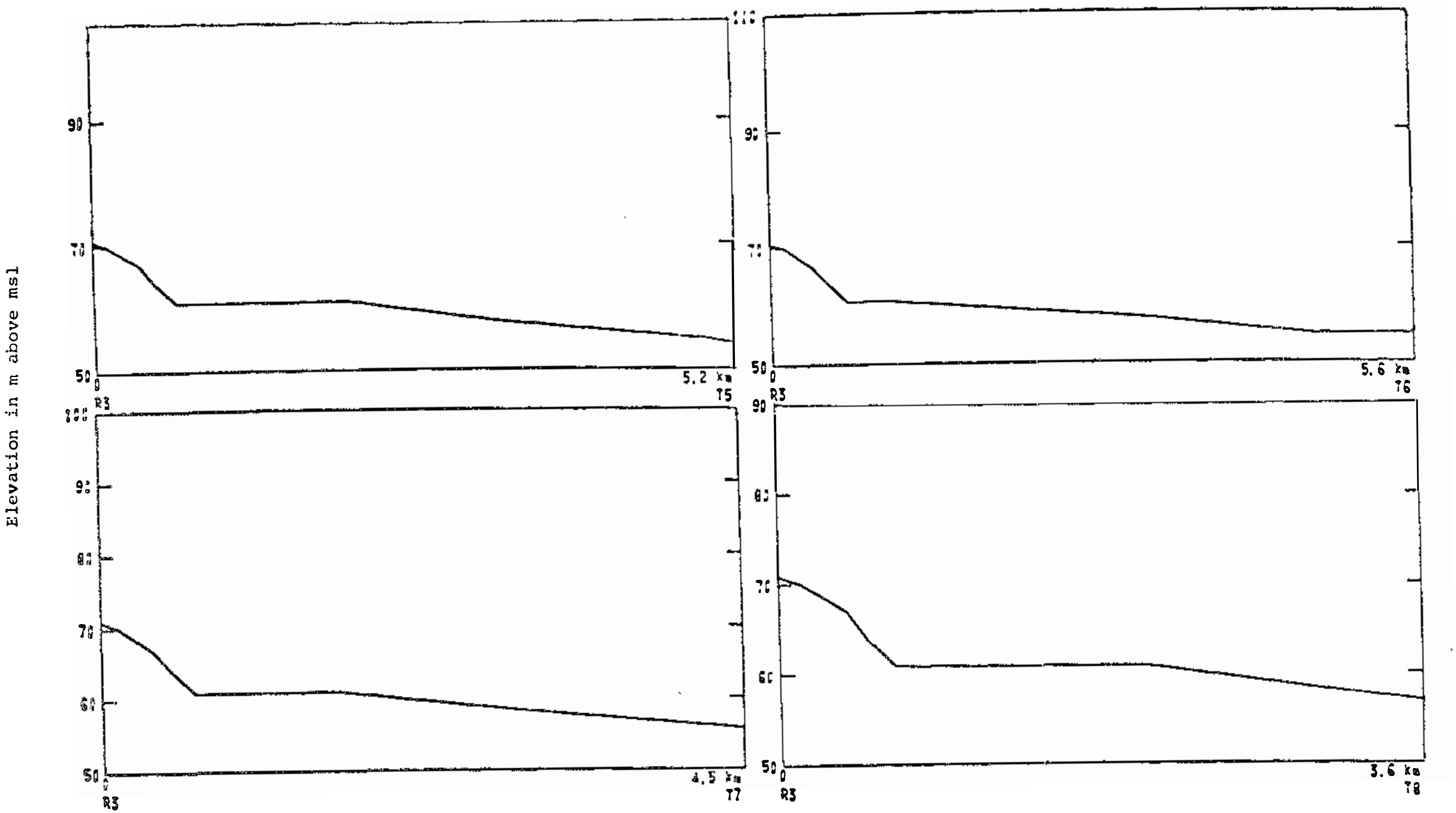

Figure E7. Terrain profiles from transmitter sites T5, T6, T7, and T8 to receiver site R3, Eglin AFB.

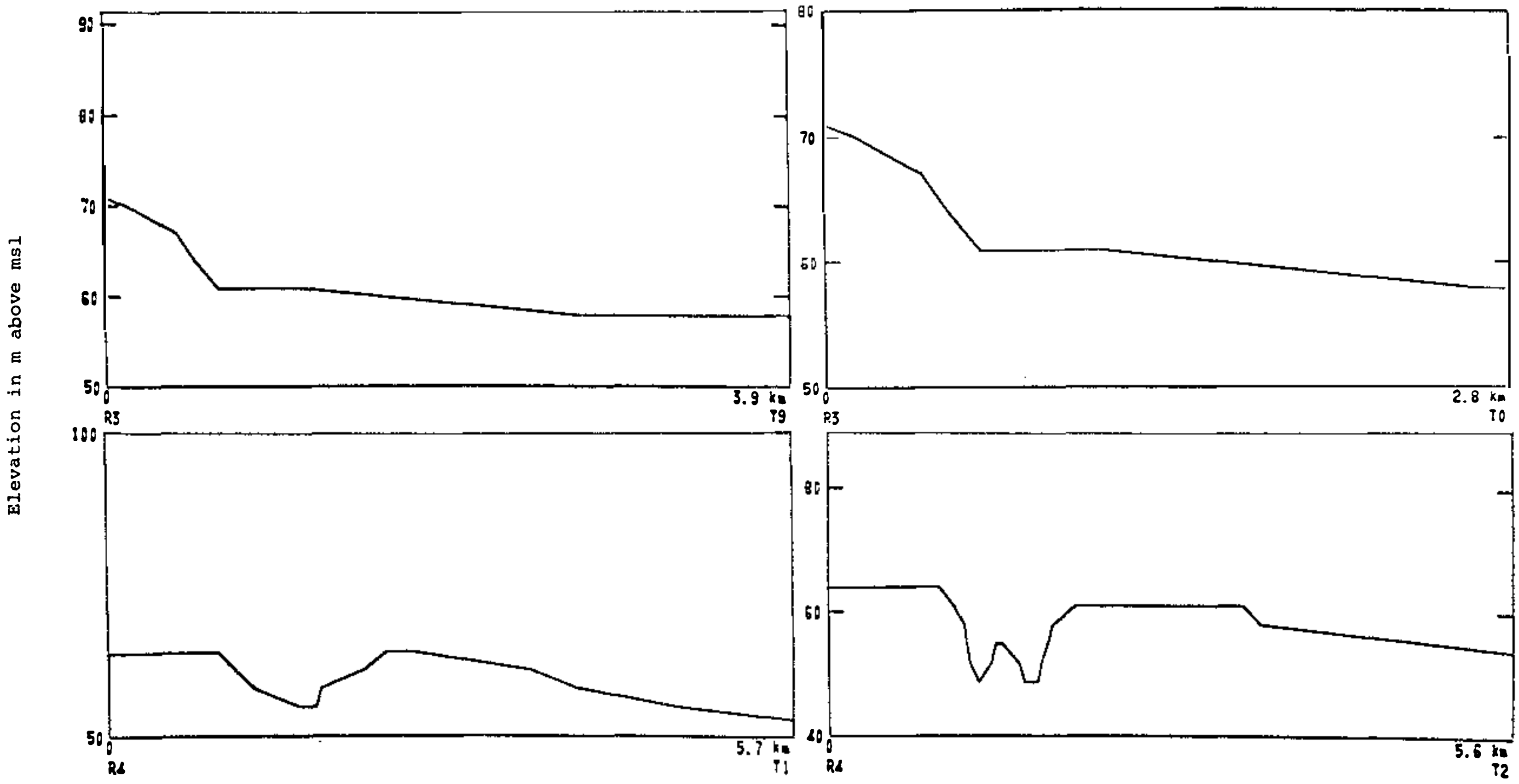

Figure E8. Terrain profiles from T9 and T10 to R3, and from T1 and T2 to R4, Eglin AFB.

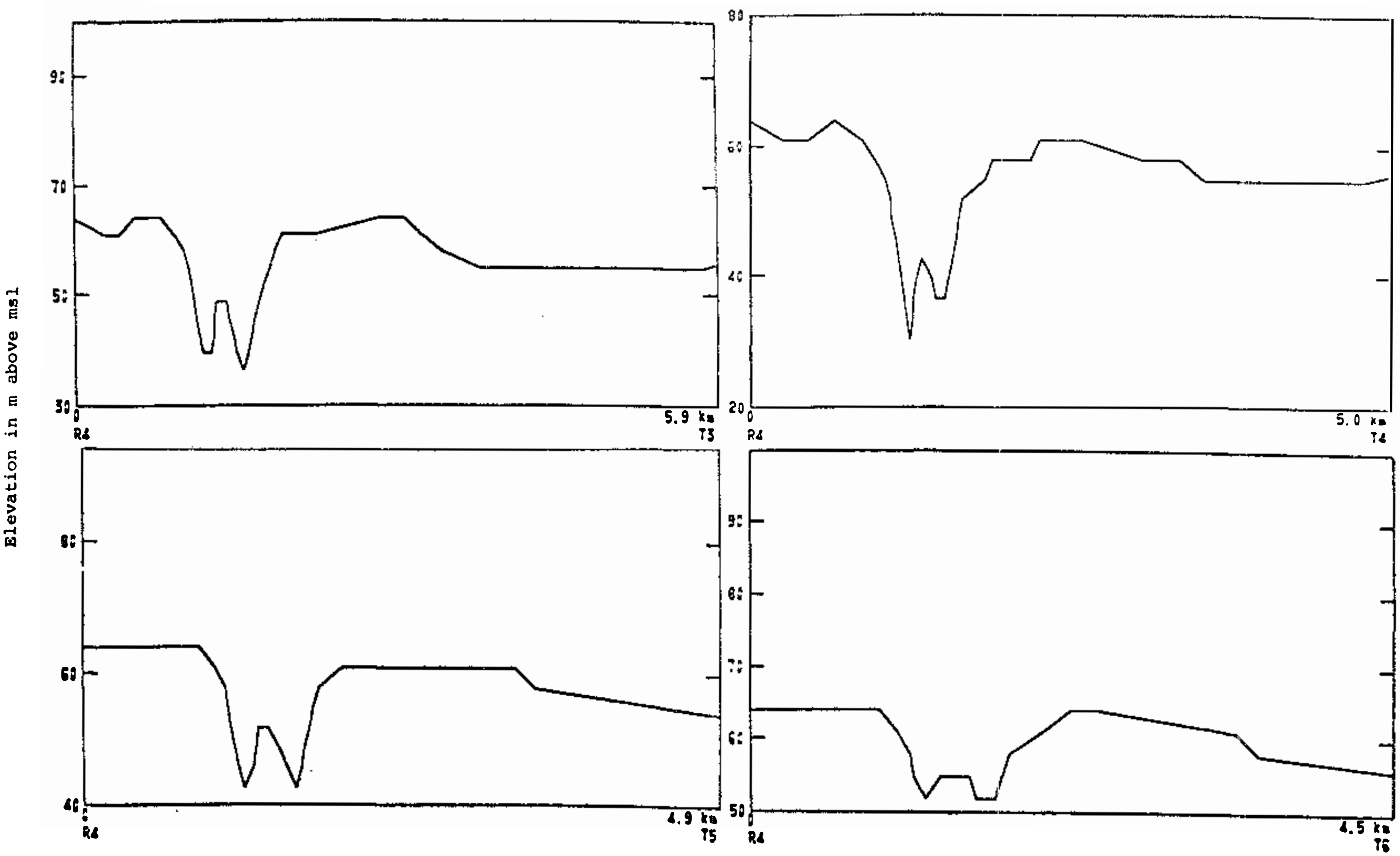

Figure E9. Terrain profiles from transmitter sites T3, T4, T5, and T6 to receiver R4, Eglin AFB.

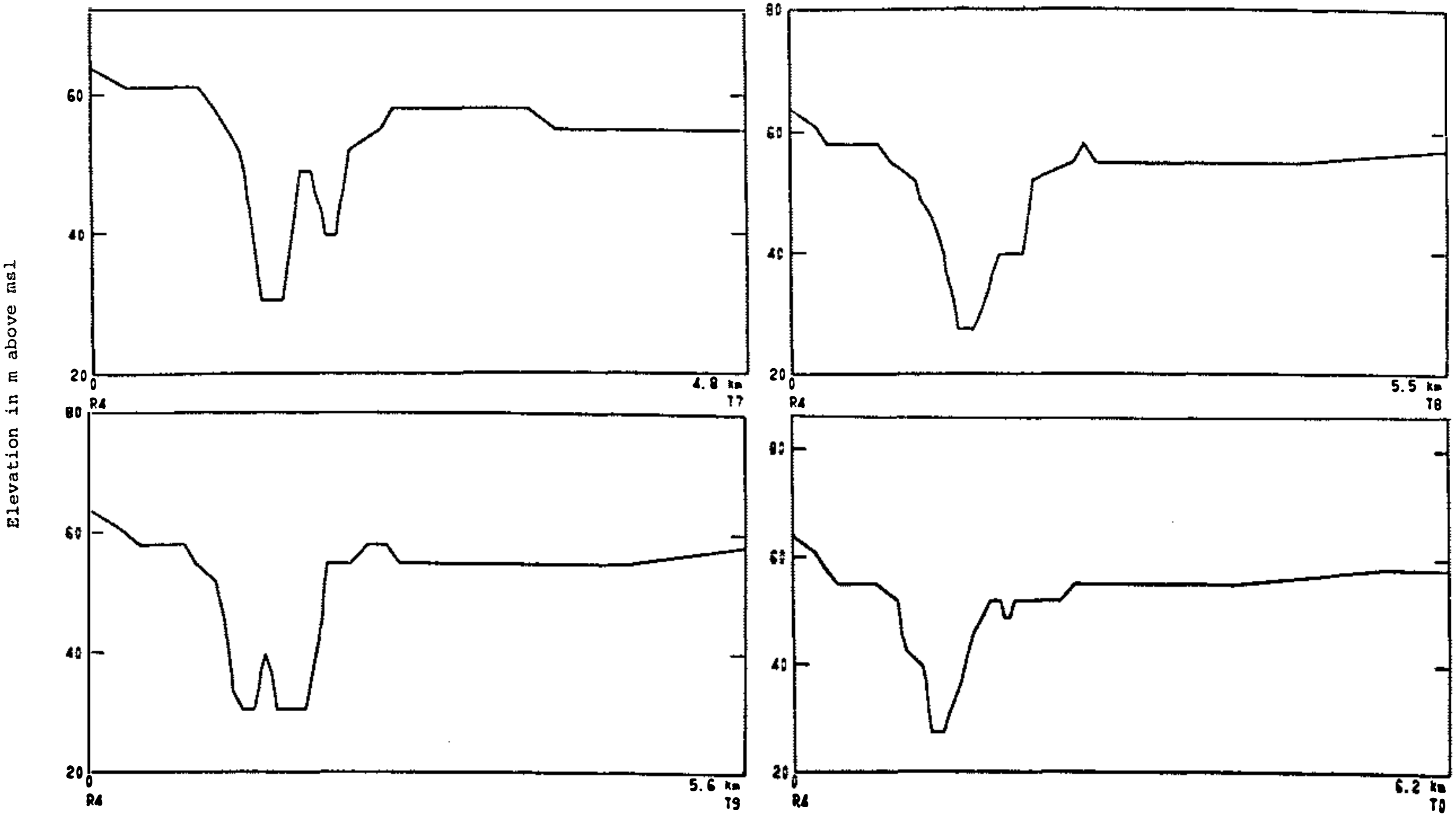

Figure E10. Terrain profiles from transmitter sites T7, T8, T9, and T10 to receiver site R4, Eglin AFB.

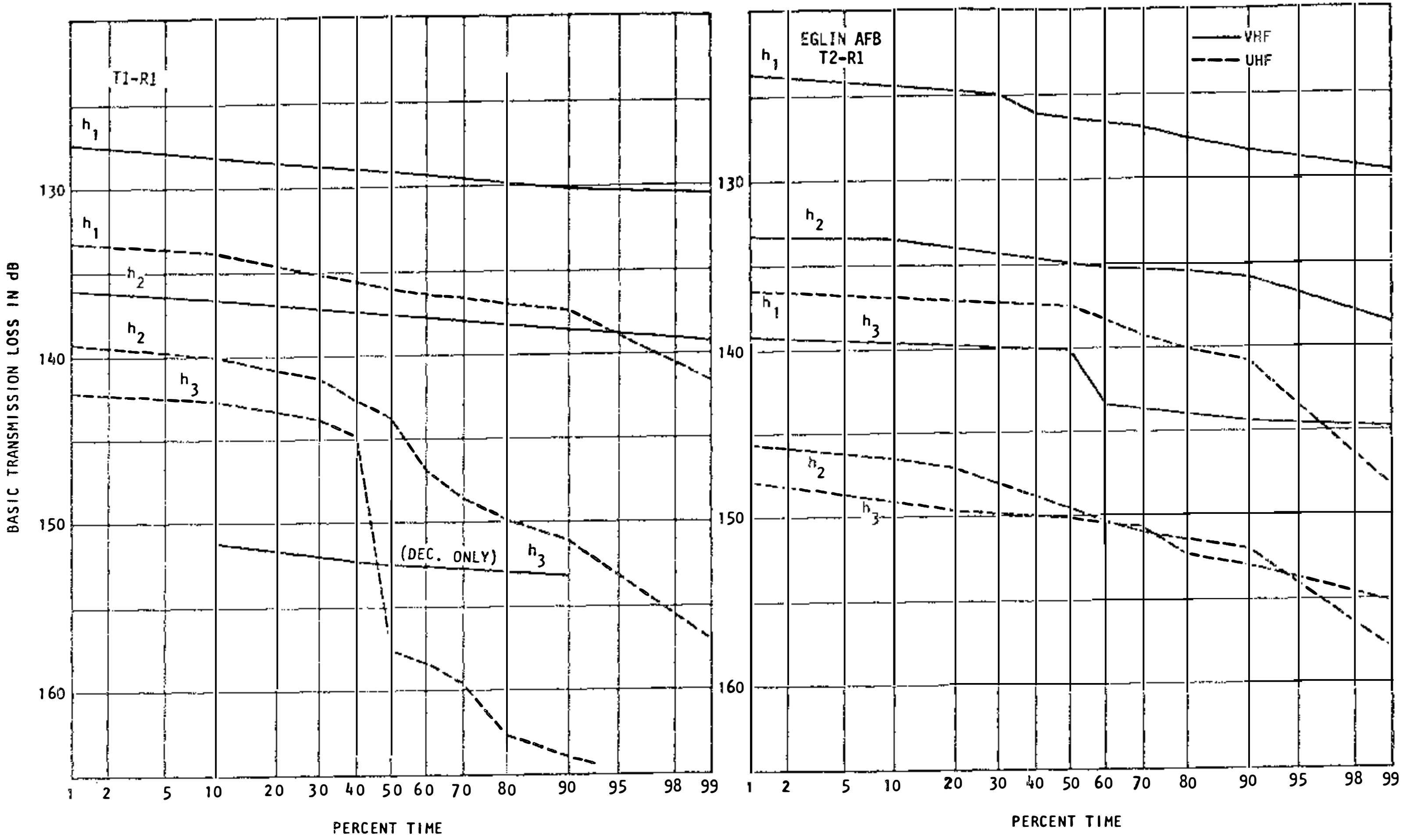

Figure E11. Cumulative distributions of basic transmission loss recorded over paths T1-R1, and T2-R1, Eglin AFB.

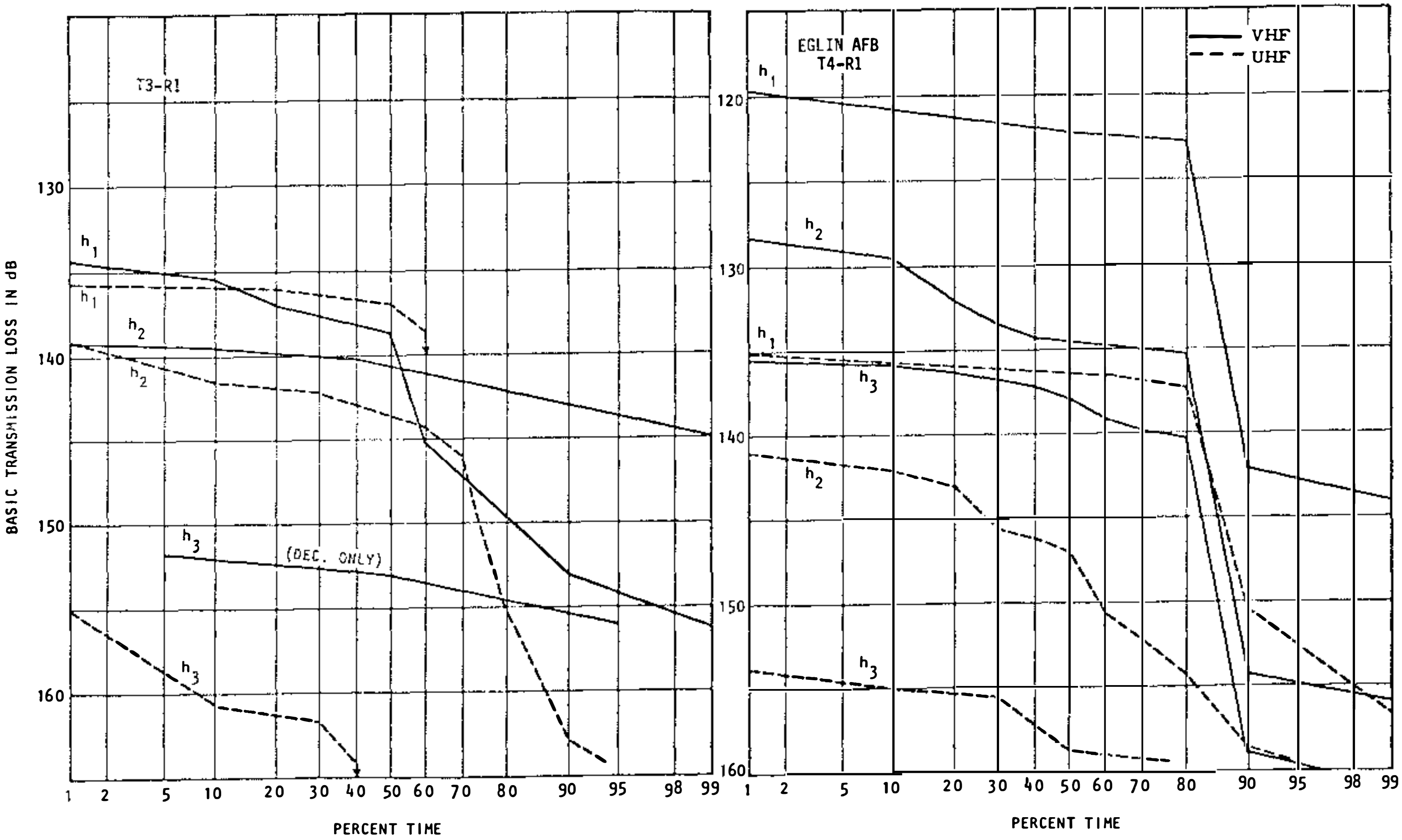

Figure E12. Cumulative distributions of basic transmission loss recorded over paths T3-R1, and T4-R1, Eglin AFB.

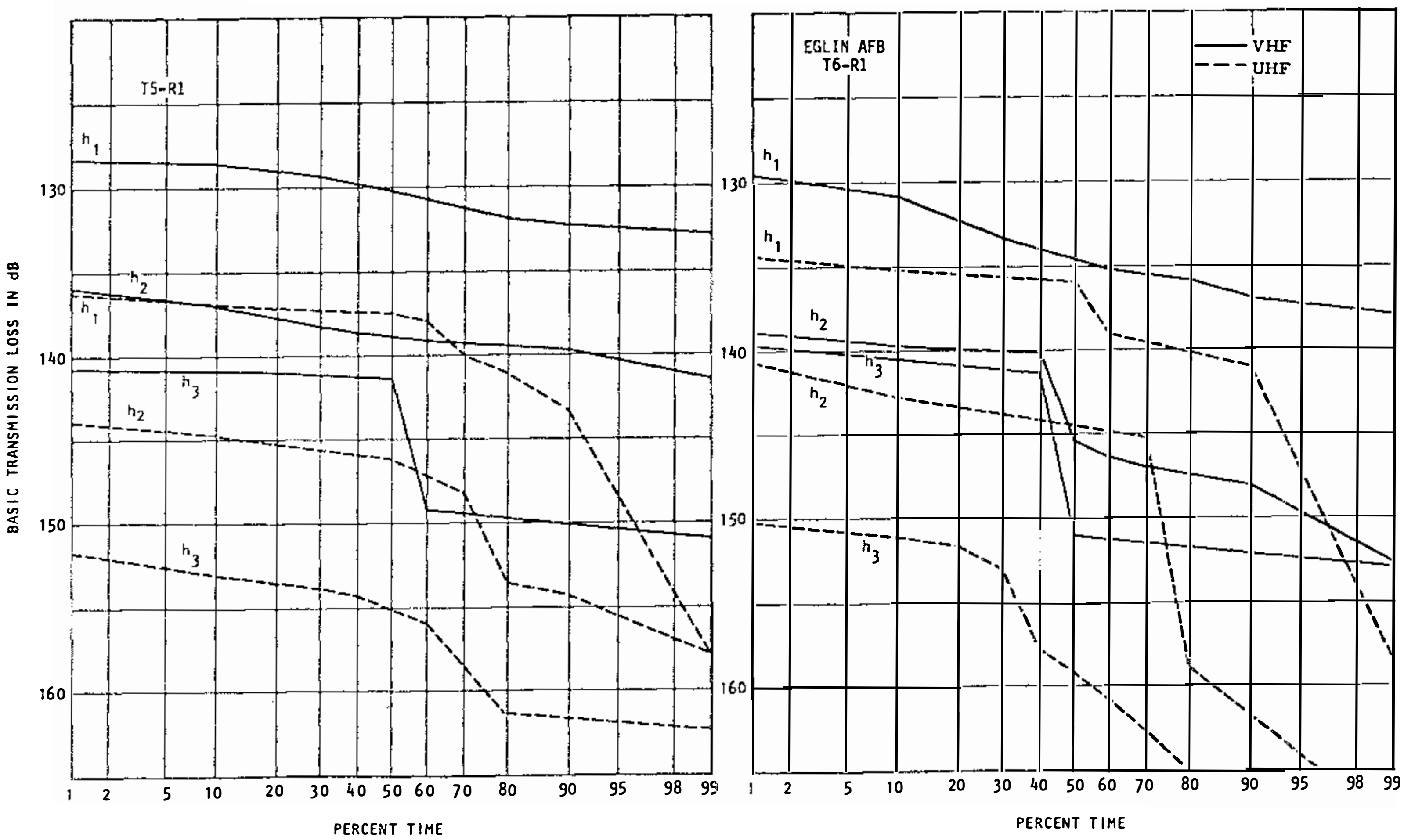

Figure E13. Cumulative distributions of basic transmission loss recorded over paths T5-R1, and T6-R1, Eglin AFB.

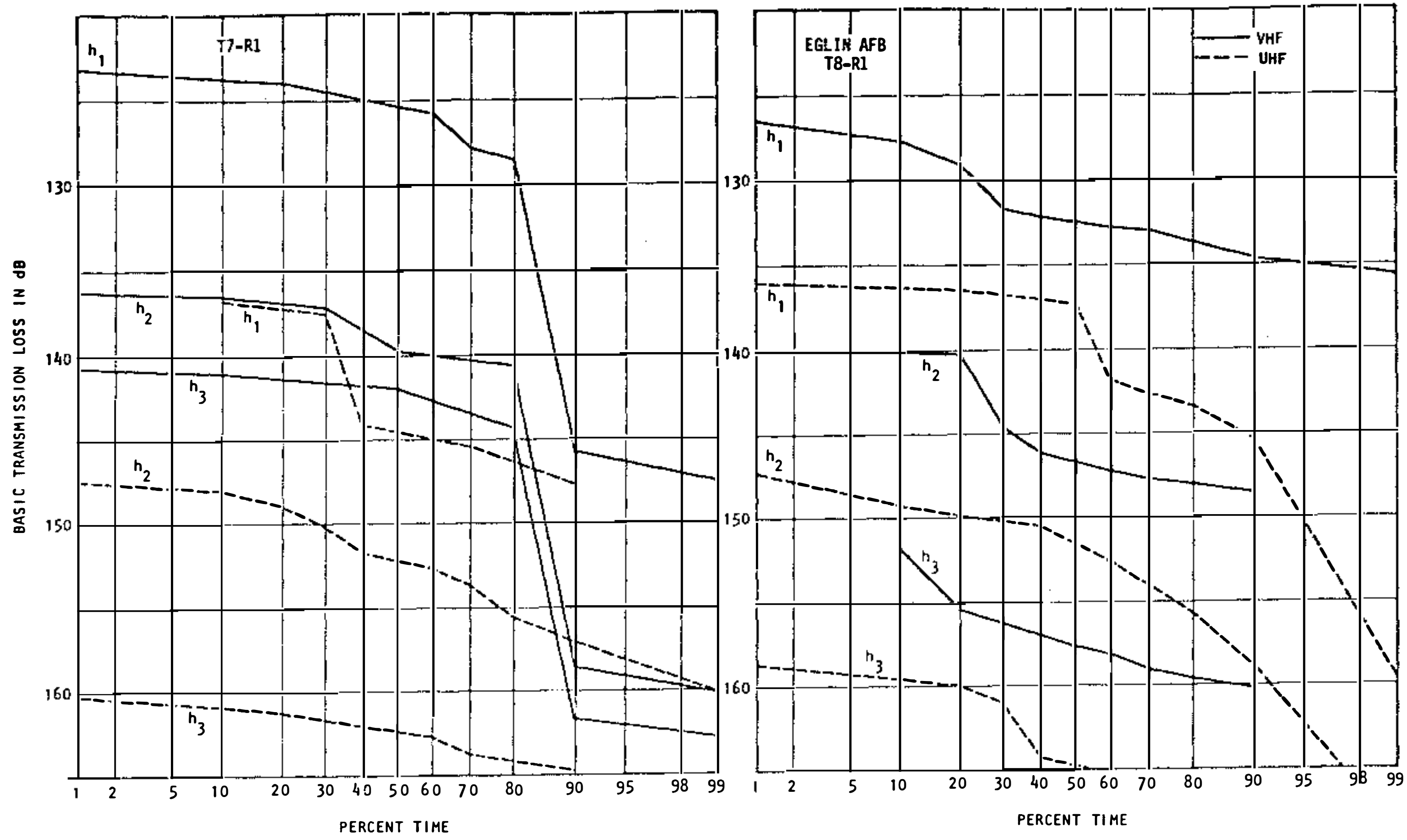

Figure E14. Cumulative distributions of basic transmission loss recorded over paths T7-R1, and T8-R1, Eglin AFB.

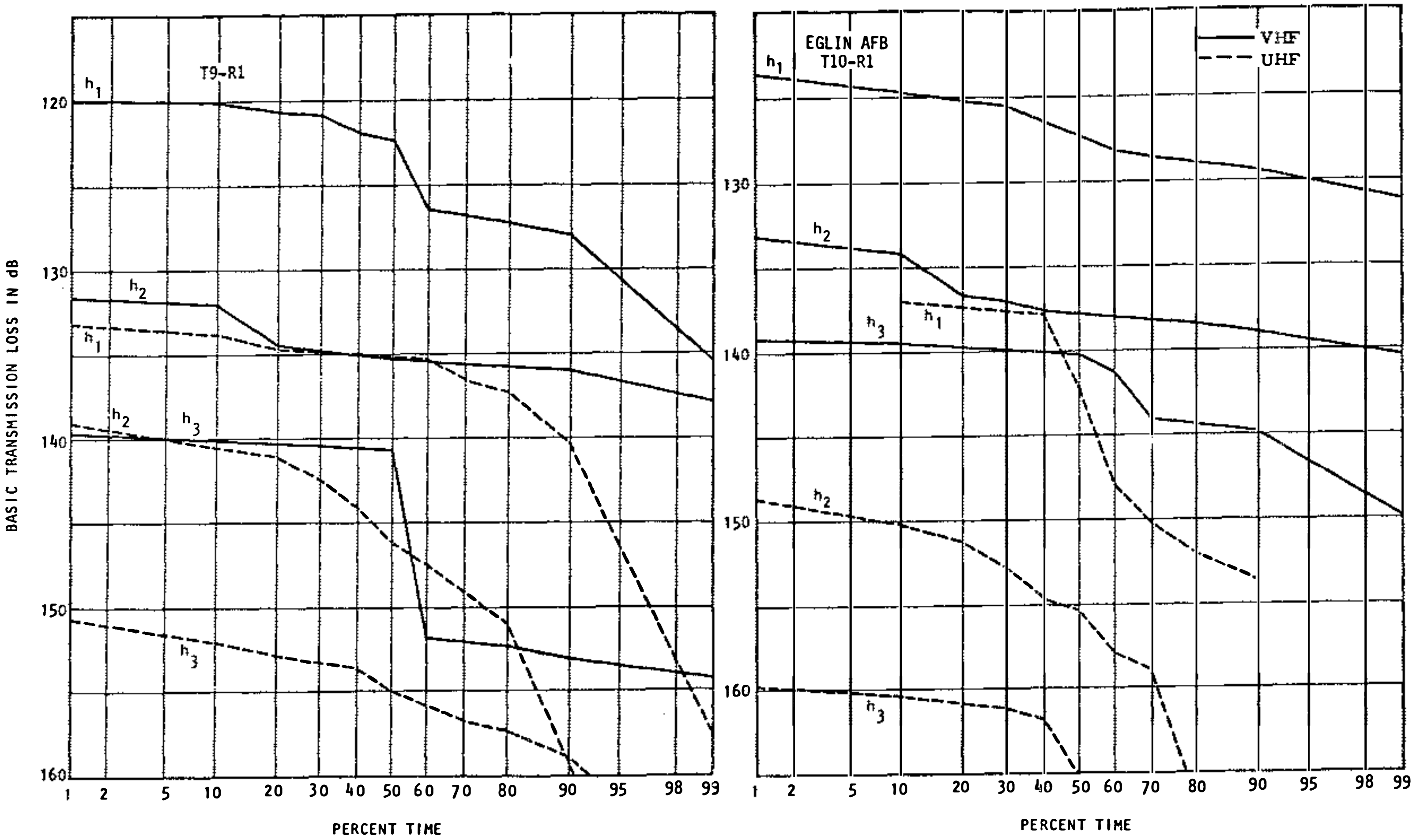

Figure E15. Cumulative distributions of basic transmission loss recorded over paths T9-R1, and T10-R1, Eglin AFB.

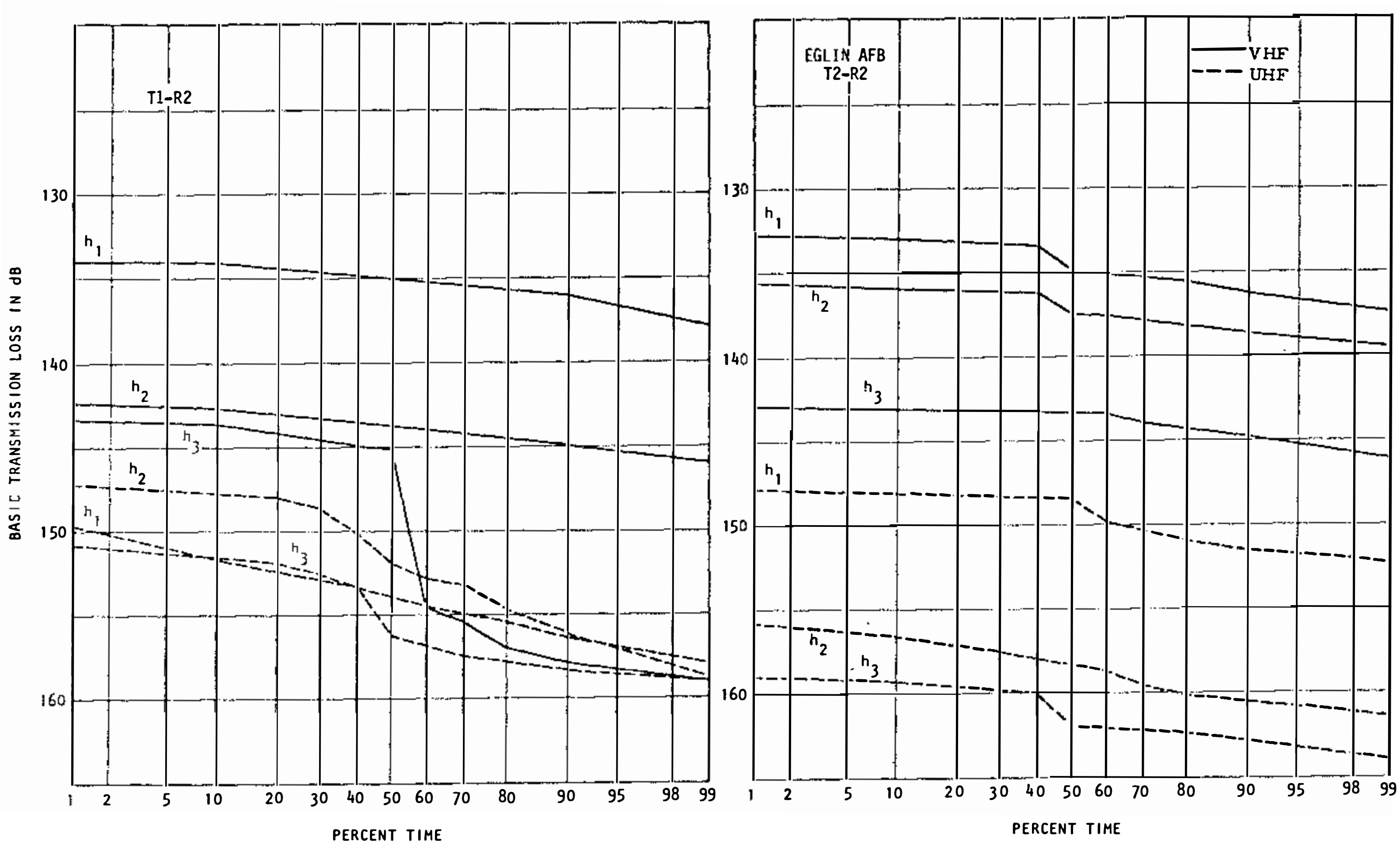

Figure E16. Cumulative distributions of basic transmission loss recorded over paths T1-R2, and T2-R2, Eglin AFB.

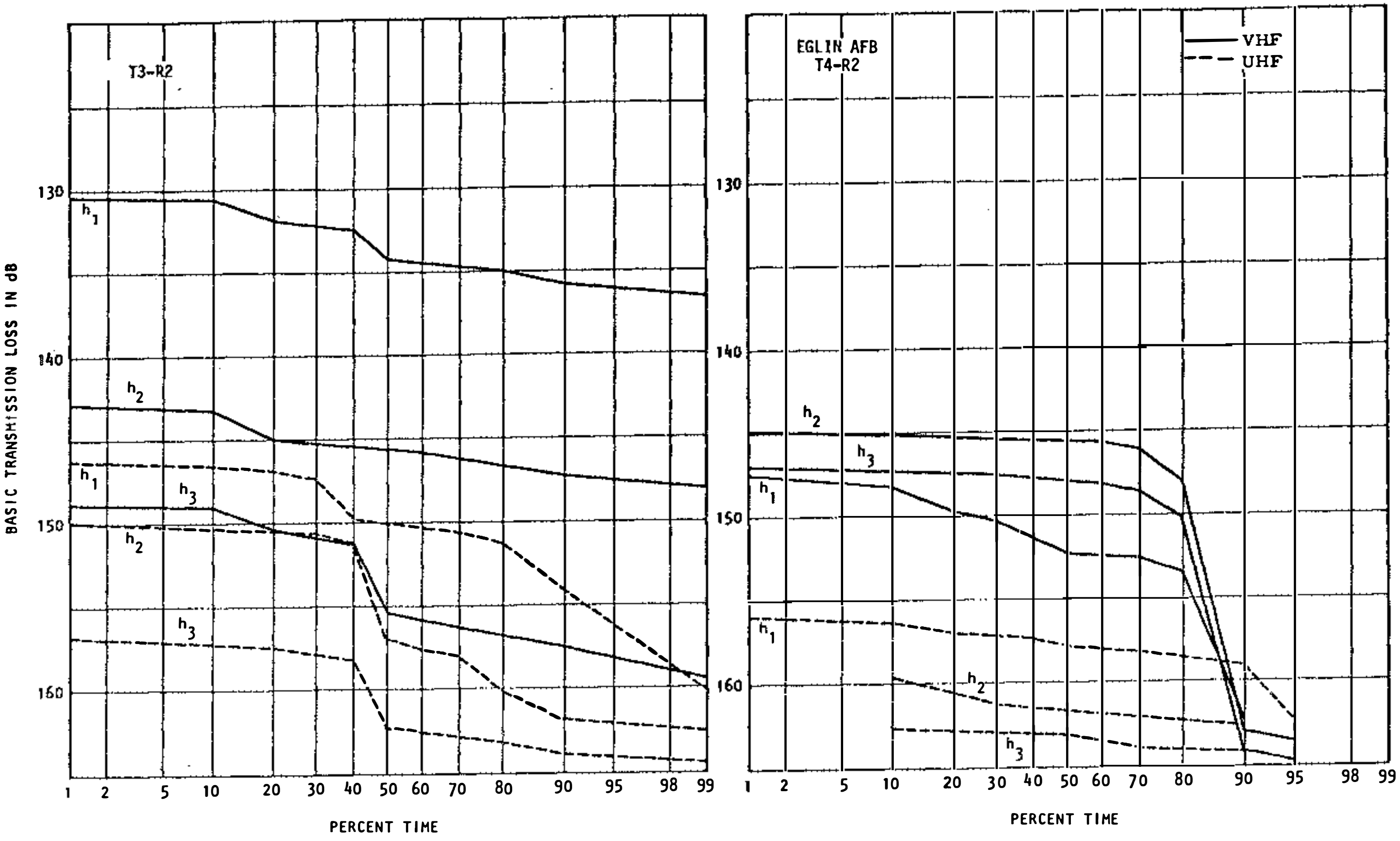

Figure E17. Cumulative distributions of basic transmission loss recorded over paths T3-R2, and T4-R2, Eglin AFB.

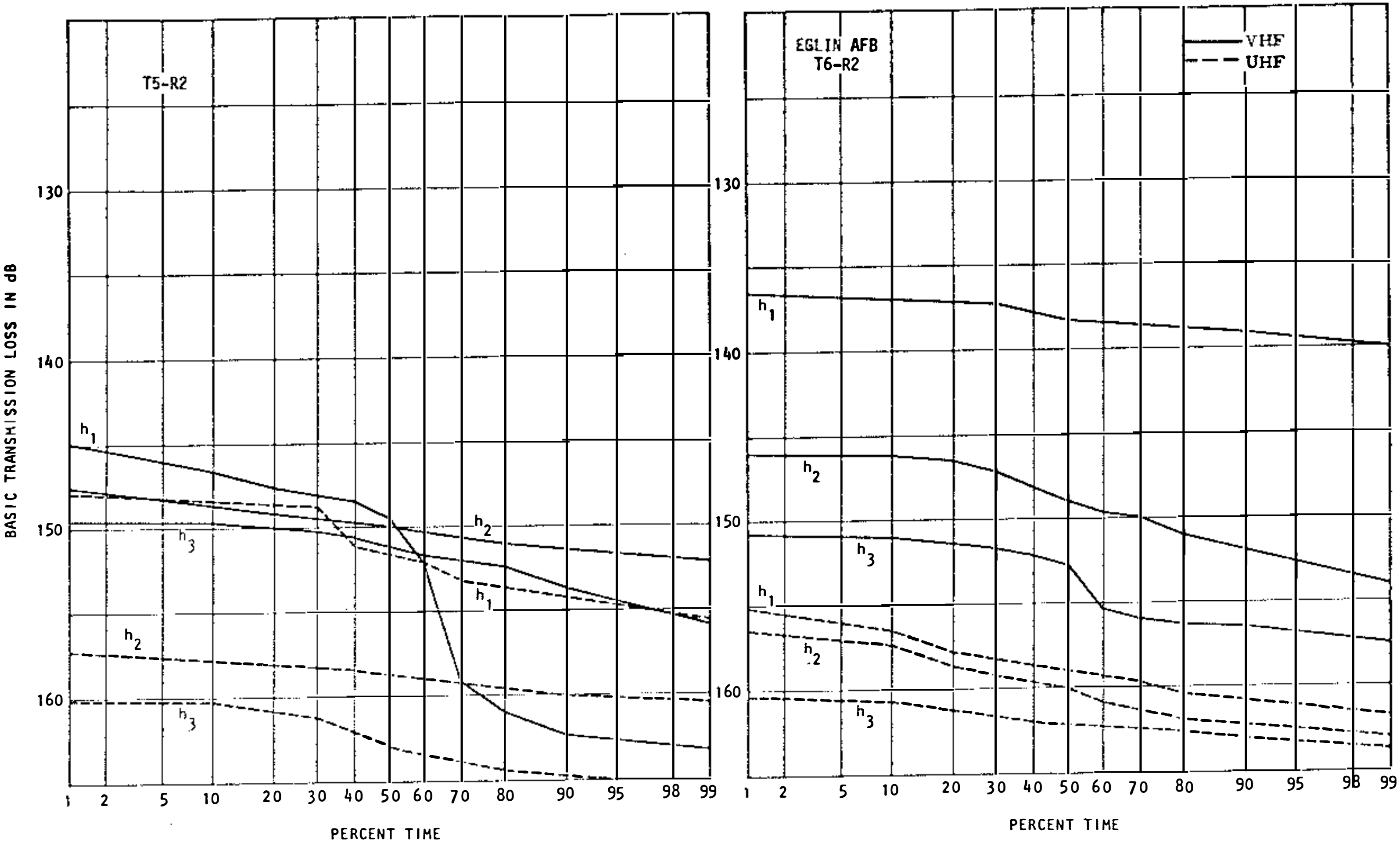

Figure E18. Cumulative distributions of basic transmission loss recorded over paths T5-R2, and T6-R2, Eglin AFB.

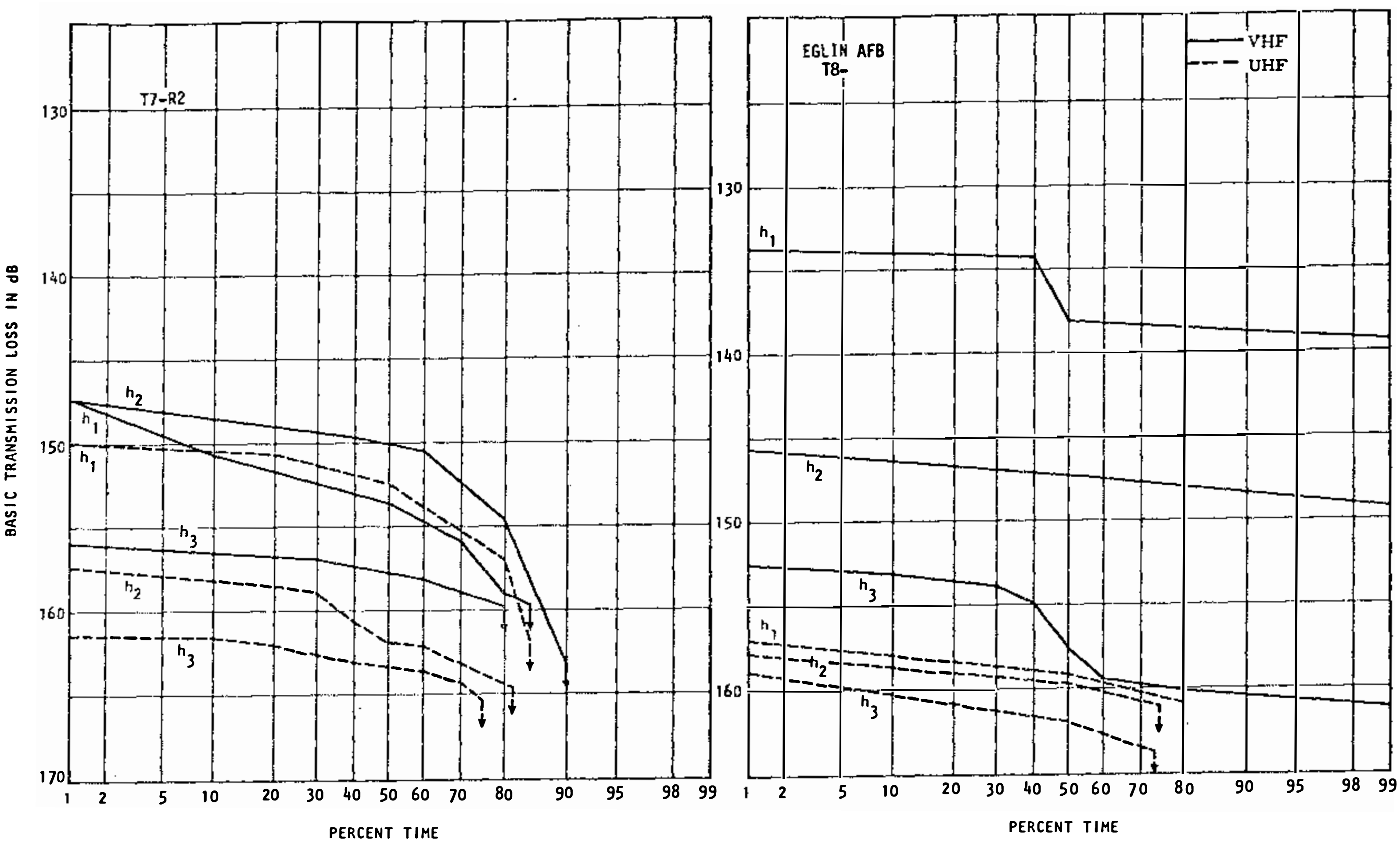

Figure E19. Cumulative distributions of basic transmission loss recorded over paths T7-R2, and T8-R2, Eglin AFB.

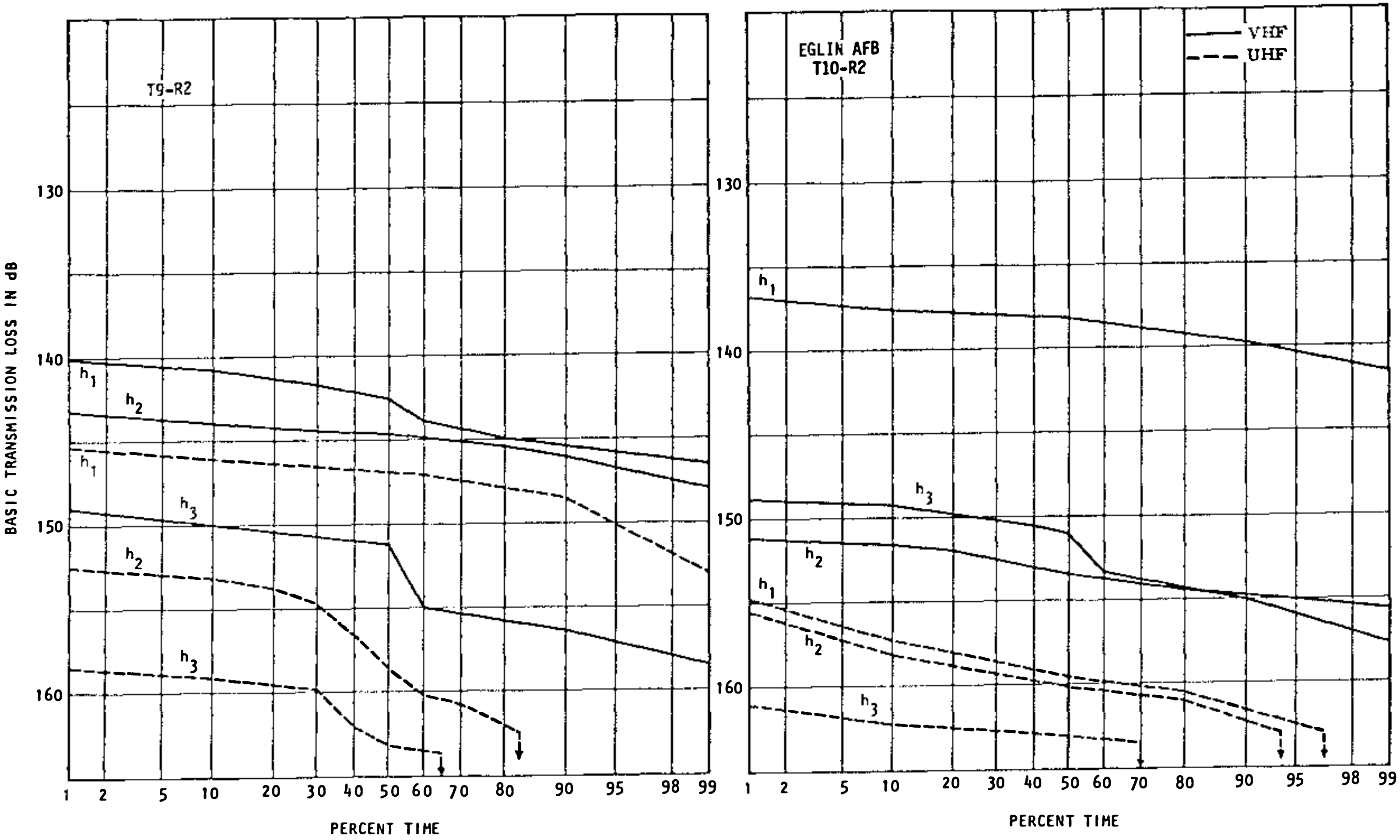

Figure E20. Cumulative distributions of basic transmission loss recorded over paths T9-R2, and T10-R2, Eglin AFB.

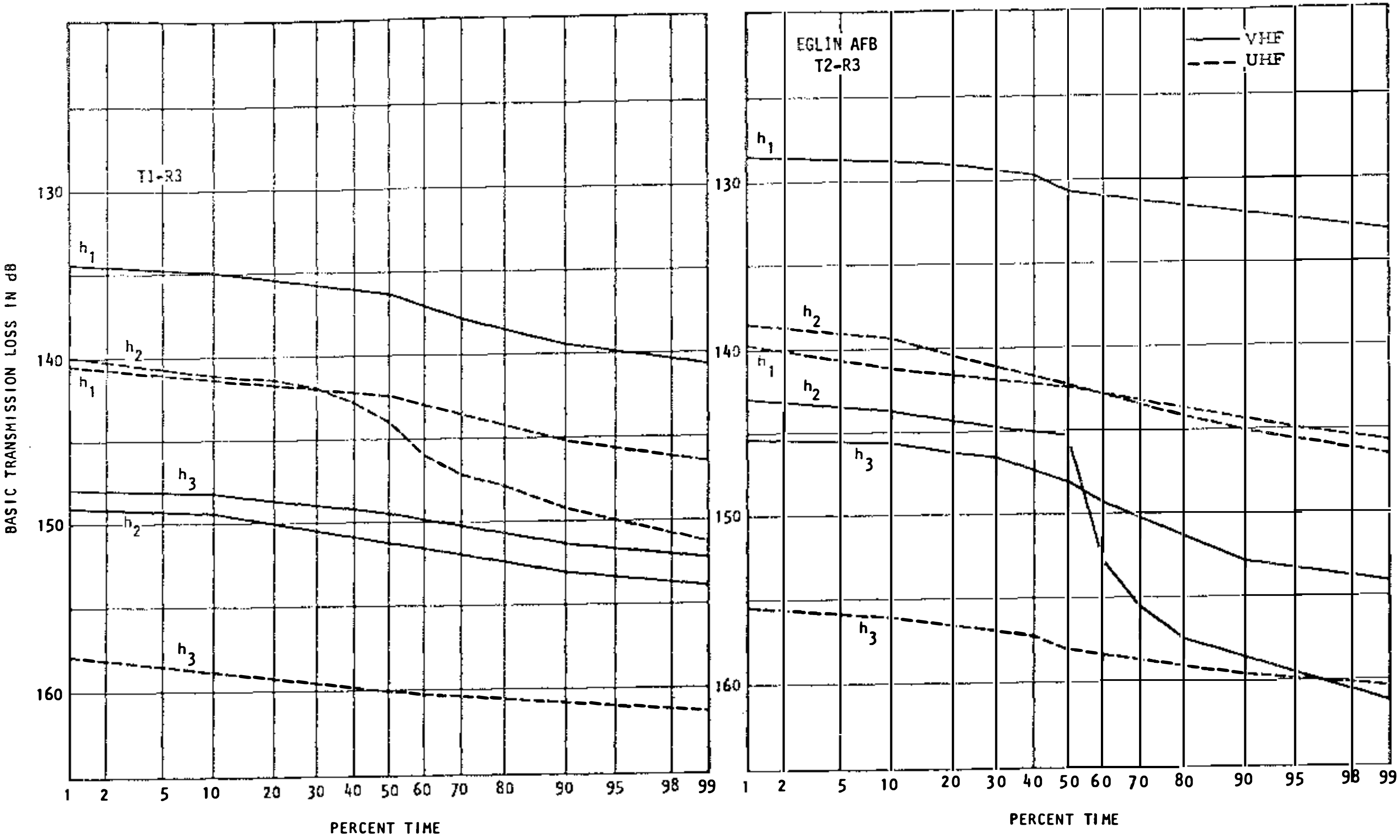

Figure E21. Cumulative distributions of basic transmission loss recorded over paths T1-R3, and T2-R3, Eglin AFB.

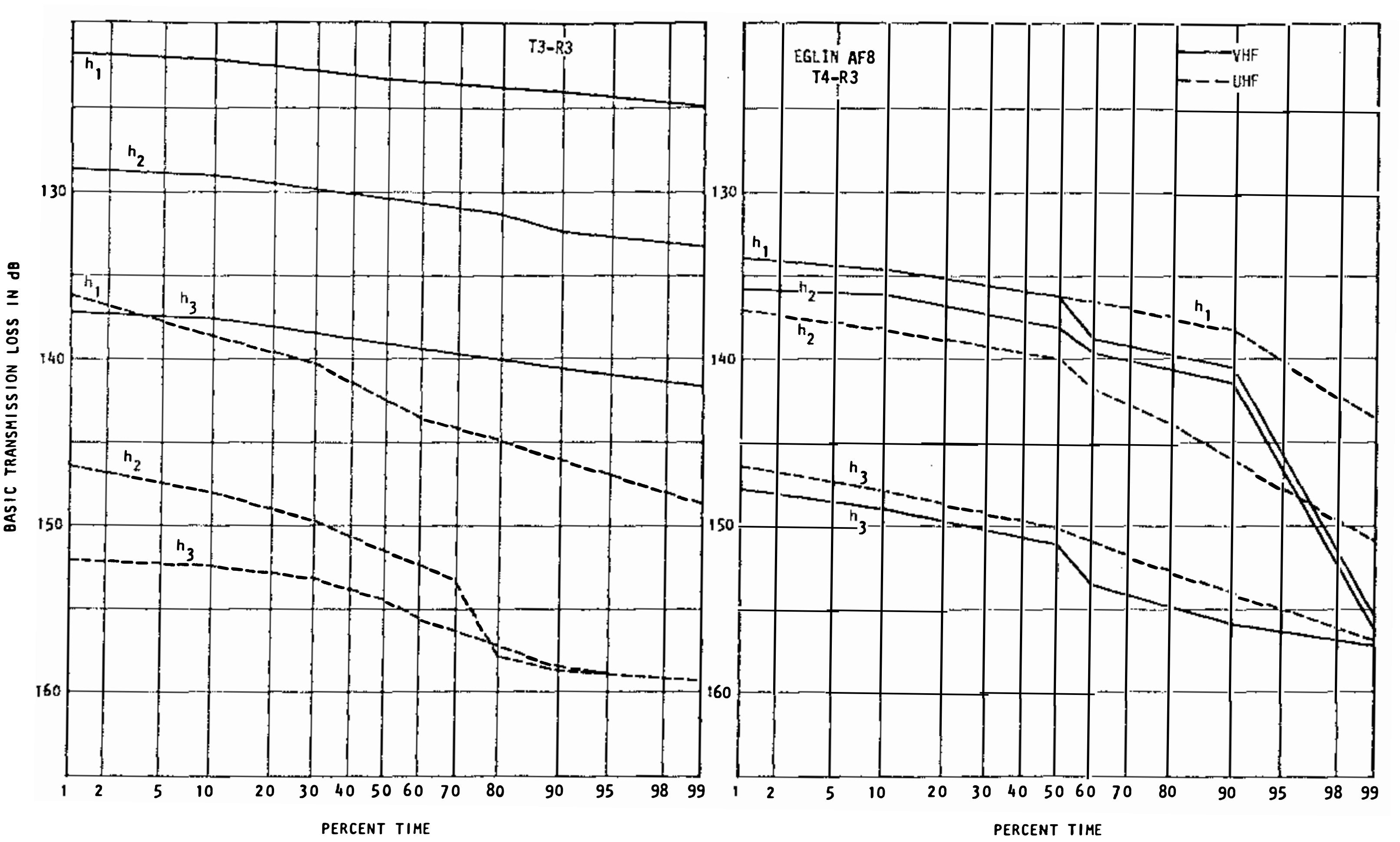

Figure E22. Cumulative distributions of basic transmission loss recorded over paths T3-R3, and T4-R3, Eglin AFB.

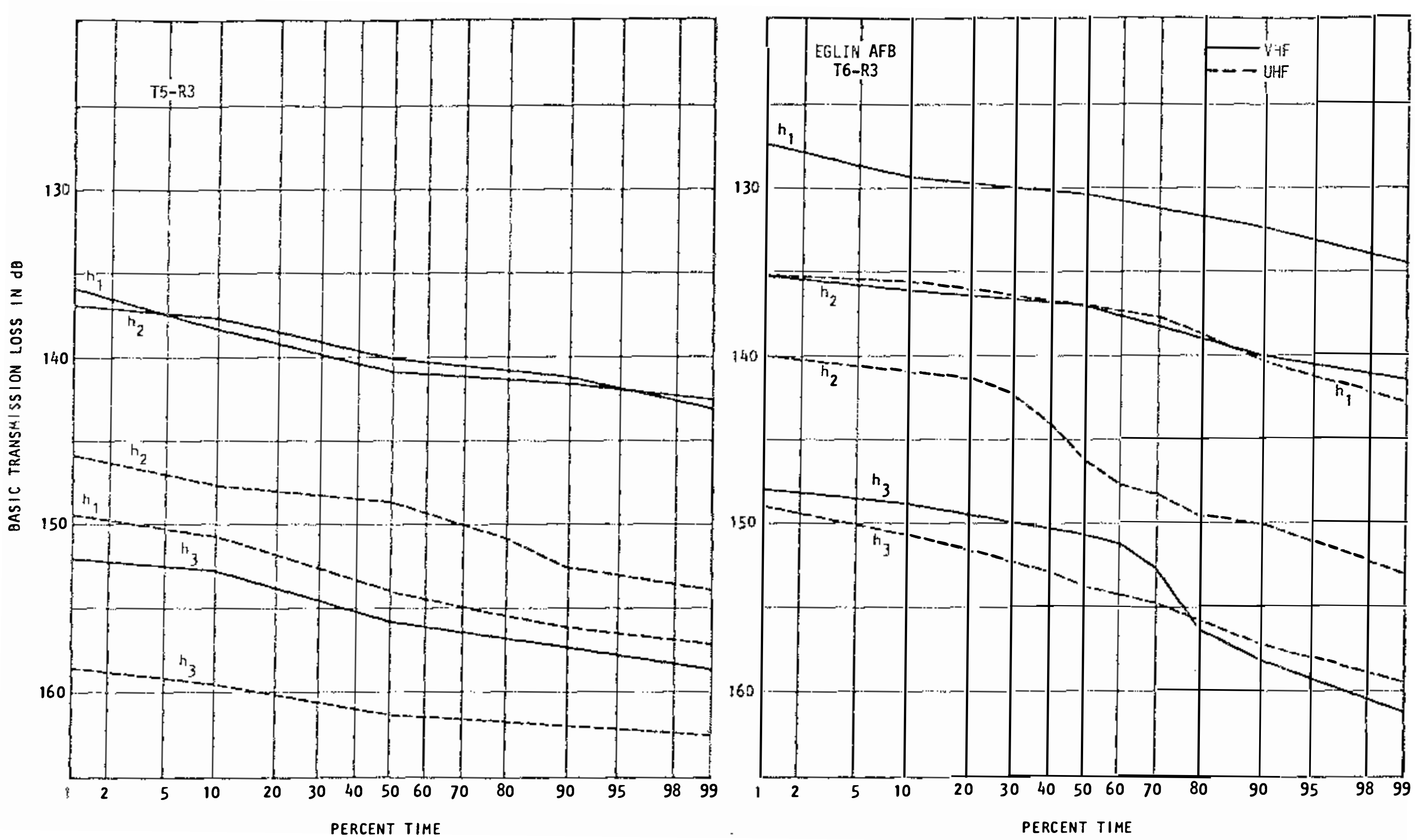

Figure E23. Cumulative distributions of basic transmission loss recorded over paths T5-R3, and T6-R3, Eglin AFB.

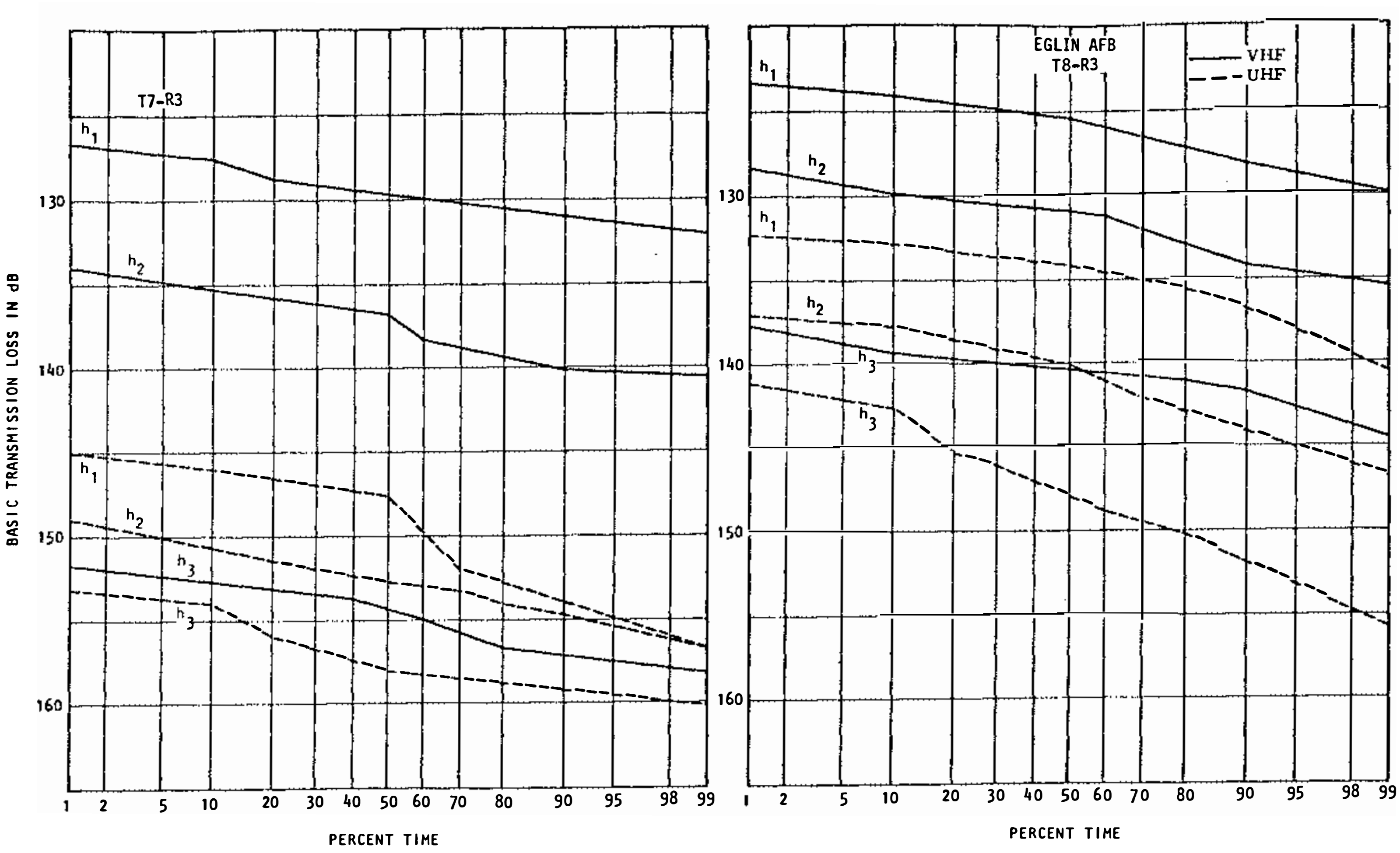

Figure E24. Cumulative distributions of basic transmission loss recorded over paths T7-R3, and T8-R3, Eglin AFB.

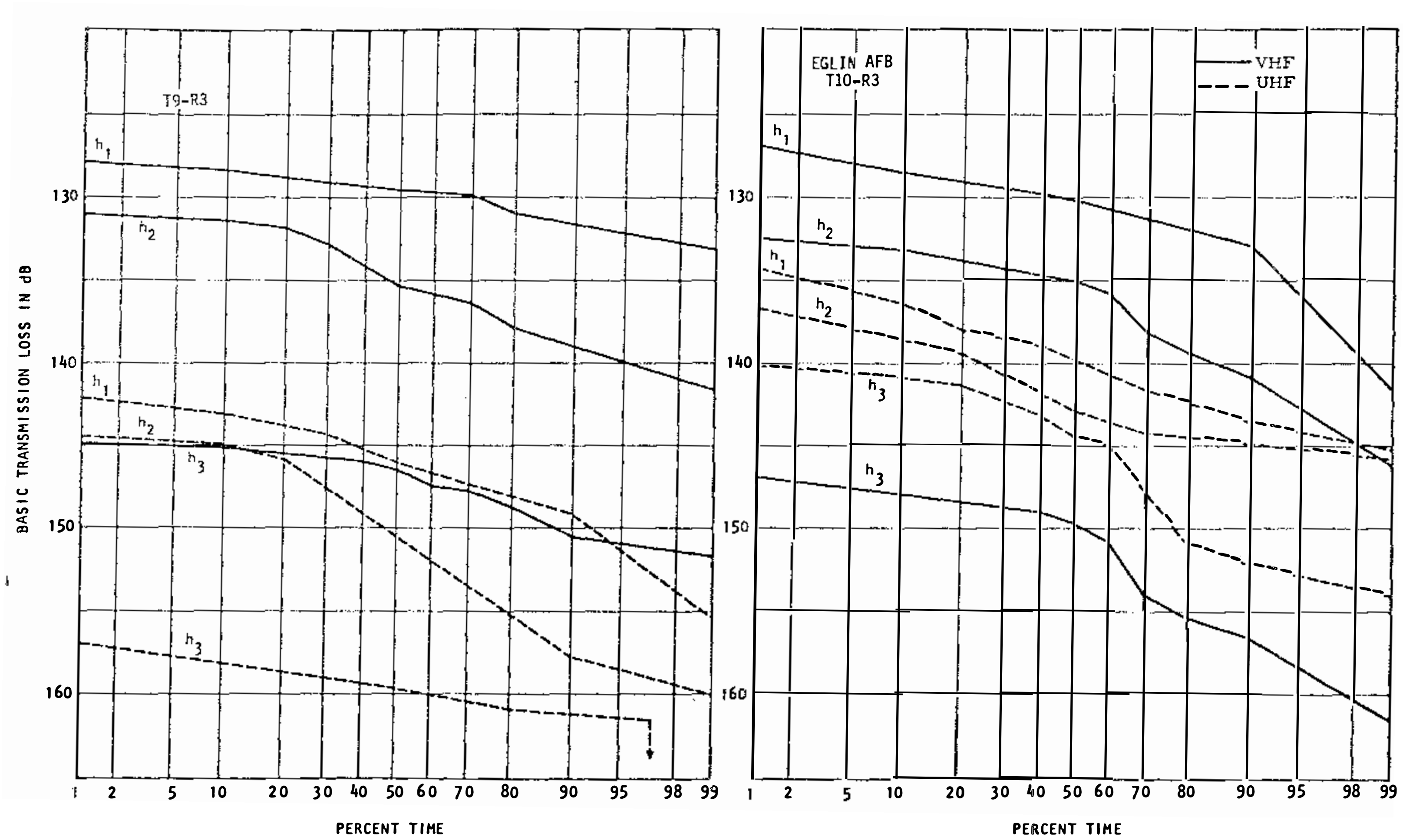

Figure E25. Cumulative distributions of basic transmission loss recorded over paths T9-R3, and T10-R3, Eglin AFB.

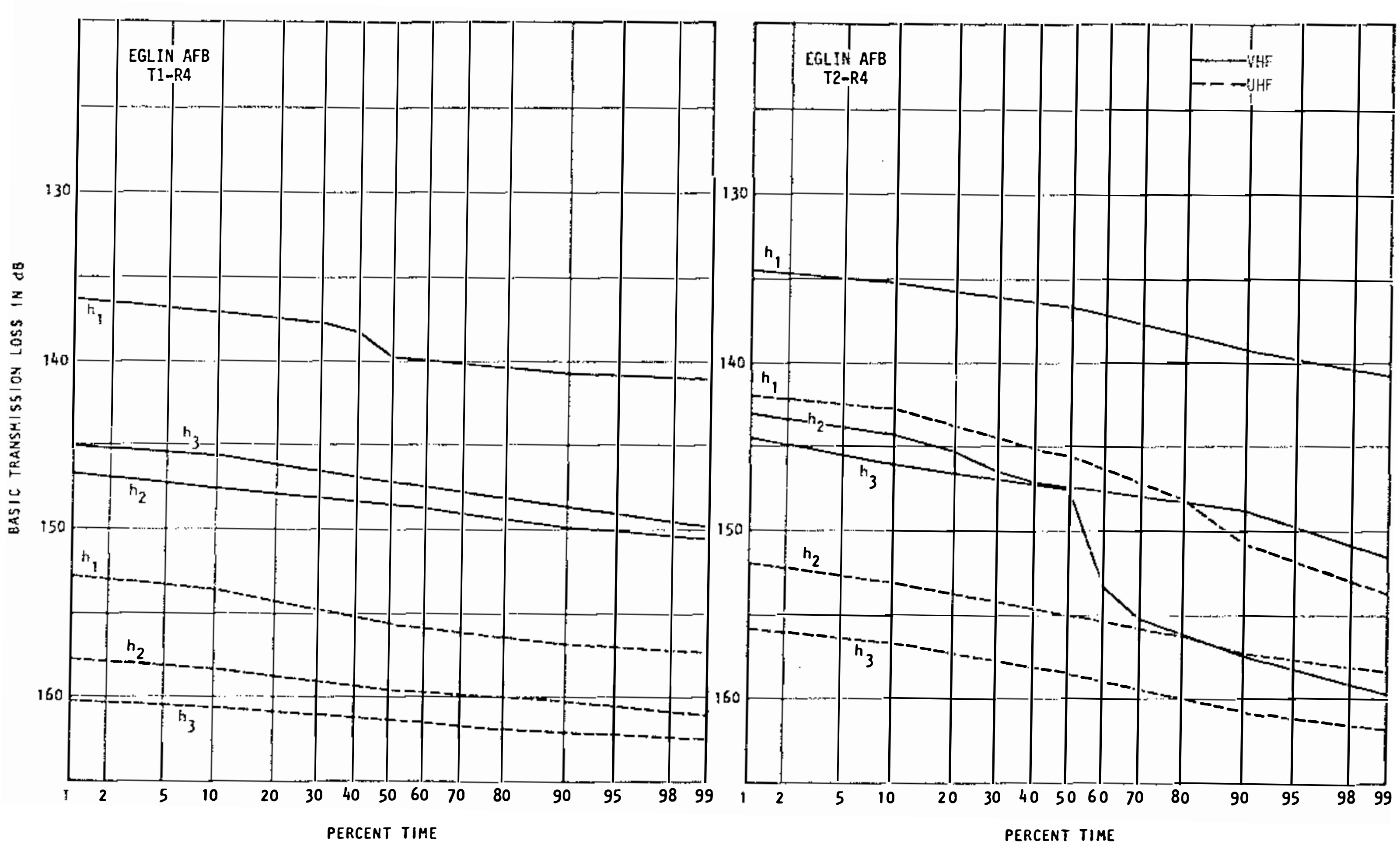

Figure E26. Cumulative distributions of basic transmission loss recorded over paths T1-R4, and T2-R4, Eglin AFB.

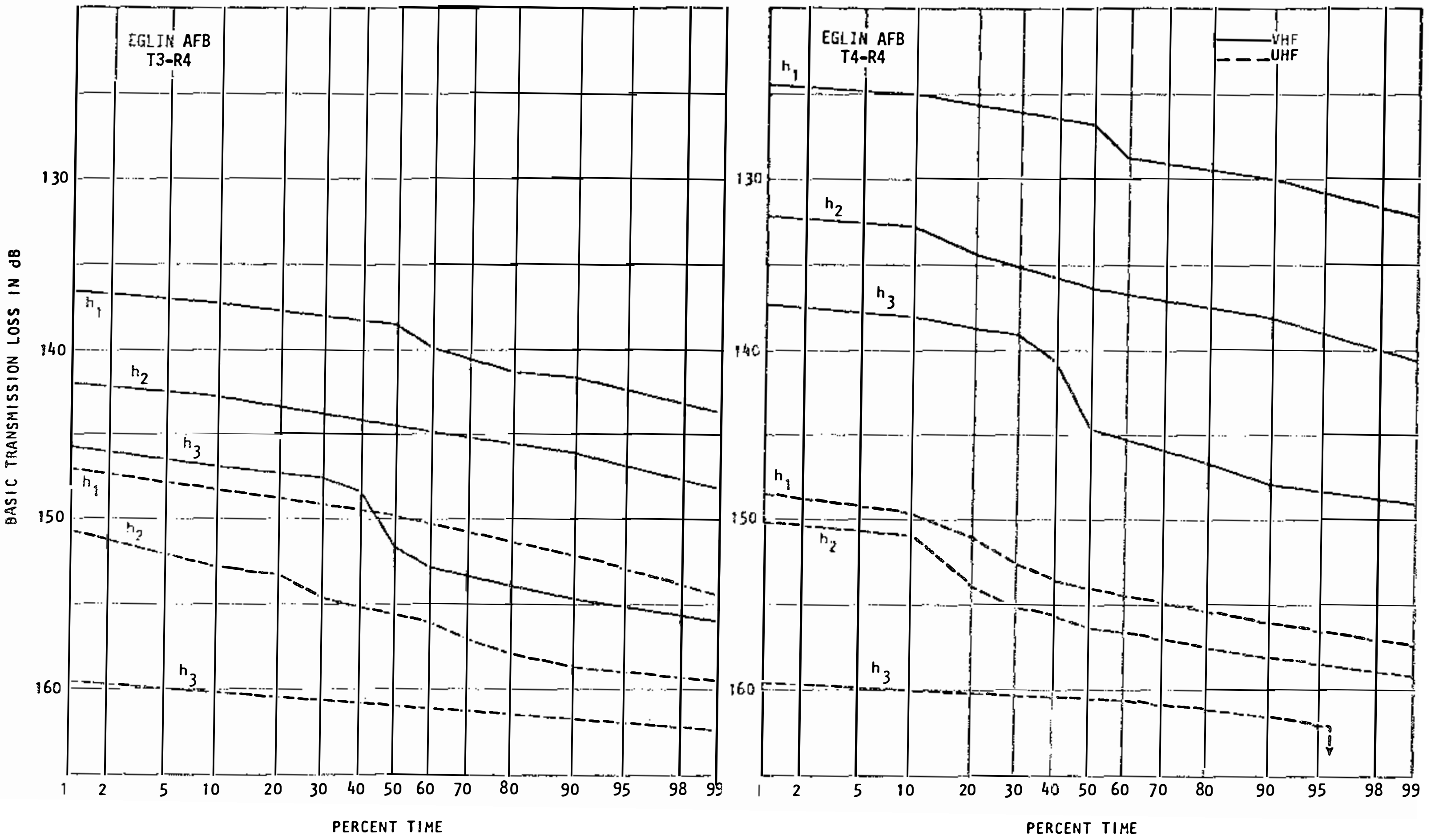

Figure E27. Cumulative distributions of basic transmission loss recorded over paths T3-R4, and T4-R4, Eglin AFB.

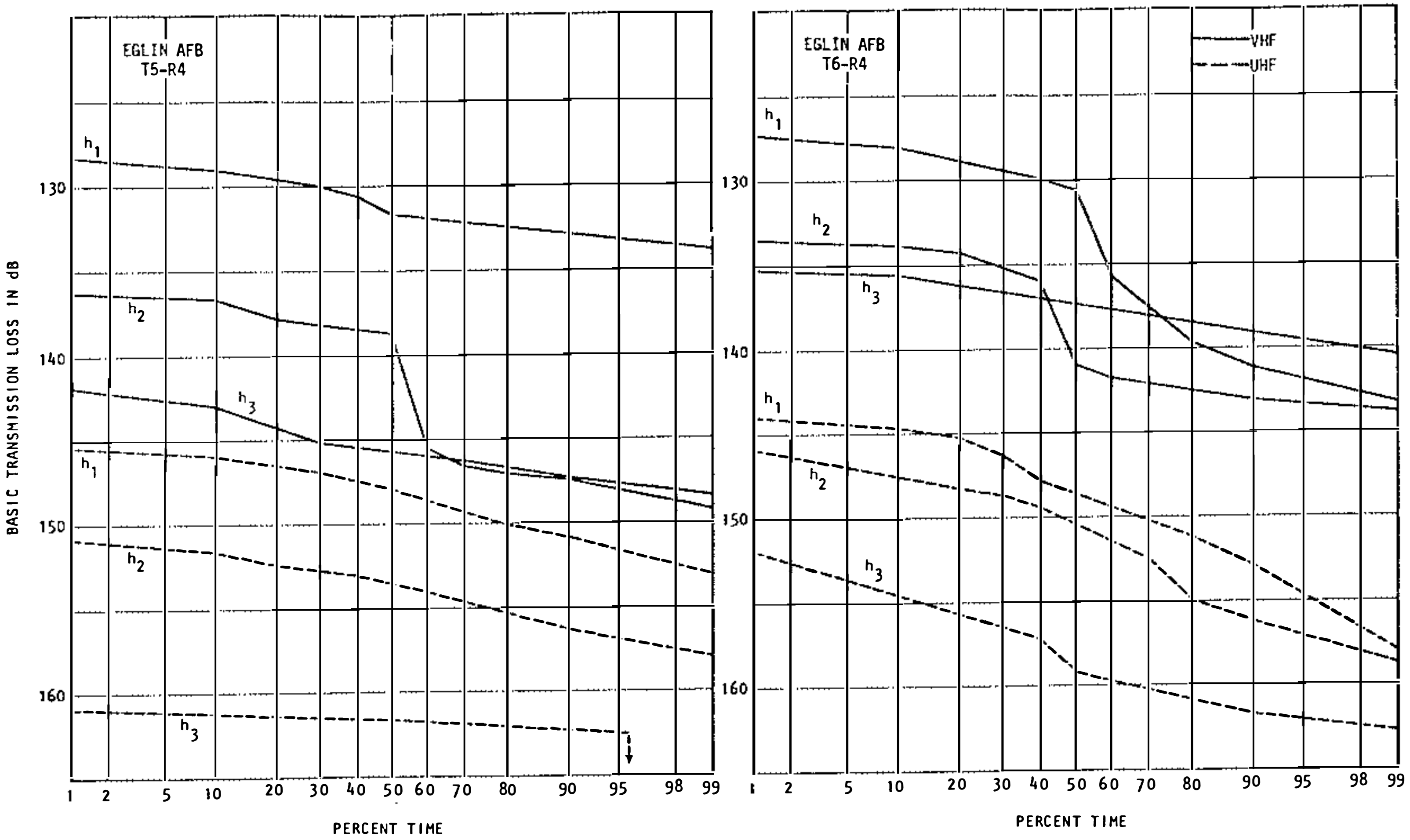

Figure E28. Cumulative distributions of basic transmission loss recorded over paths T5-R4, and T6-R4, Eglin AFB.

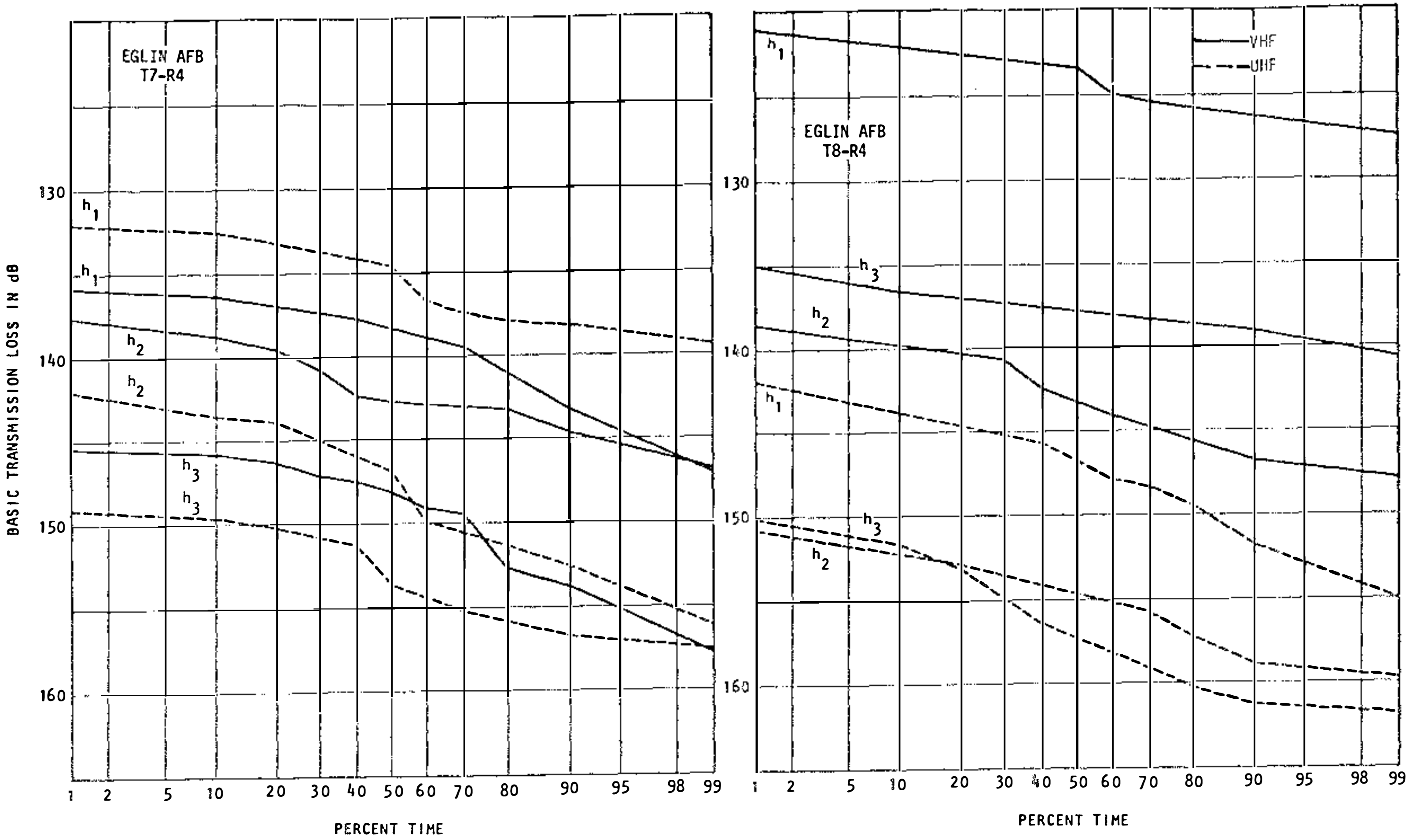

Figure E29. Cumulative distributions of basic transmission loss recorded over paths T7-R4, and T8-R4, Eglin AFB.

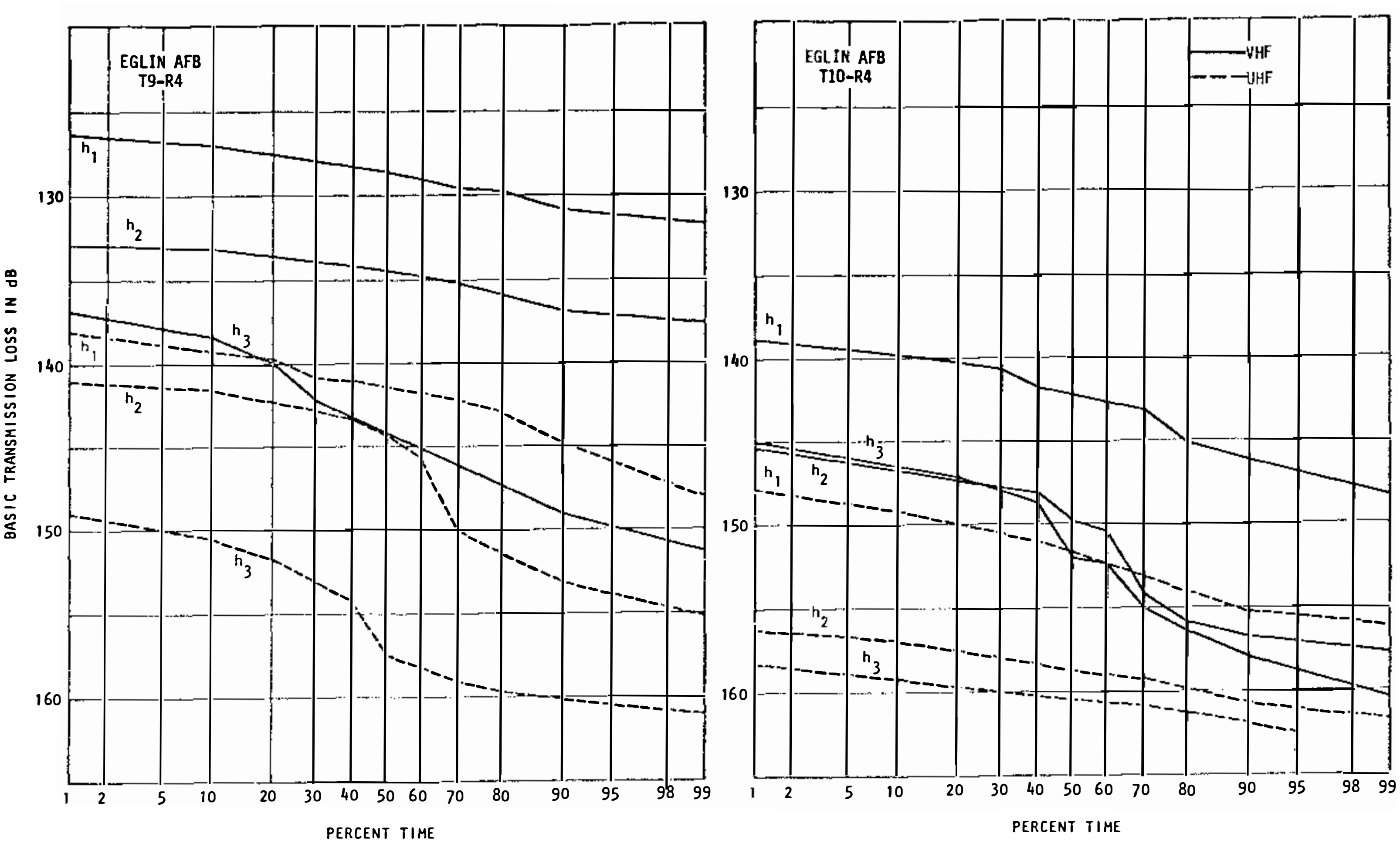

Figure E30. Cumulative distributions of basic transmission loss recorded over paths T9-R4, and T10-R4, Eglin AFB.

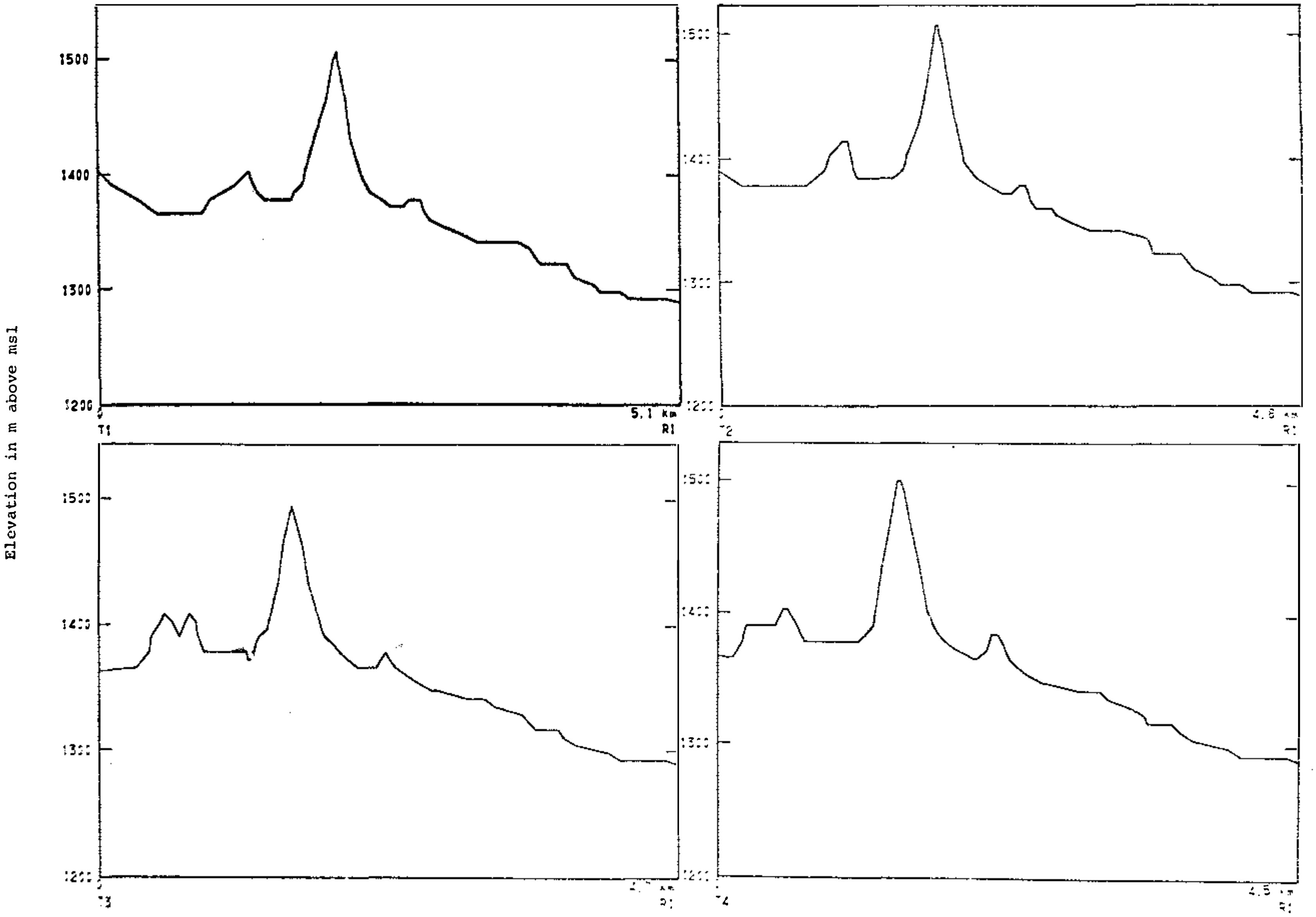

Figure GM1. Terrain profiles from transmitter sites T1, T2, T3, and T4 to receiver site R1, Graham Mountains.

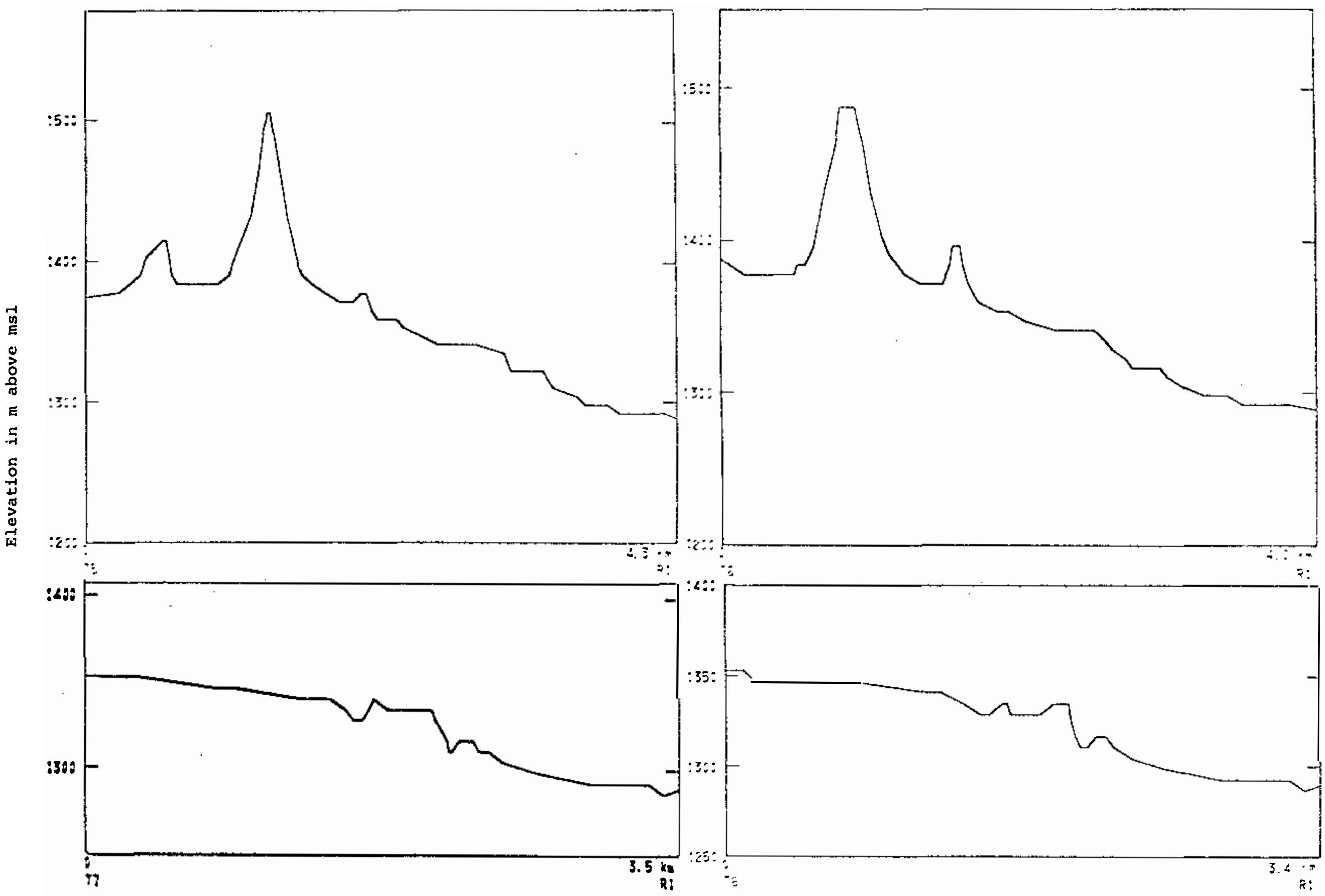

Figure GM2. Terrain profiles from transmitter sites T5, T6, T7, and T8 to receiver site R1, Graham Mountains.

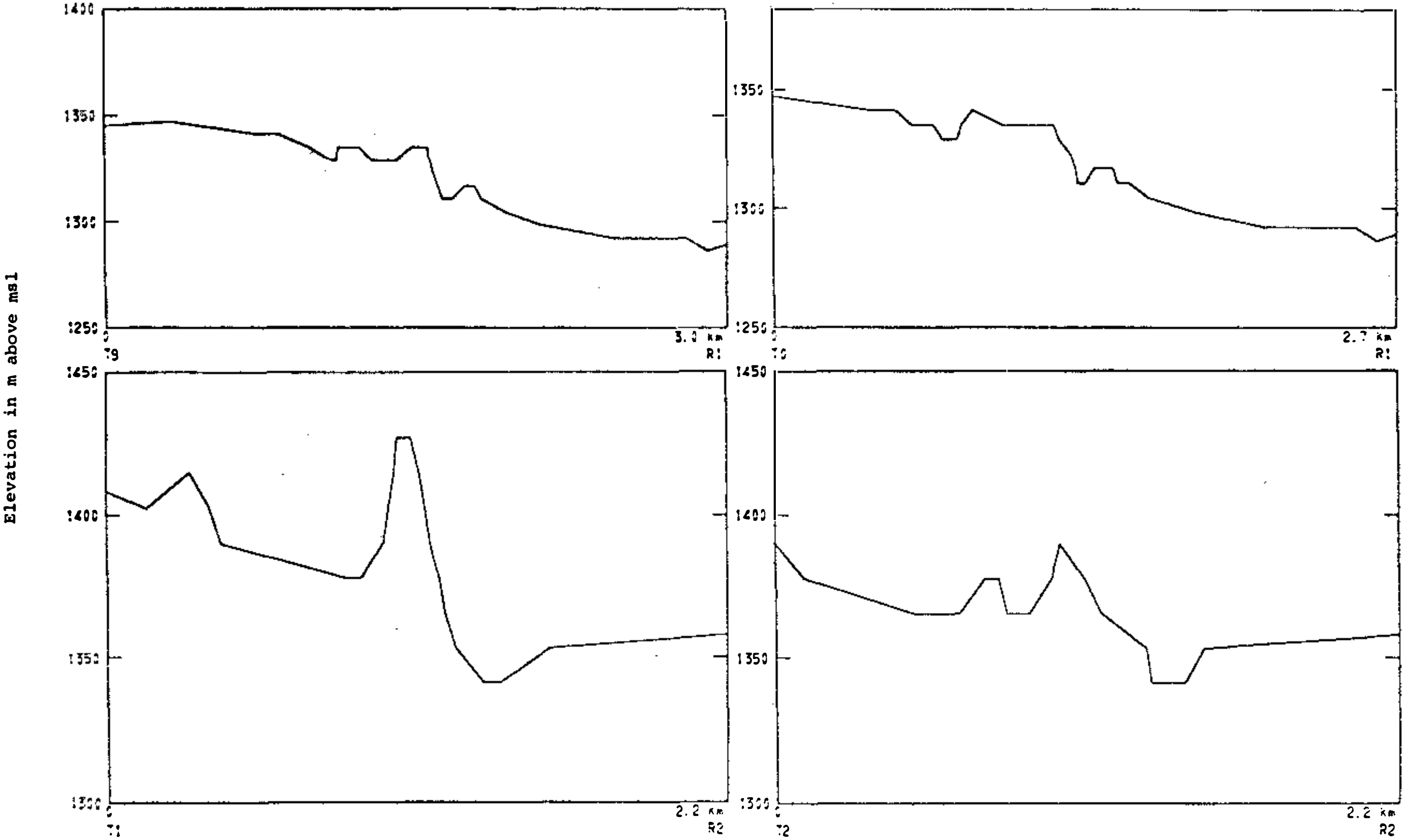

Figure GM3. Terrain profiles from T9 and T10 to R1, and from T1 and T2 to R2, Graham Mountains.

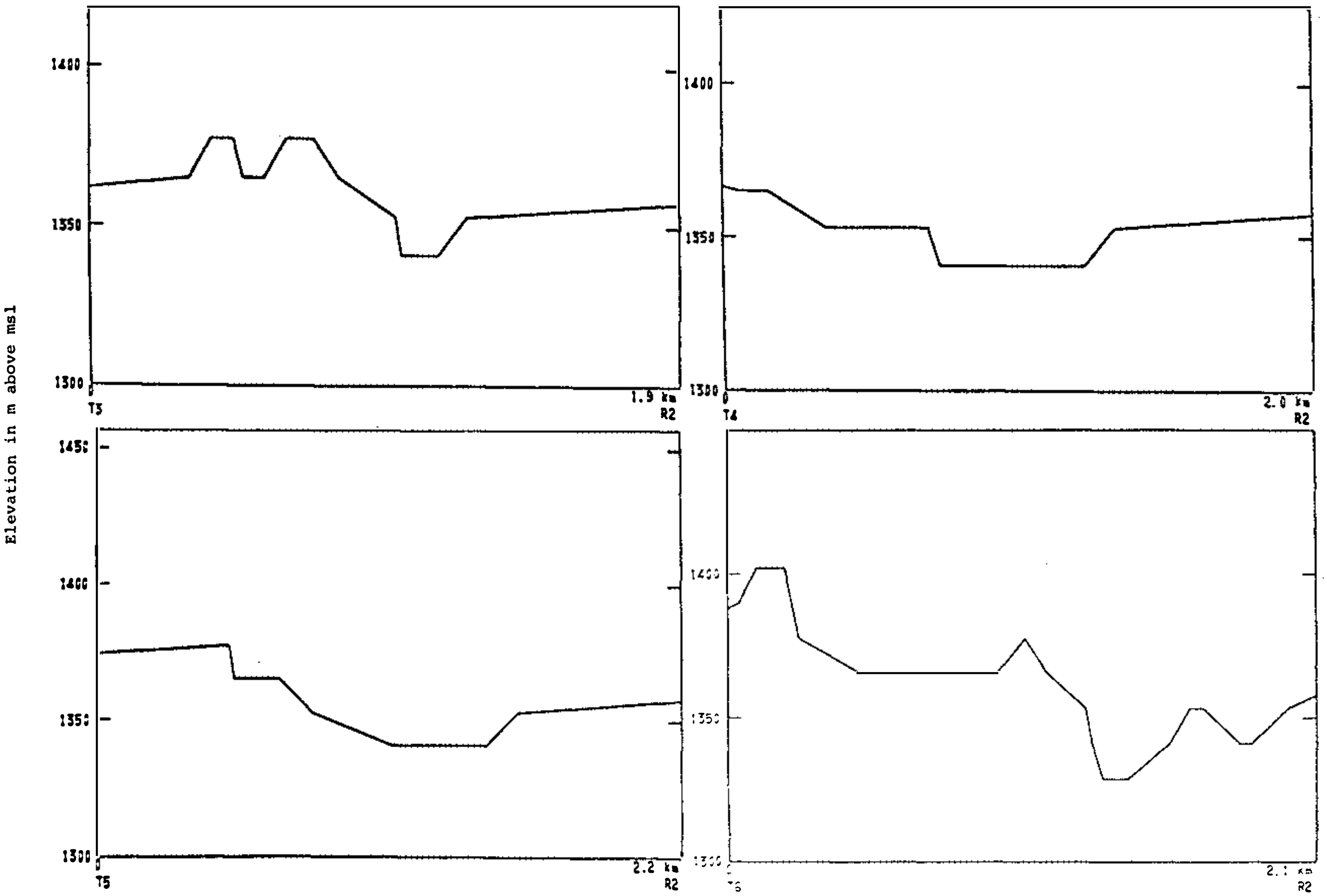

Figure GM4. Terrain profiles from transmitter sites T3, T4, T5, and T6 to receiver site R2, Graham Mountains.

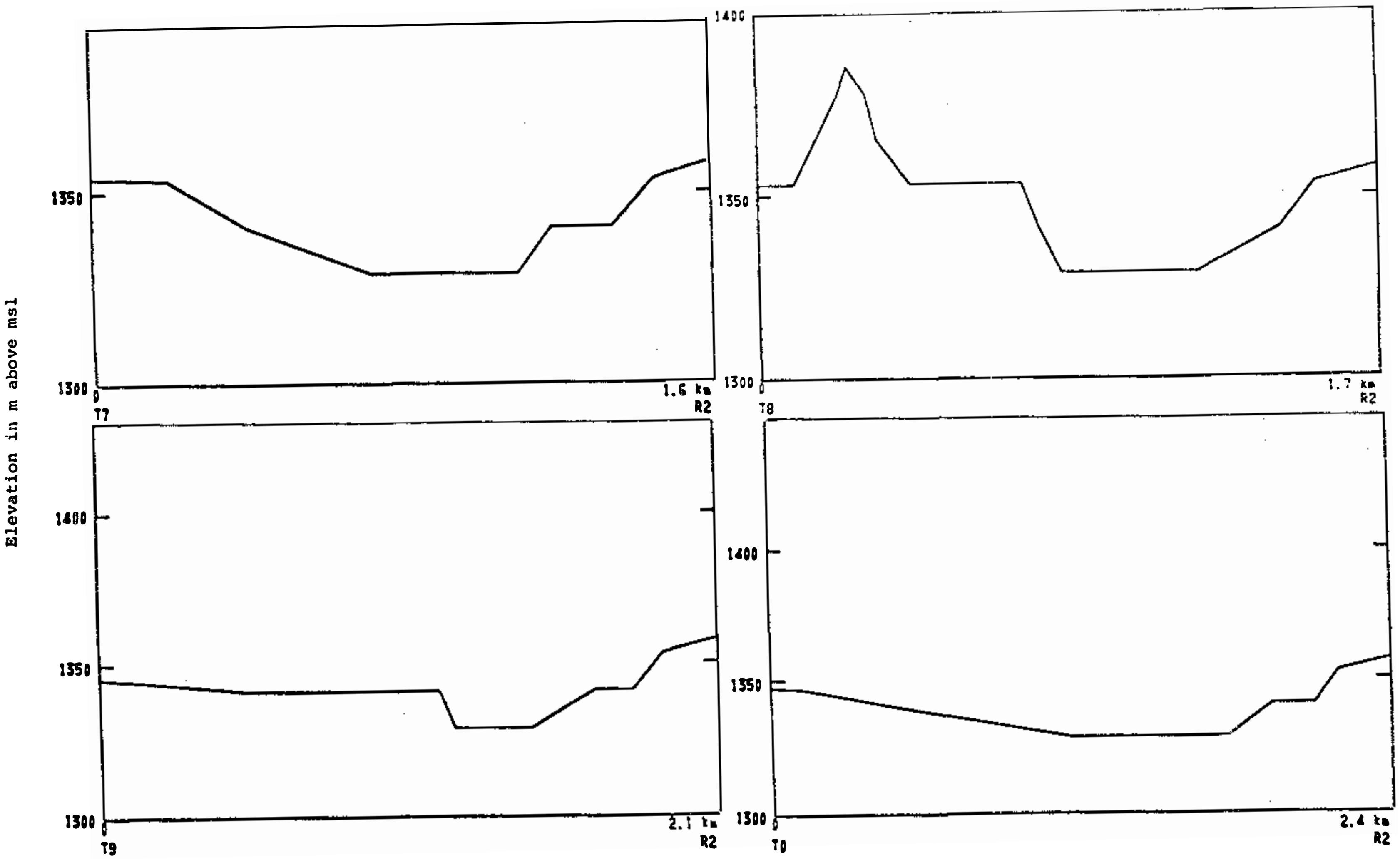

Figure GM5. Terrain profiles from transmitter sites T7, T8, T9, and T10 to receiver site R2, Graham Mountains.

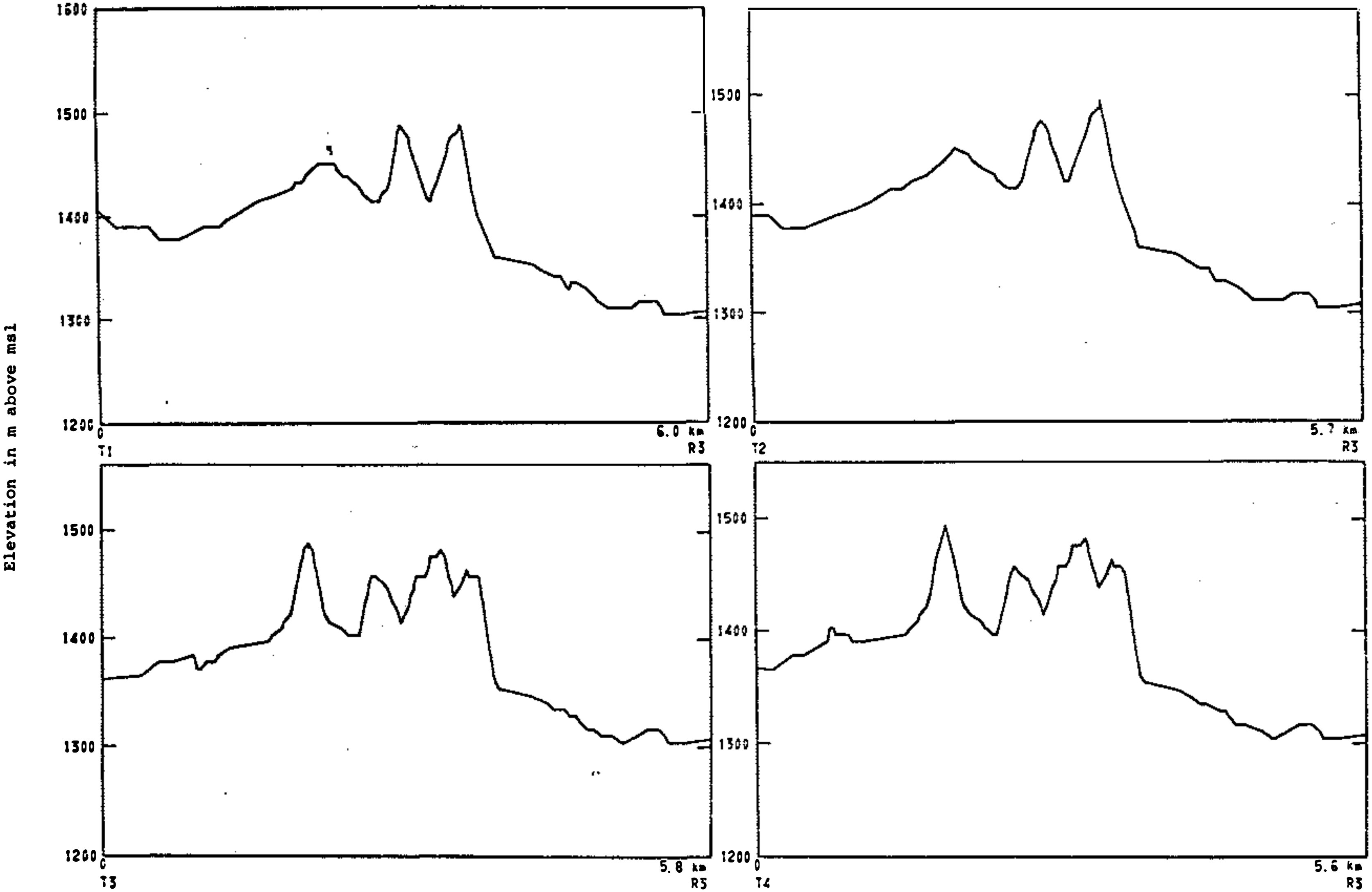

Figure GM6. Terrain profiles from transmitter sites T1, T2, T3, and T4 to receiver site R3, Graham Mountains.

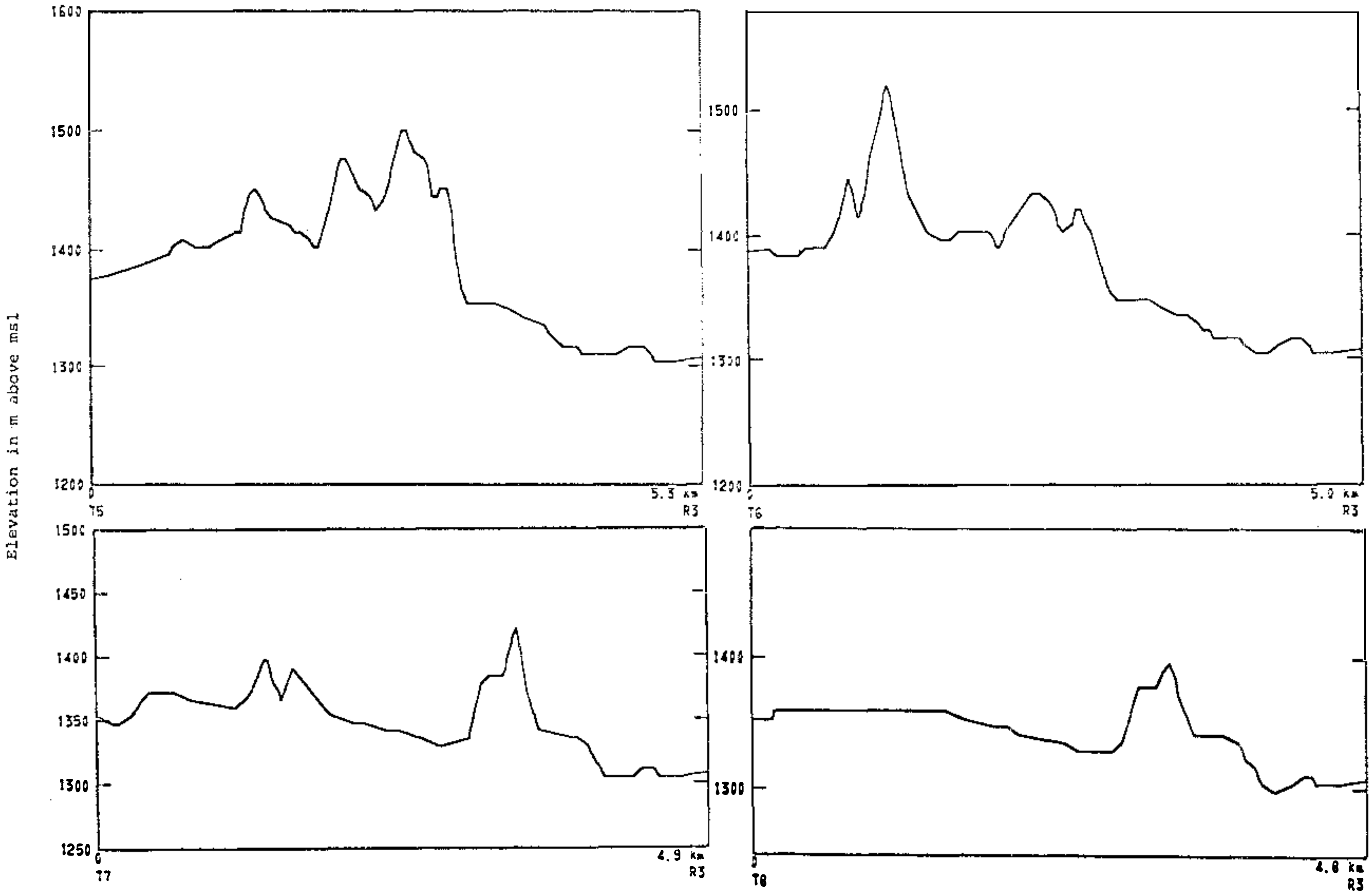

Figure GM7. Terrain profiles from transmitter sites T5, T6, T7, and T8 to receiver site R3, Graham Mountains.

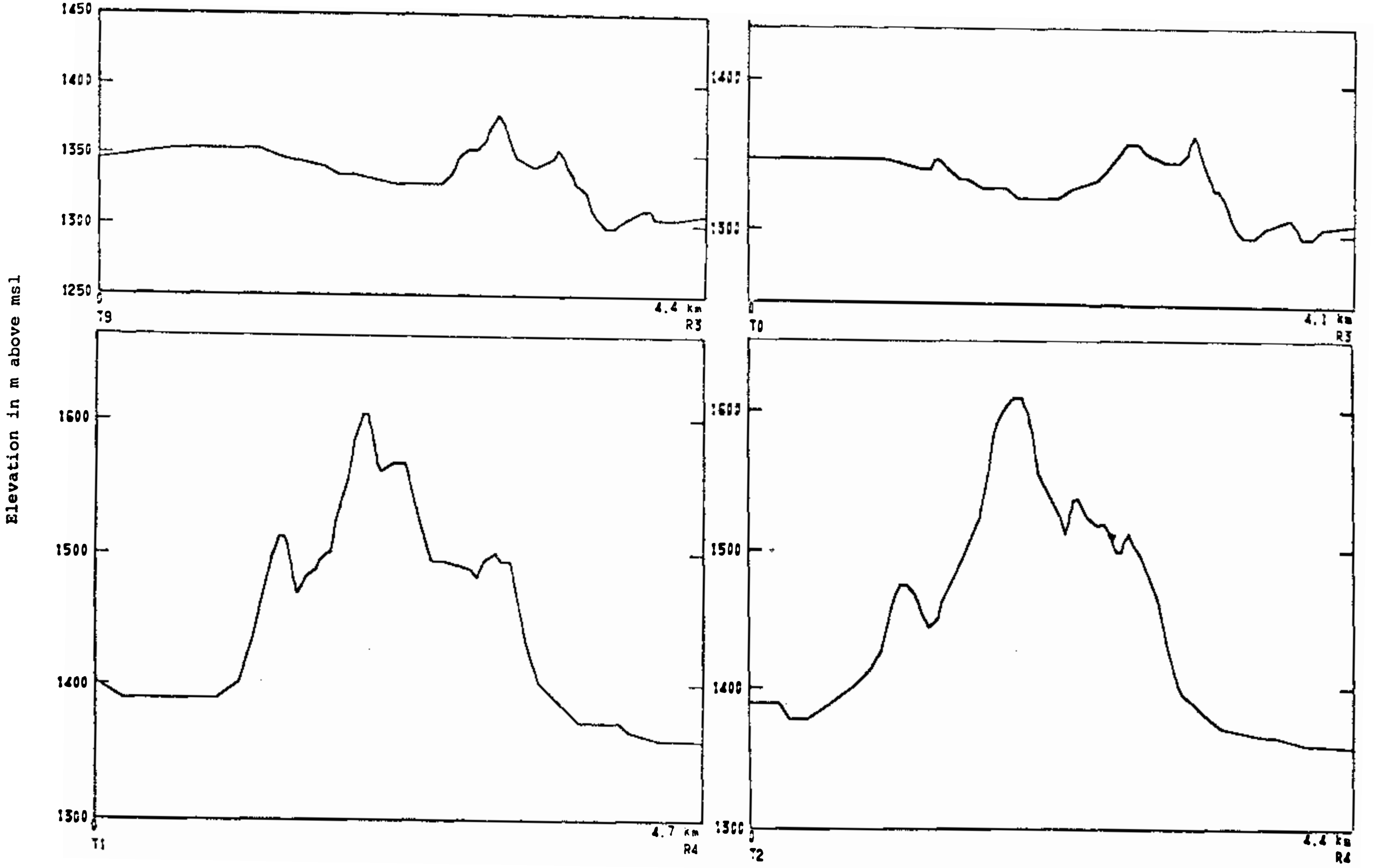

Figure GM8. Terrain profiles from T9 and T10 to R3, and from T1 and T2 to R4, Graham Mountains.

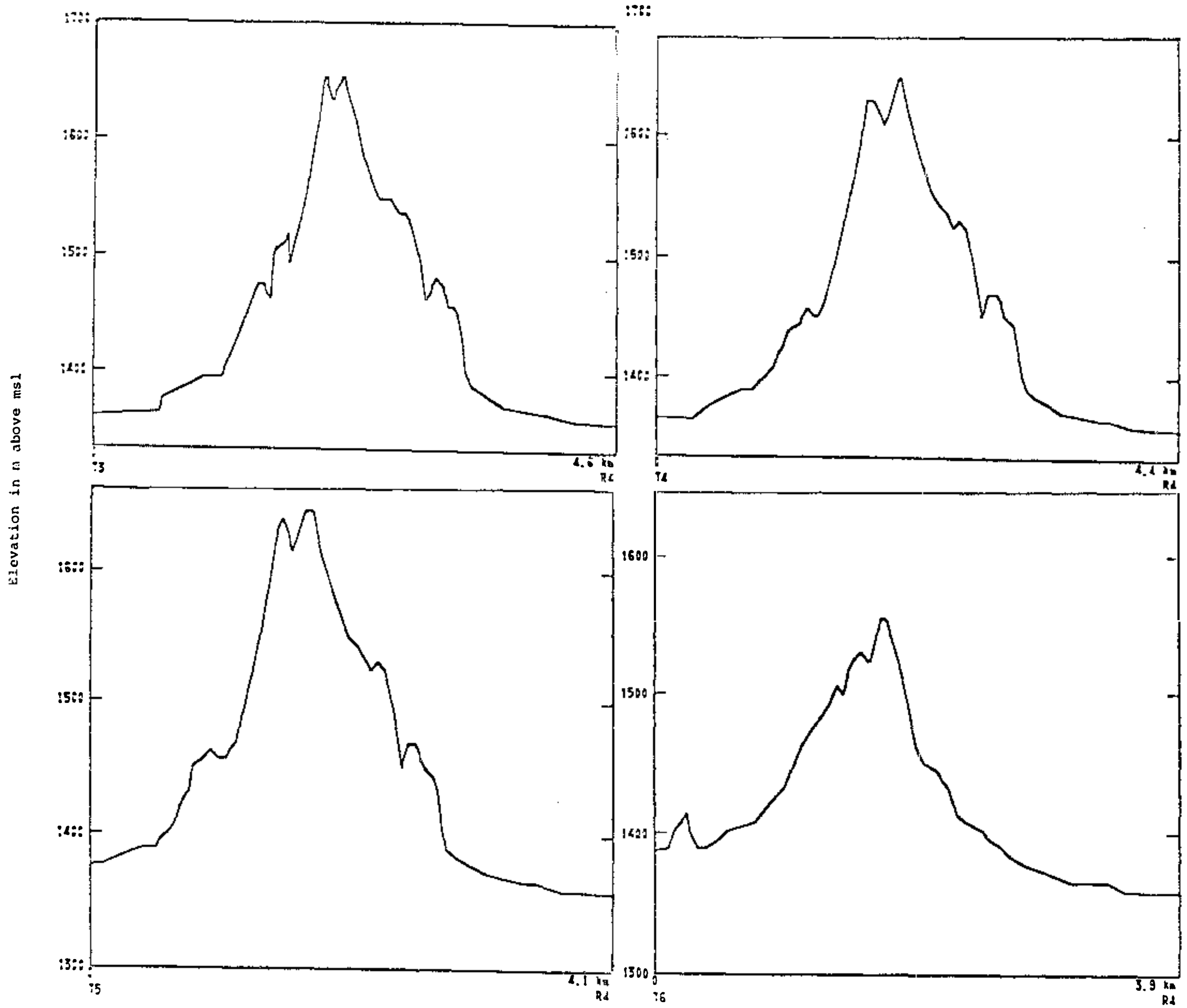

Figure GM9. Terrain profiles from transmitter sites T3, T4, T5, and T6 to receiver site R4, Graham Mountains.

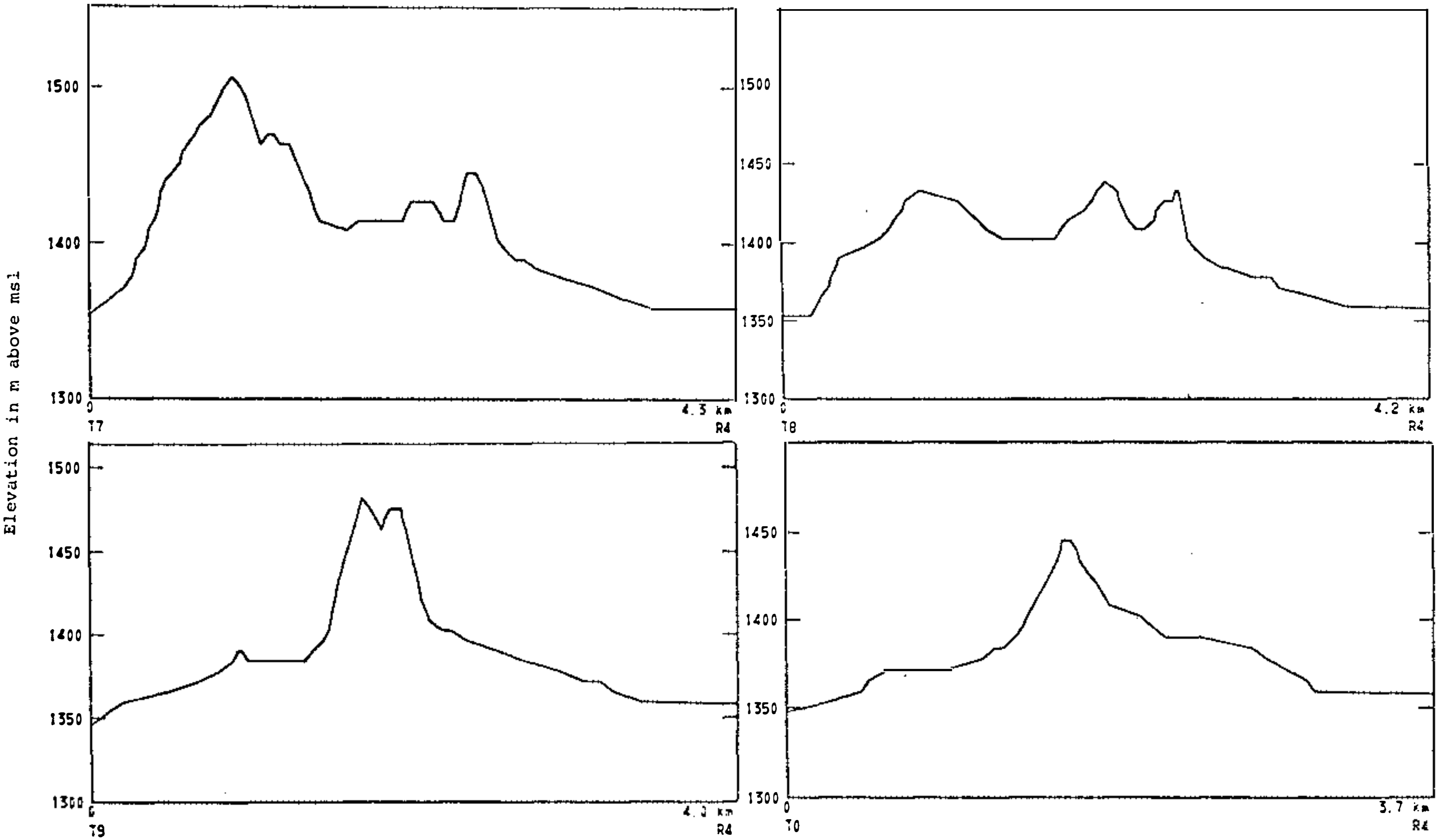

Figure GM10. Terrain profiles from transmitter sites T7, T8, T9, and T10 to receiver site R4, Graham Mountains.

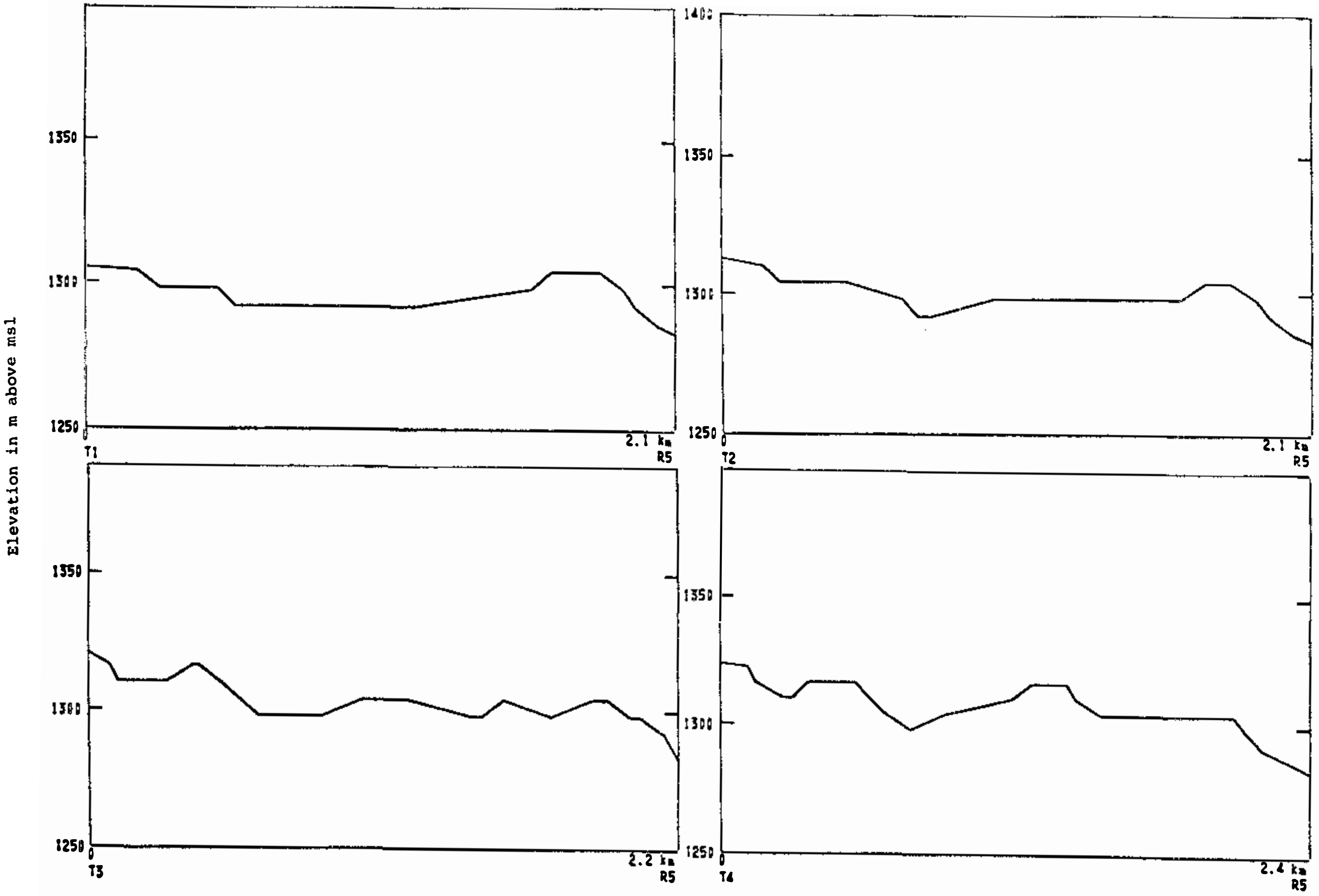

Figure GM11. Terrain profiles from transmitter sites T1, T2, T3, and T4 to receiver site R5, Graham Mountains.

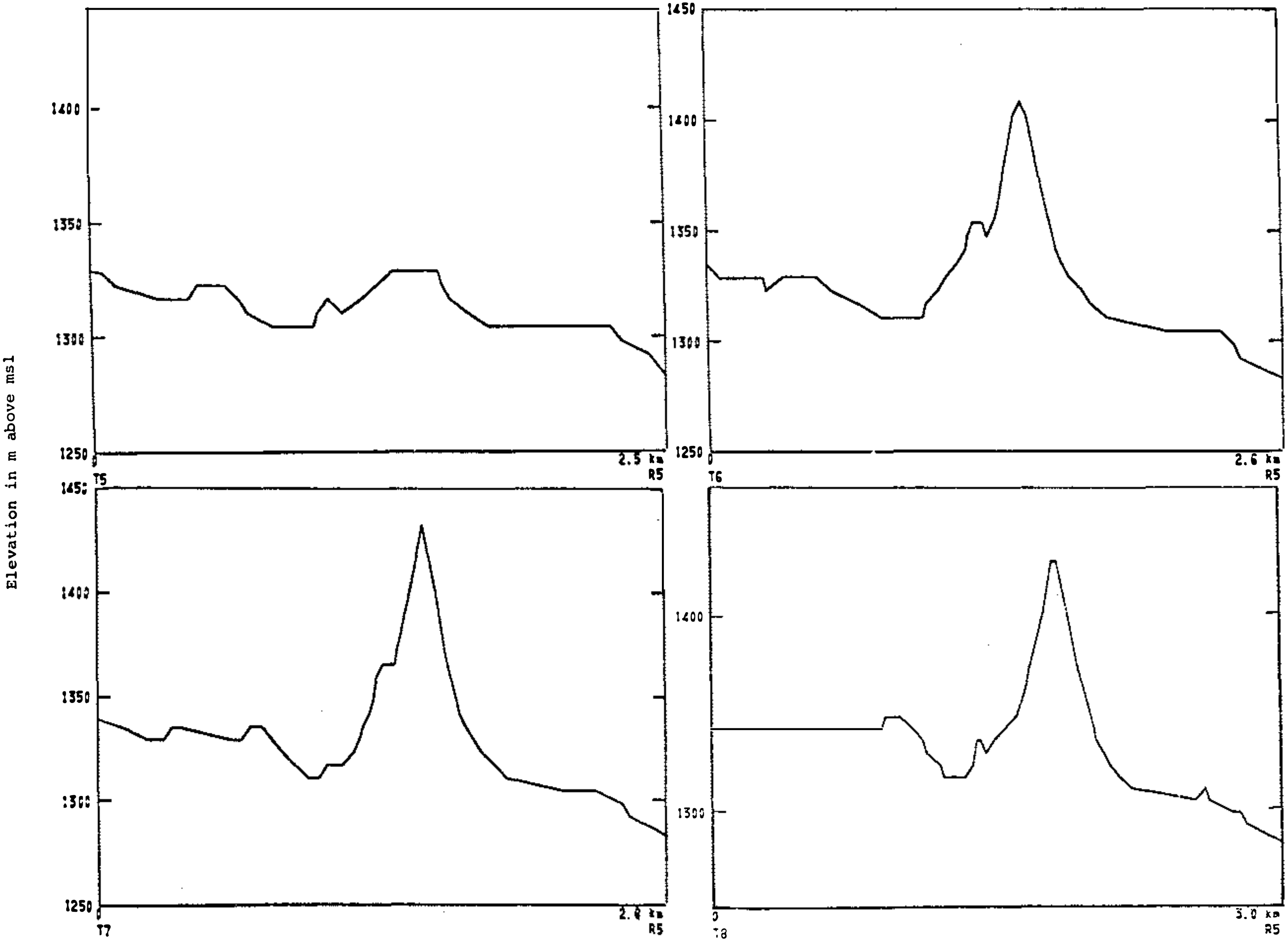

Figure GM12. Terrain profiles from transmitter sites T5, T6, T7, and T8 to receiver site R5, Graham Mountains.

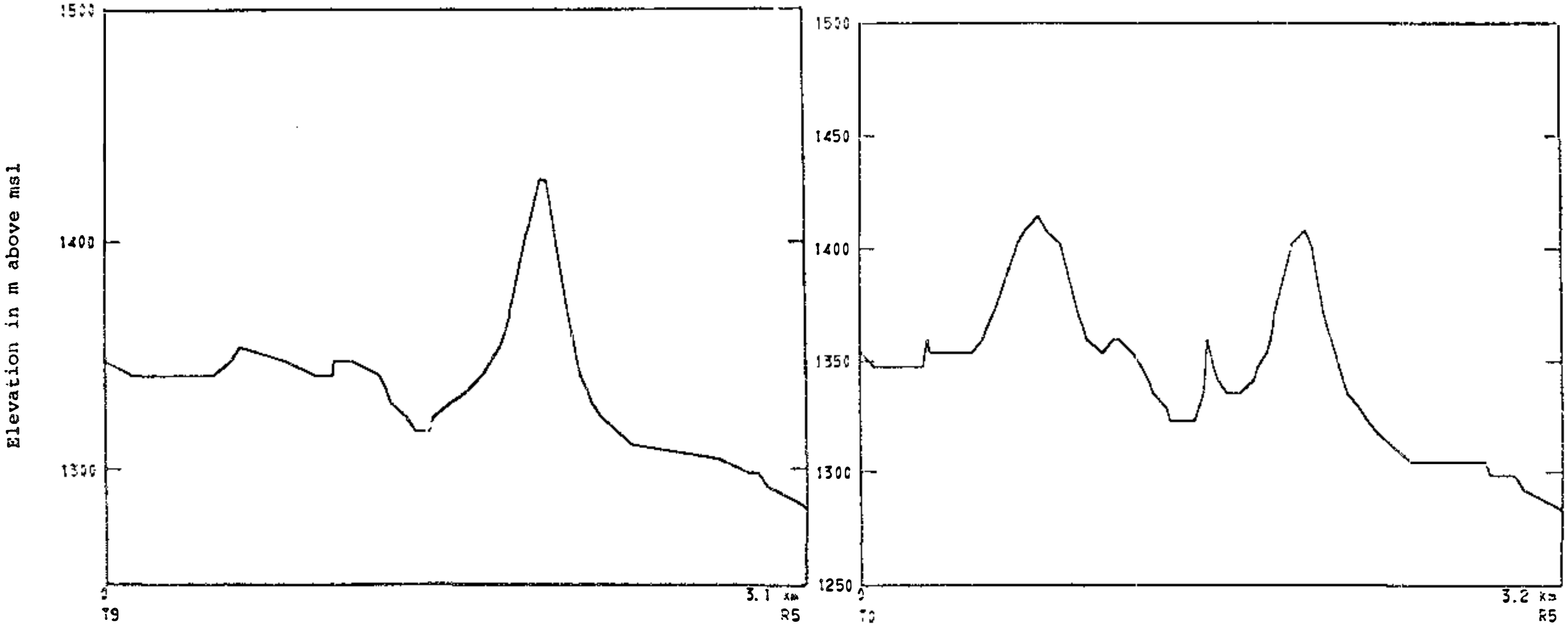

Figure GM13. Terrain Profiles T9 and T10 to receiver site R5, Graham Mountains.

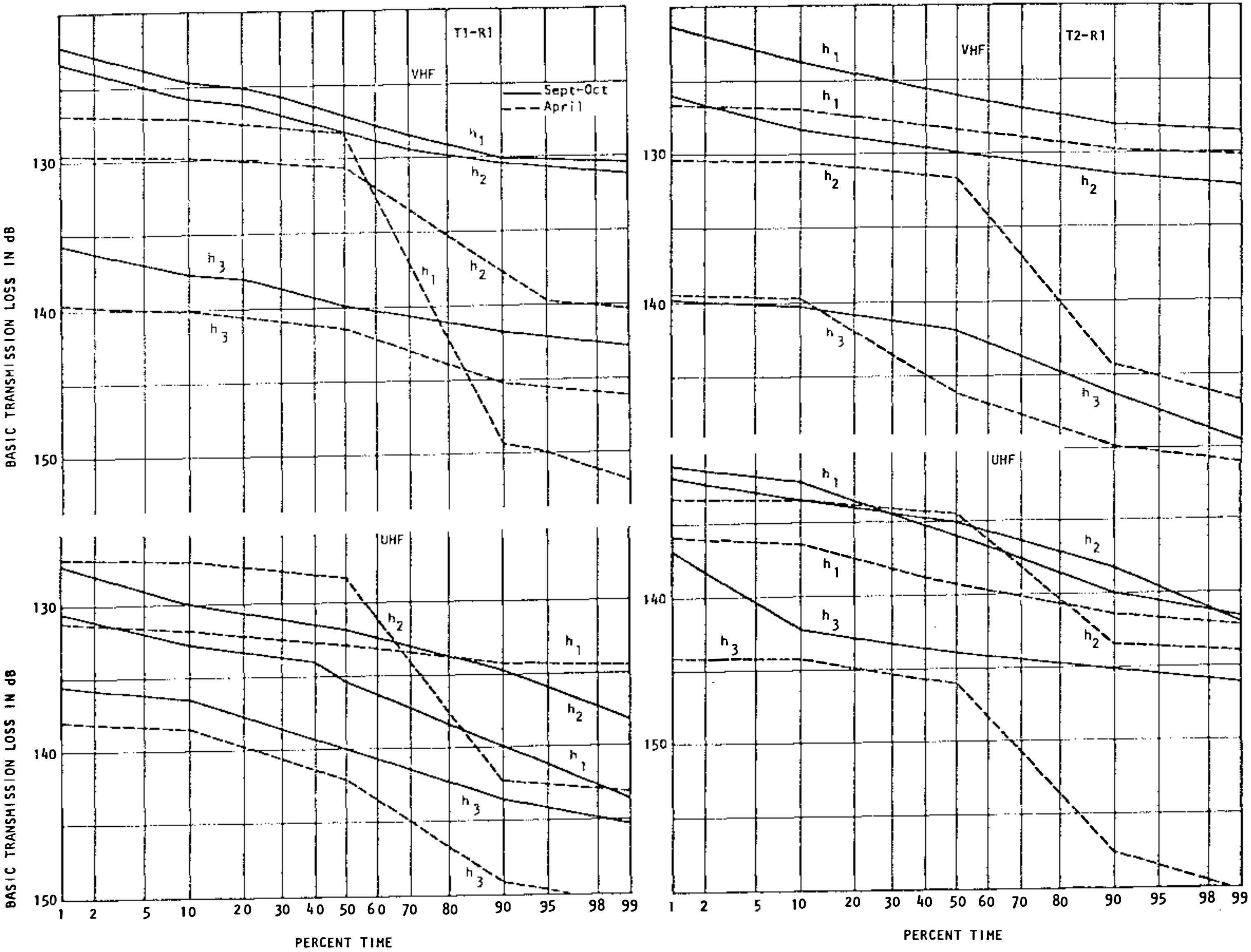

Figure GM14. Cumulative distributions of basic transmission loss recorded over paths T1-R1 and T2-R1, Graham Mountains.

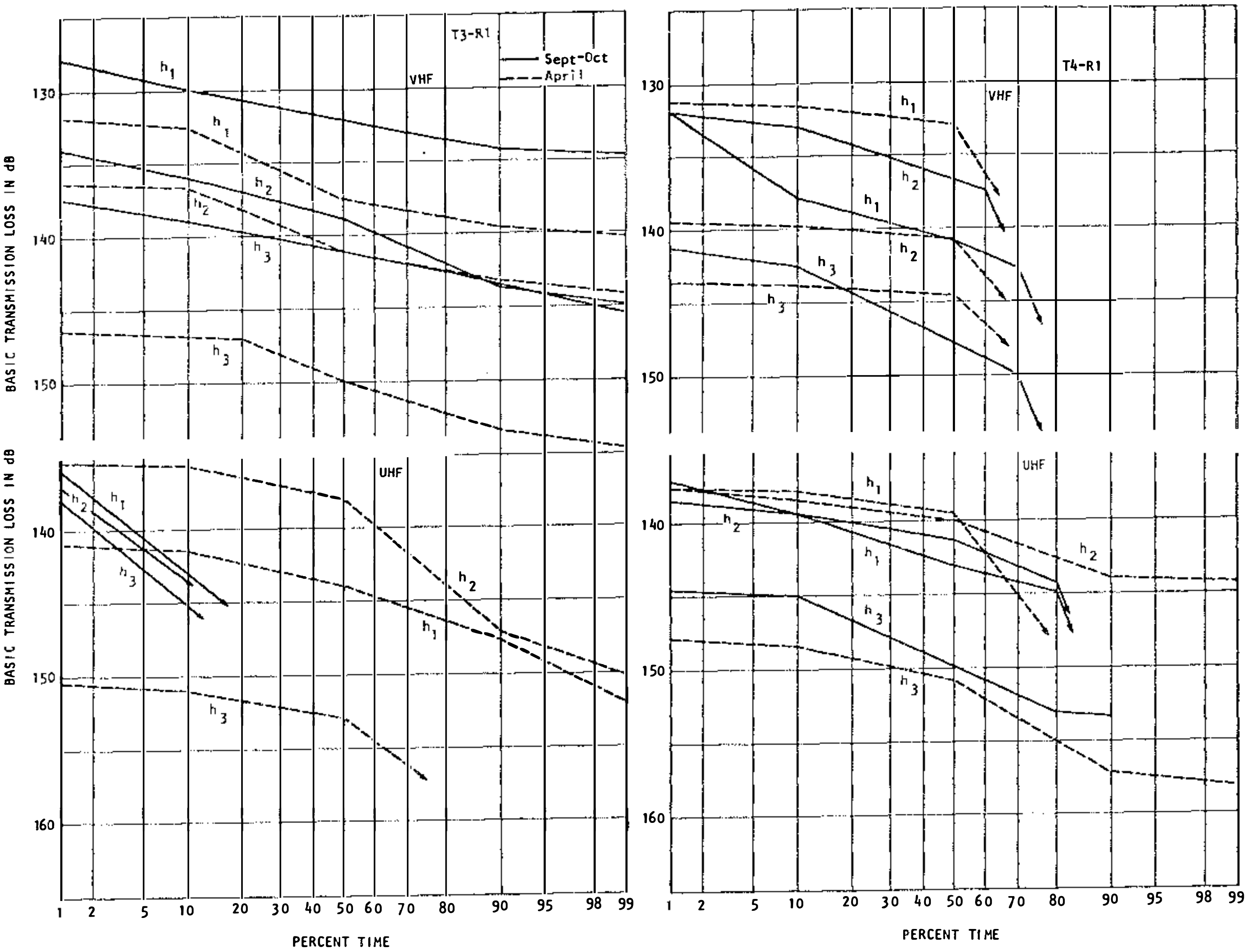

Figure GM15. Cumulative distributions of basic transmission loss recorded over paths T3-R1 and T4-R1, Graham Mountains.

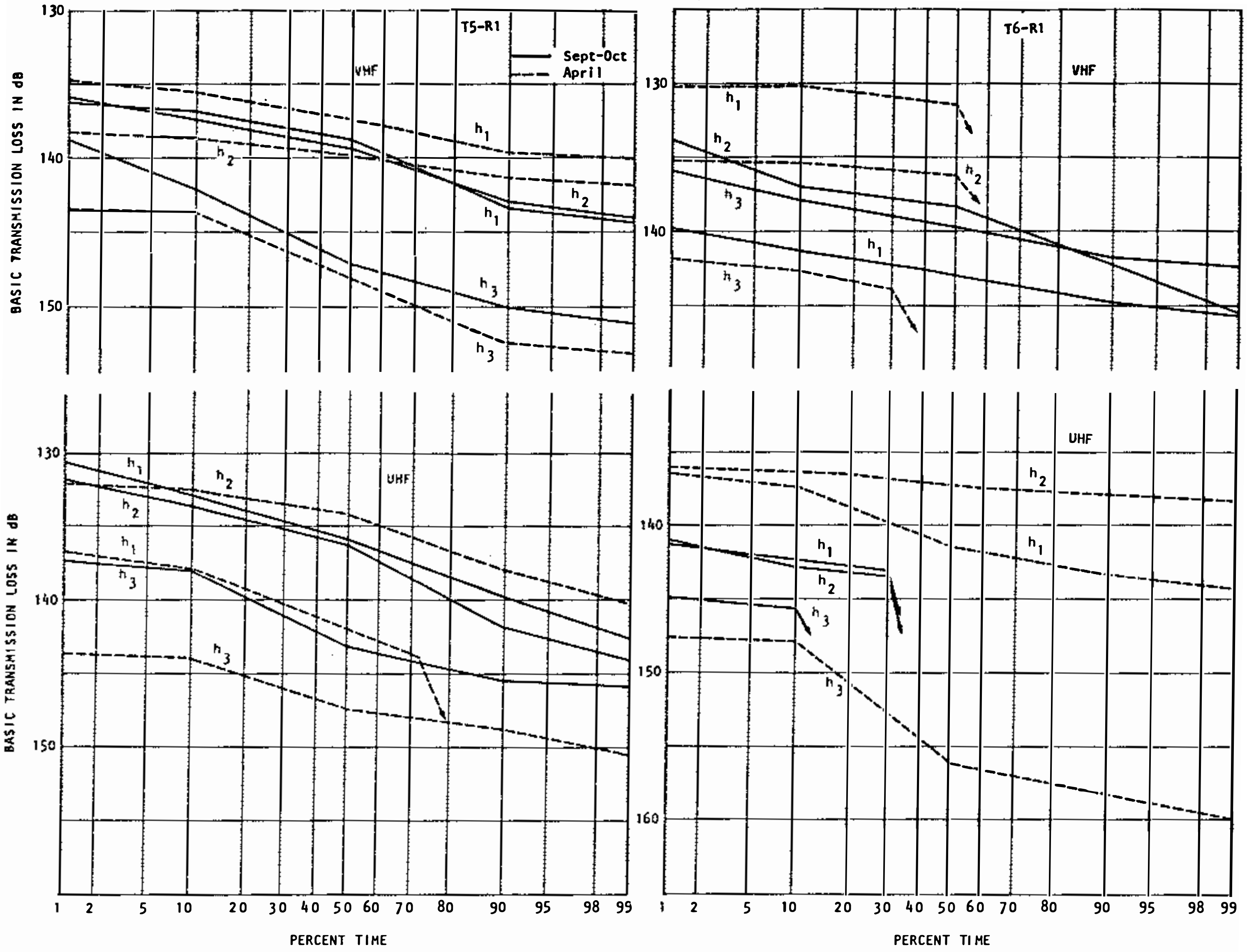

Figure GM16. Cumulative distributions of basic transmission loss recorded over paths T5-R1 and T6-R1, Graham Mountains.

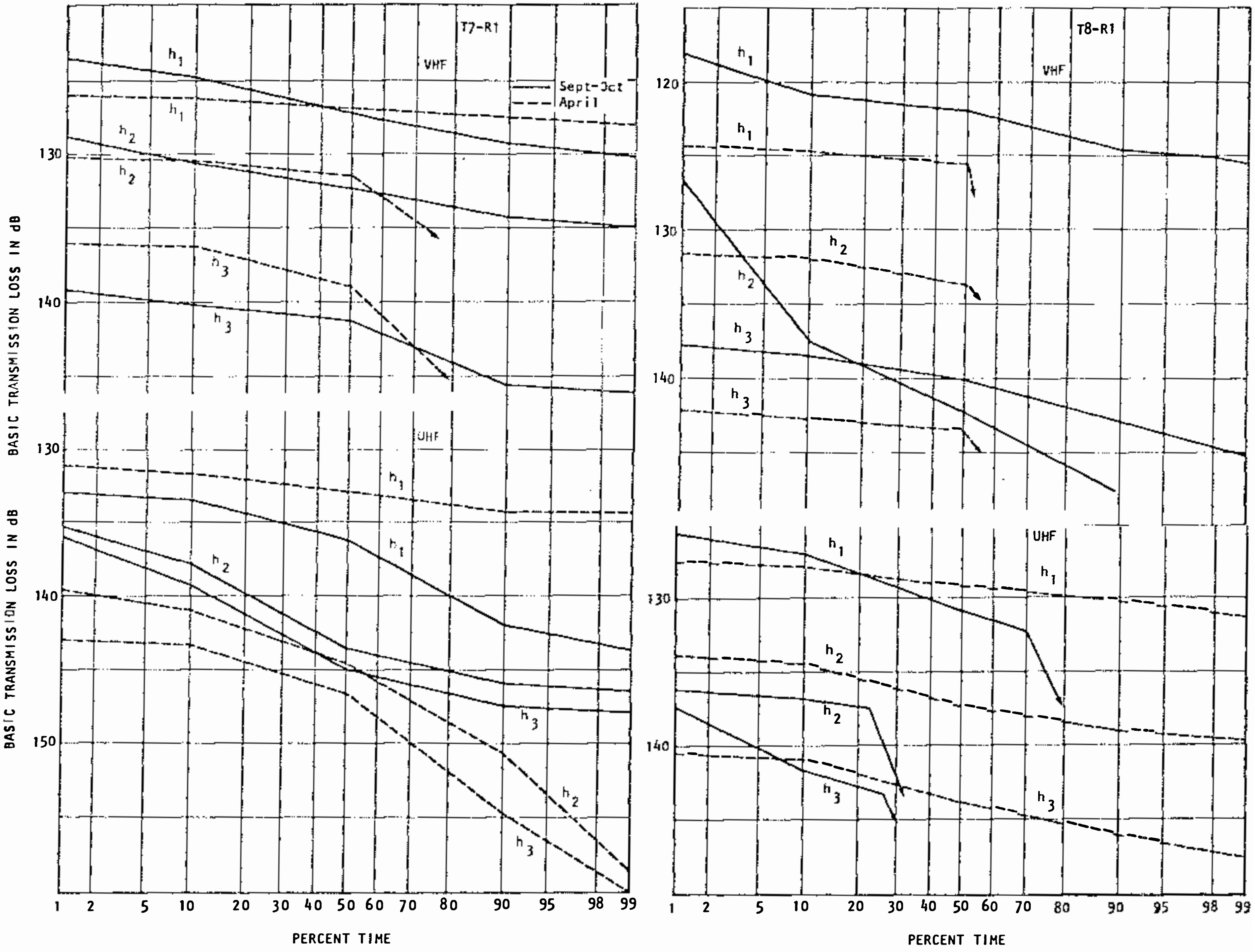

Figure GM17. Cumulative distributions of basic transmission loss recorded over paths T7-R1 and T8-R1, Graham Mountains.

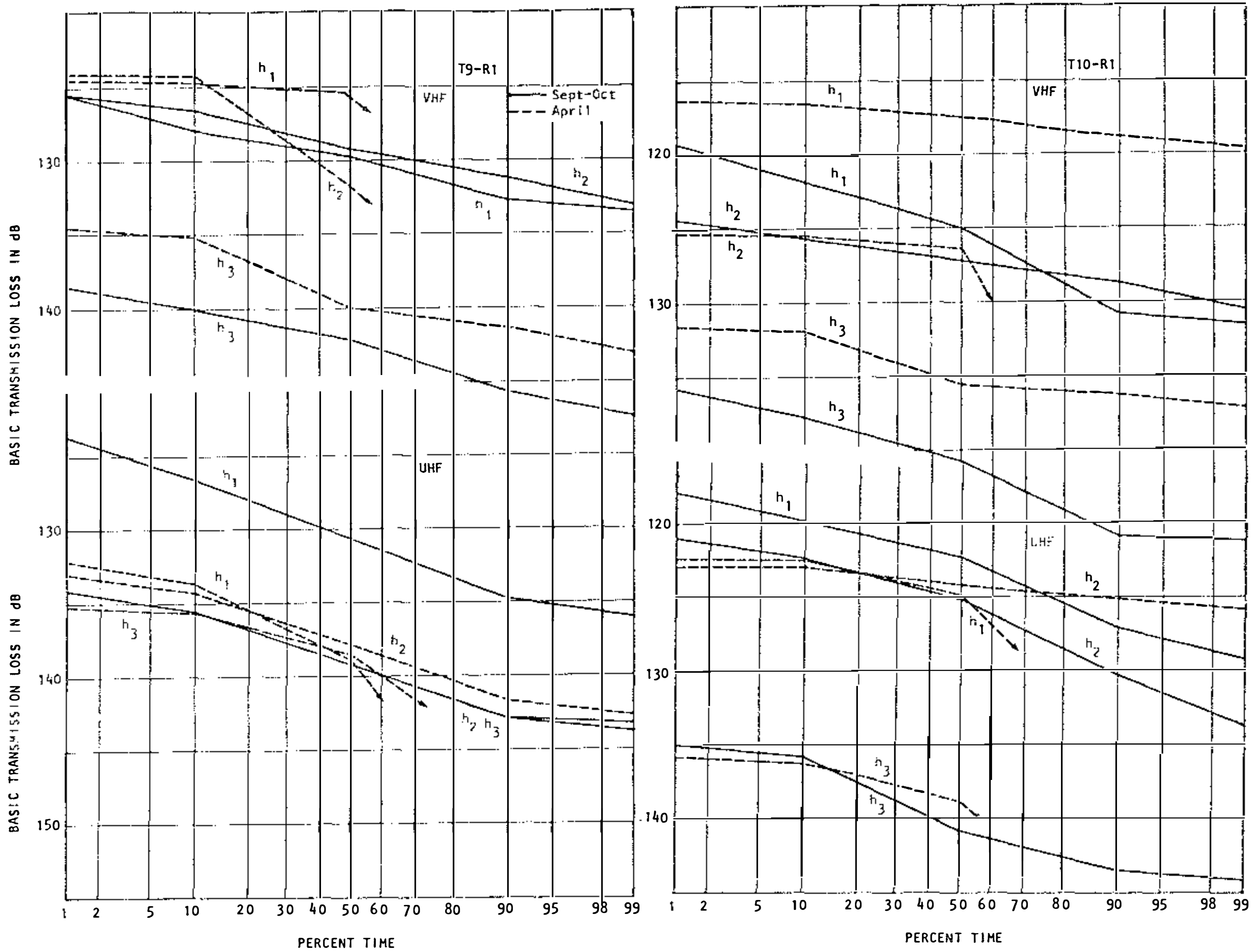

Figure GM18. Cumulative distributions of basic transmission loss recorded over paths T9-R1 and T10-R1, Graham Mountains.

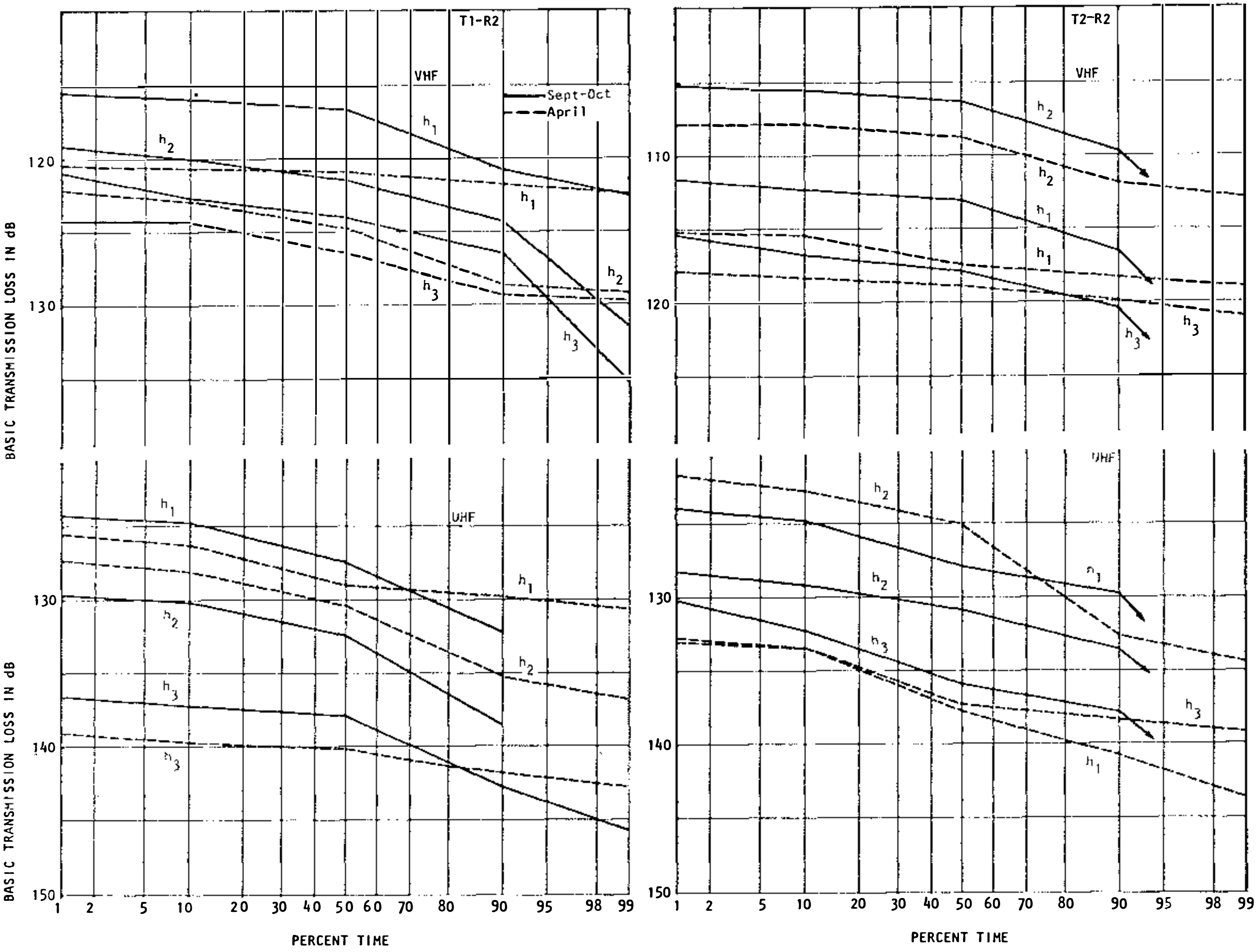

Figure GM19. Cumulative distributions of basic transmission loss recorded over paths T1-R2 and T2-R2, Graham Mountains.

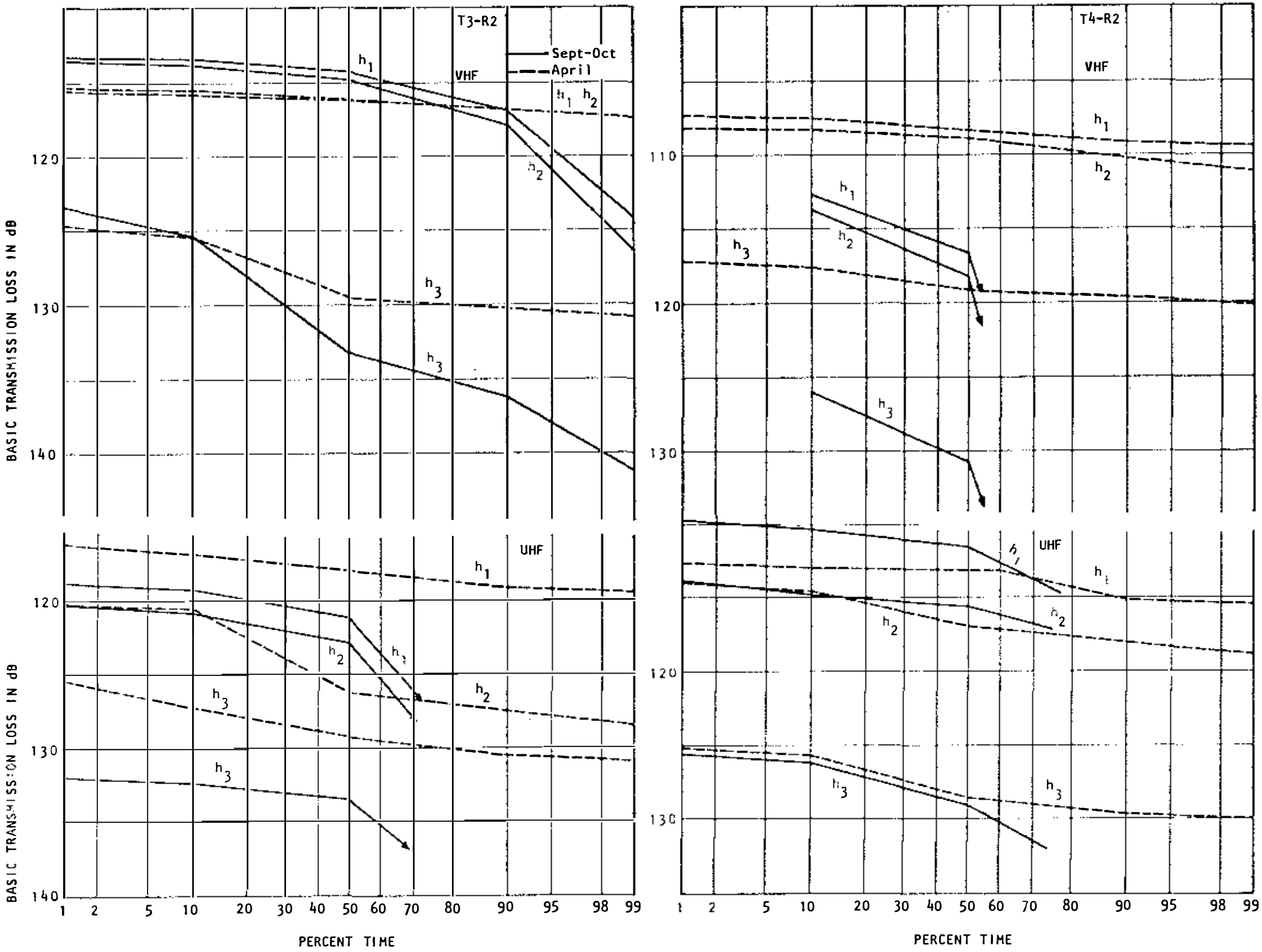

Figure GM20. Cumulative distributions of basic transmission loss recorded over paths T3-R2 and T4-R2, Graham Mountains.

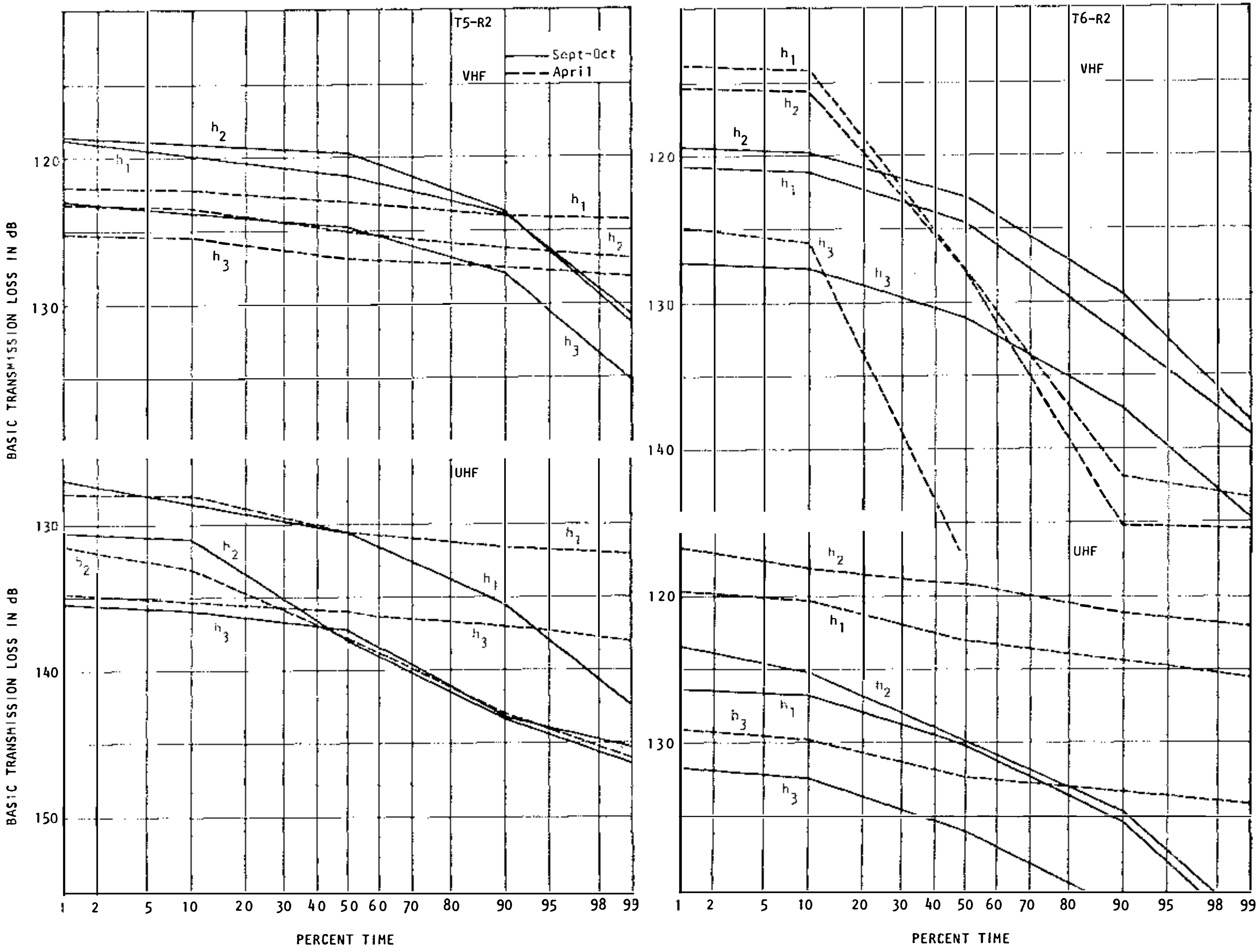

Figure GM21. Cumulative distributions of basic transmission loss recorded over paths T5-R2 and T6-R2, Graham Mountains.

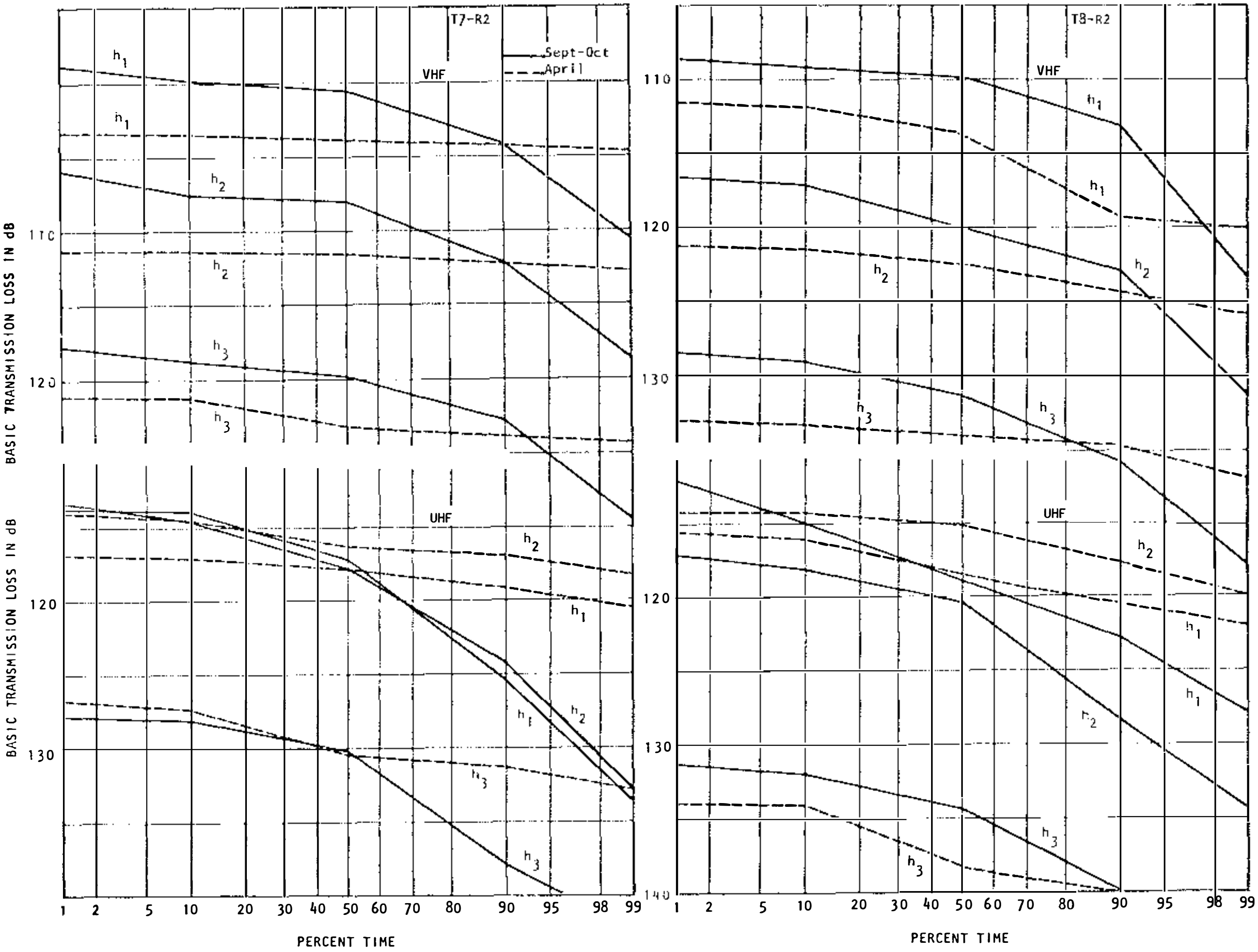

Figure GM22. Cumulative distributions of basic transmission loss recorded over paths T7-R2 and T8-R2, Graham Mountains.

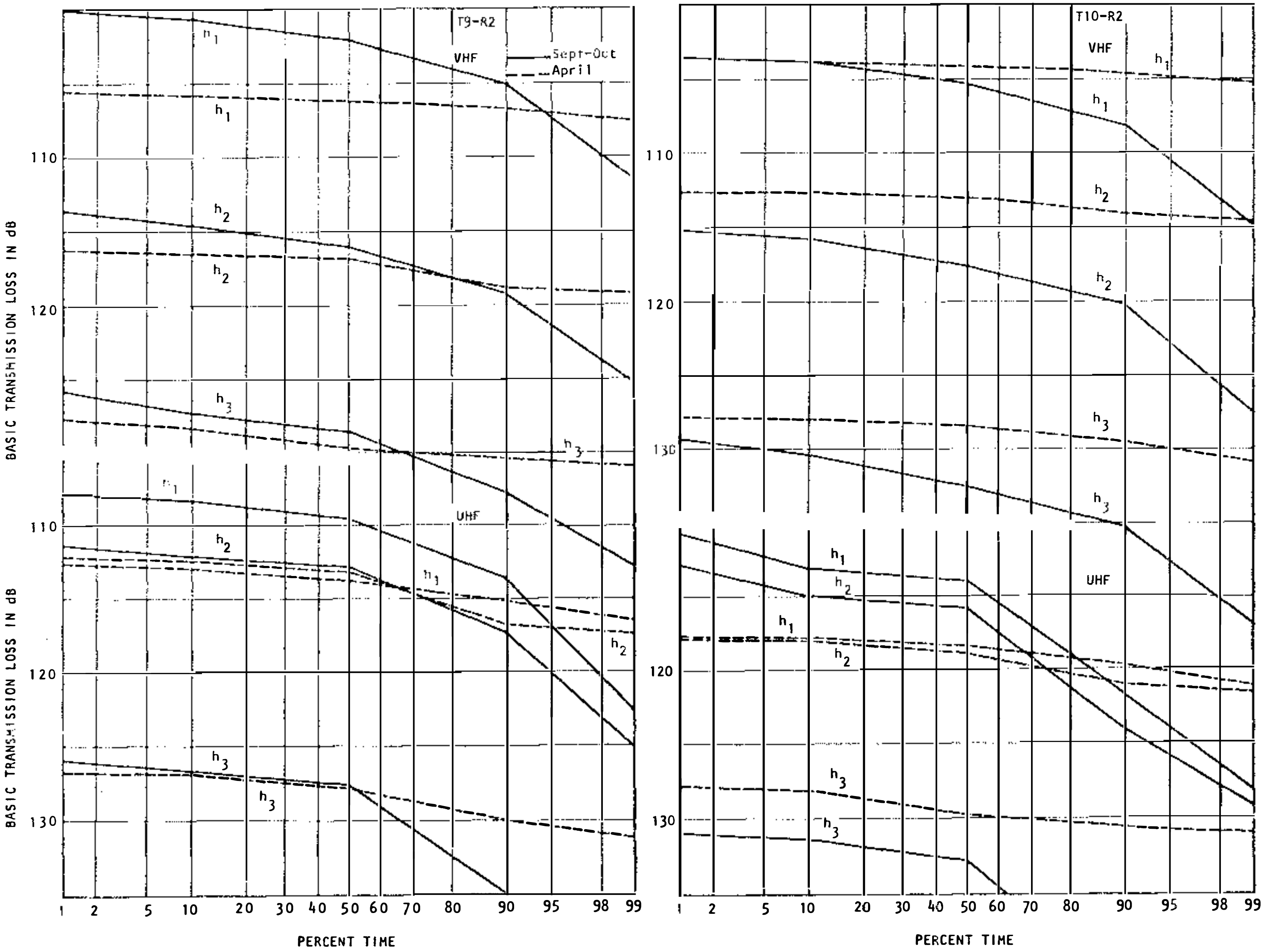

Figure GM23. Cumulative distributions of basic transmission loss recorded over paths T9-R2 and T10-R2, Graham Mountains.

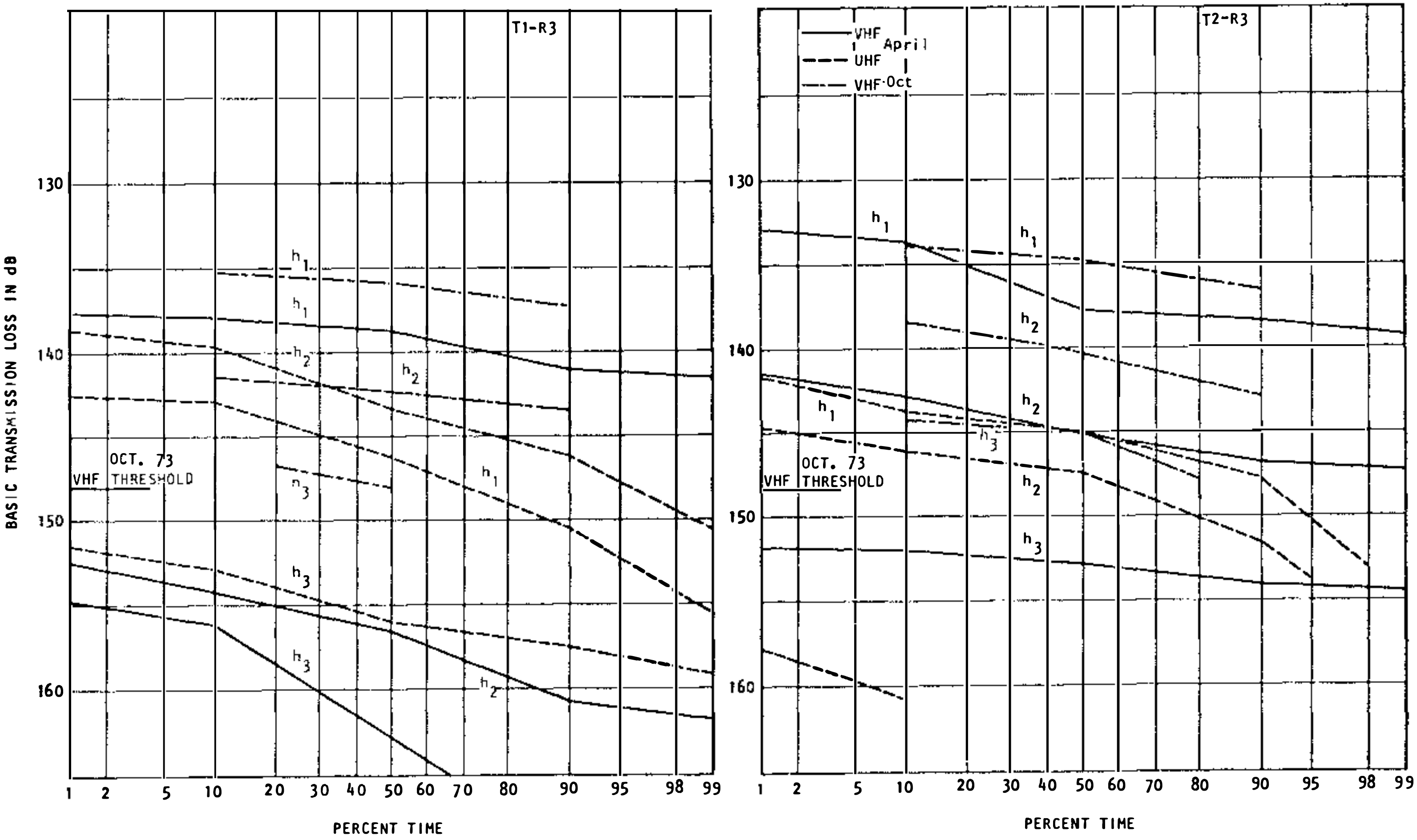

Figure GM24. Cumulative distributions of basic transmission loss recorded over paths T1-R3 and T2-R3, Graham Mountains.

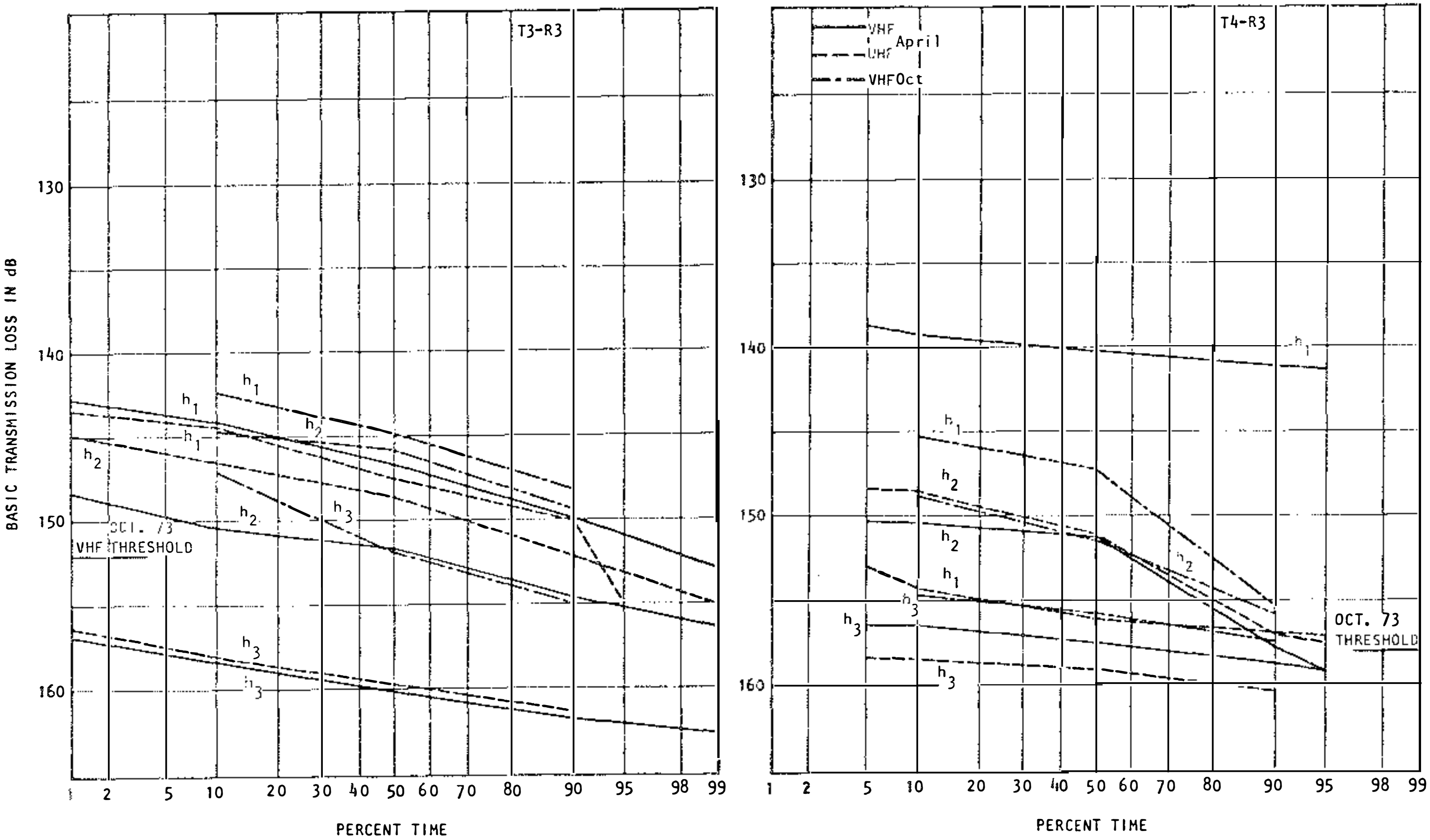

Figure G125. Cumulative distributions of basic transmission loss recorded over paths T3-R3 and T4-R3, Graham Mountains.

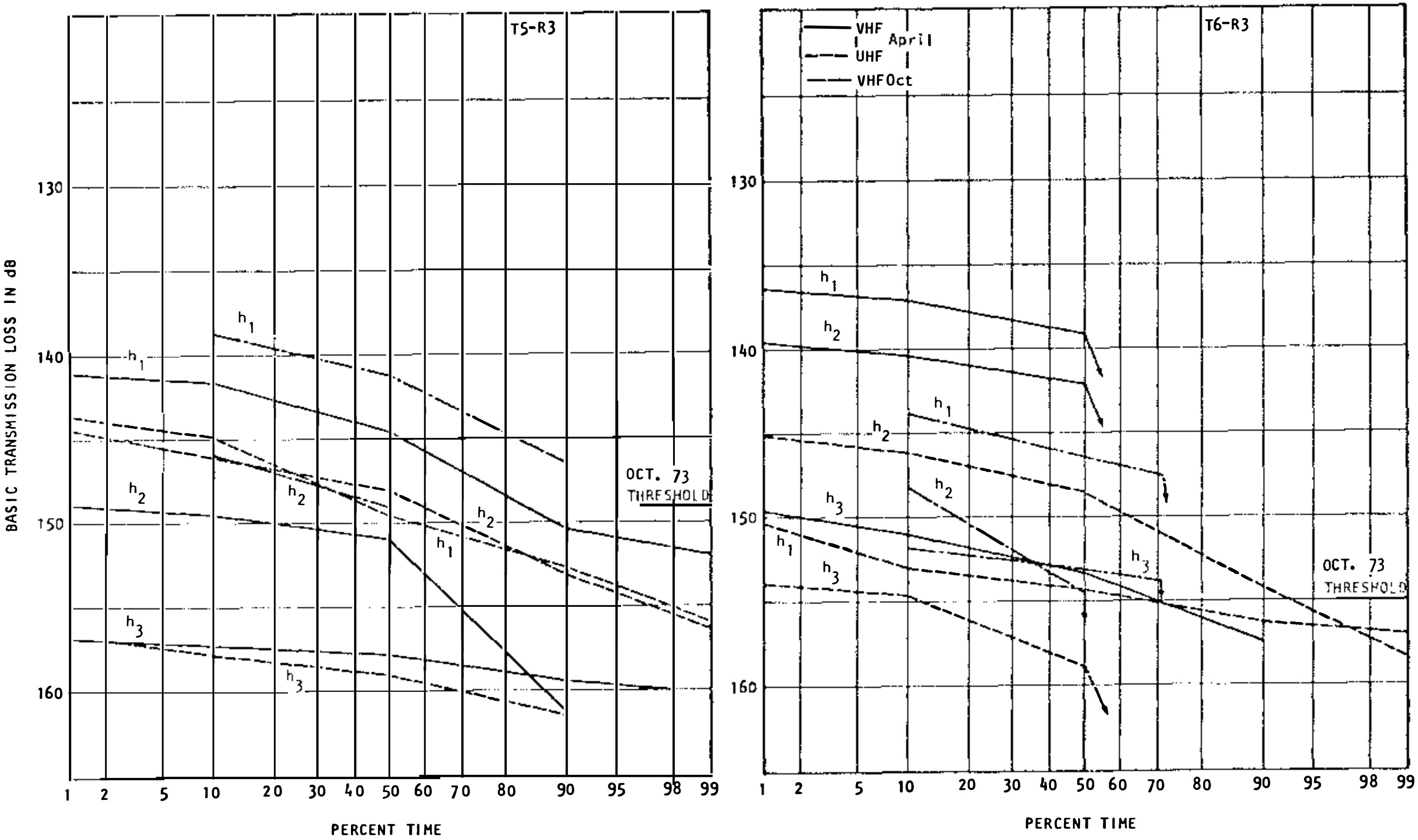

Figure GM26. Cumulative distributions of basic transmission loss recorded over paths T5-R3 and T6-R3, Graham Mountains.

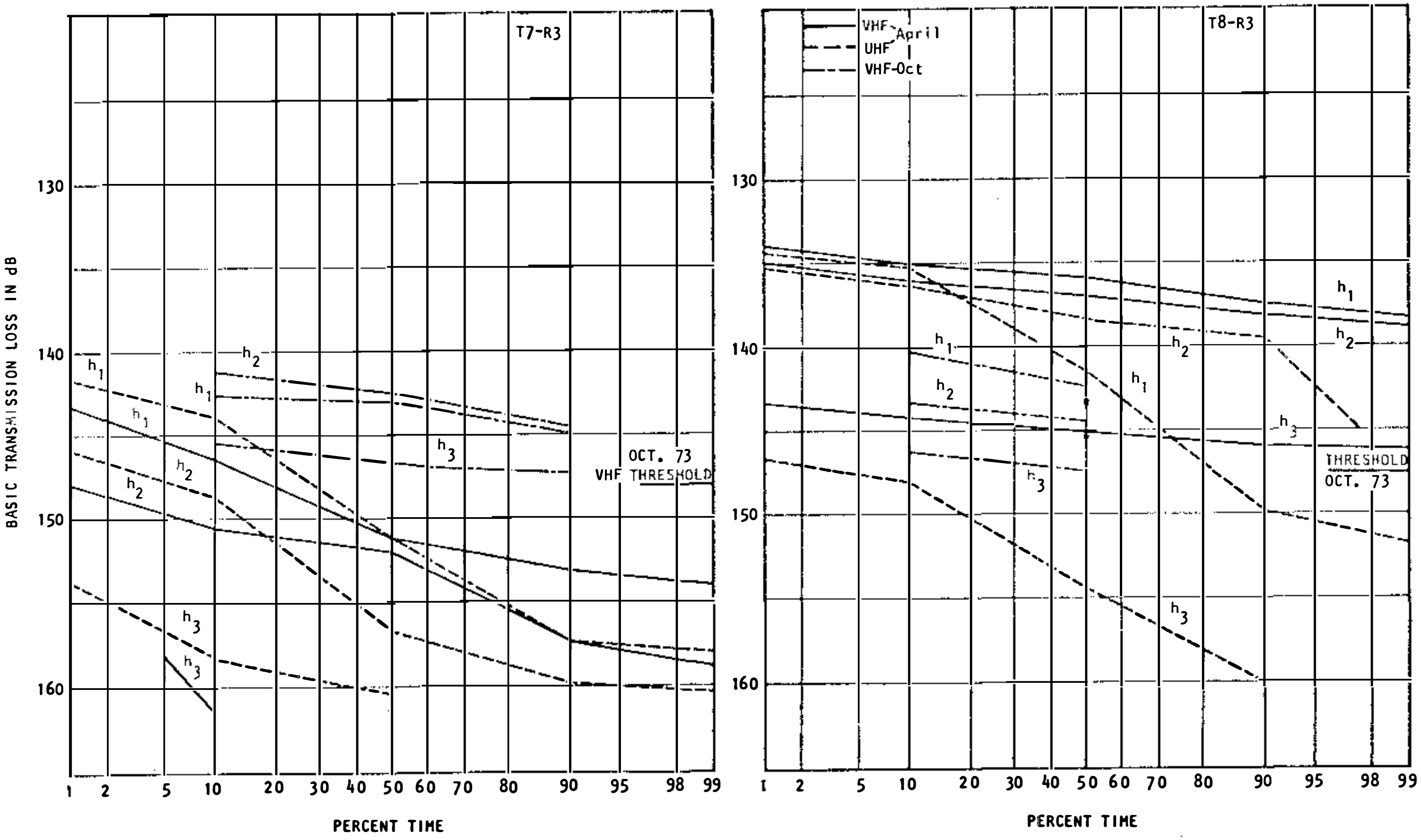

Figure GM27. Cumulative distributions of basic transmission loss recorded over paths T7-R3 and T8-R3, Graham Mountains.

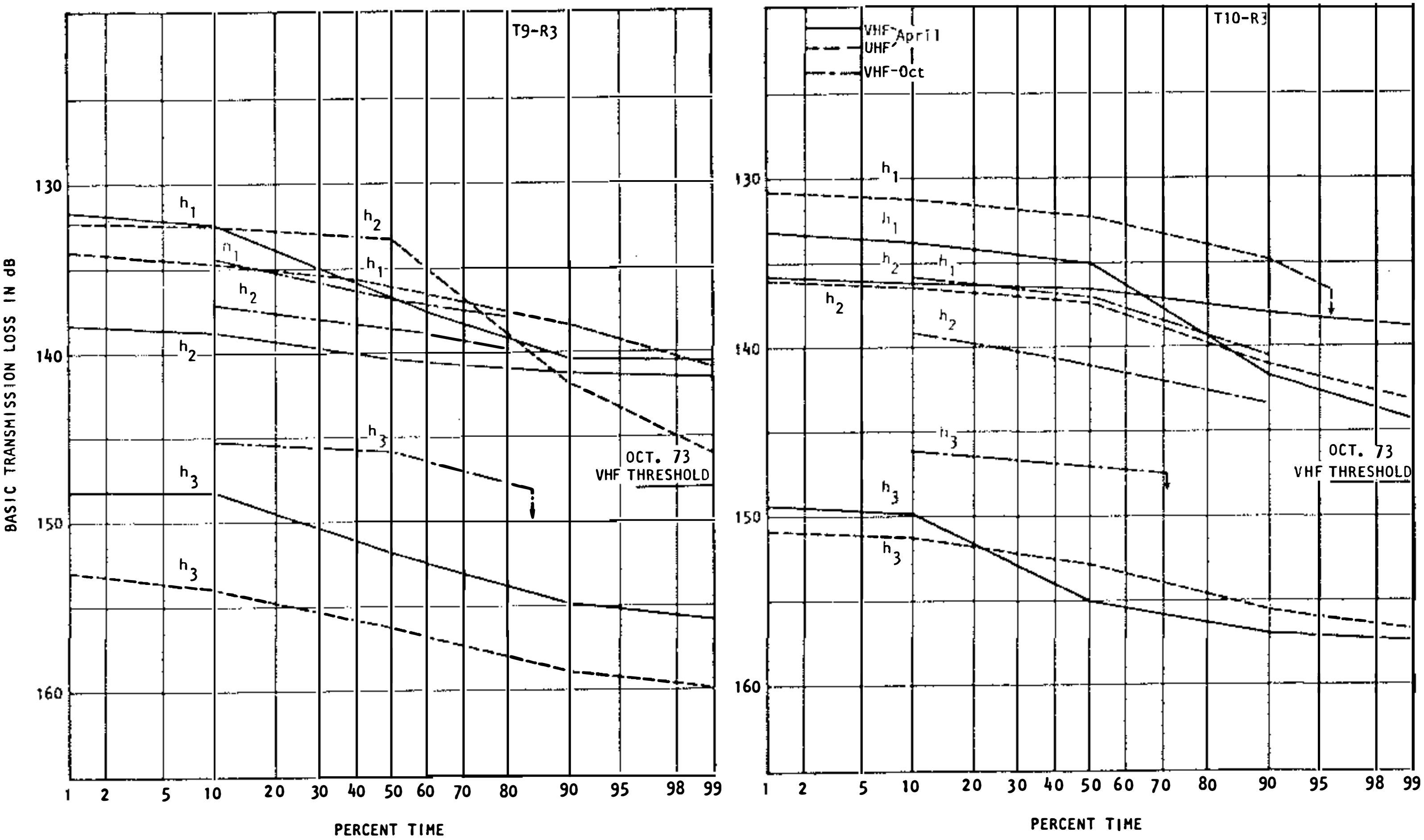

Figure GM28. Cumulative distributions of basic transmission loss recorded over paths T9-R3 and T10-R3, Graham Mountains.

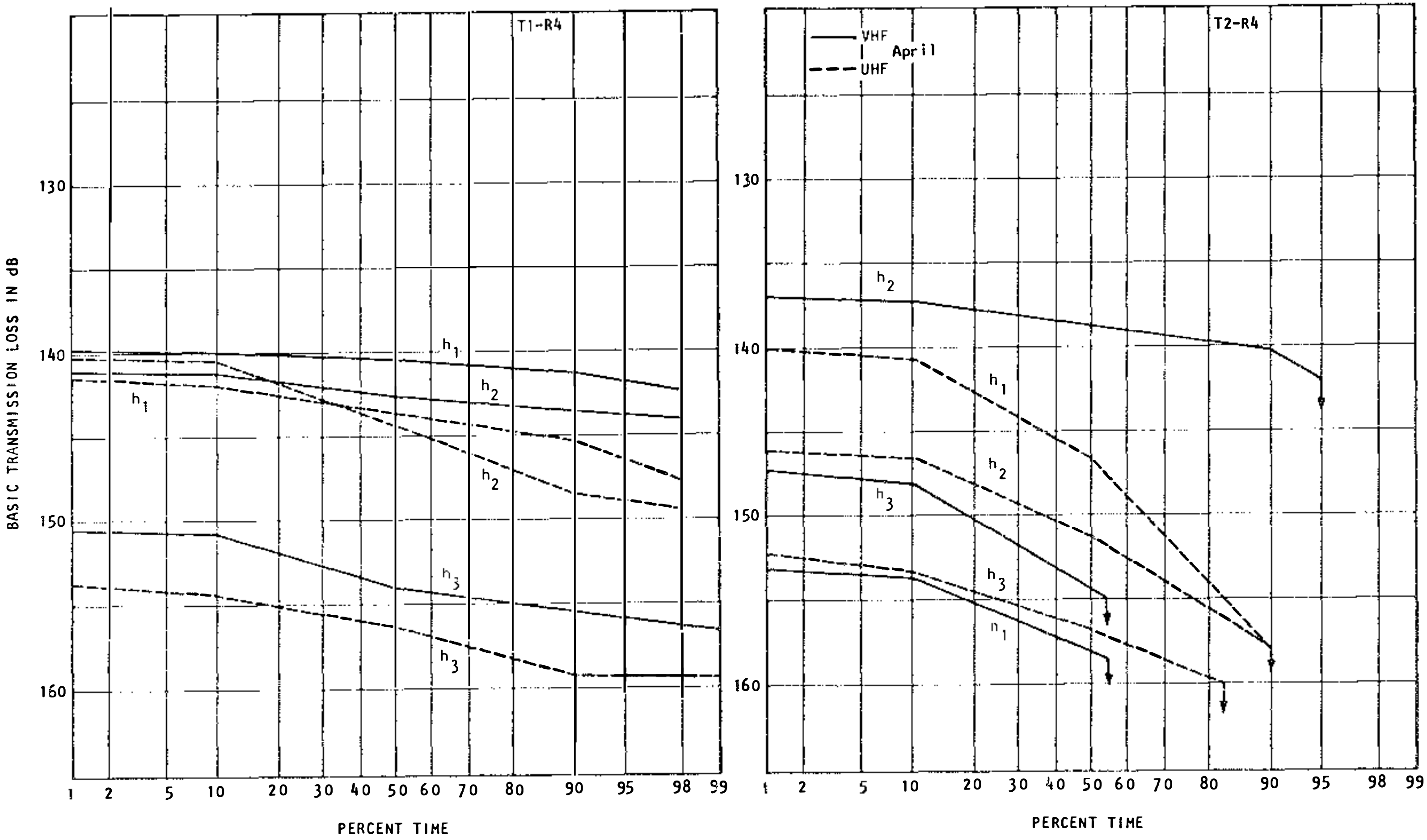

Figure GM29. Cumulative distributions of basic transmission loss recorded over paths T1-R4 and T2-R4, Graham Mountains.

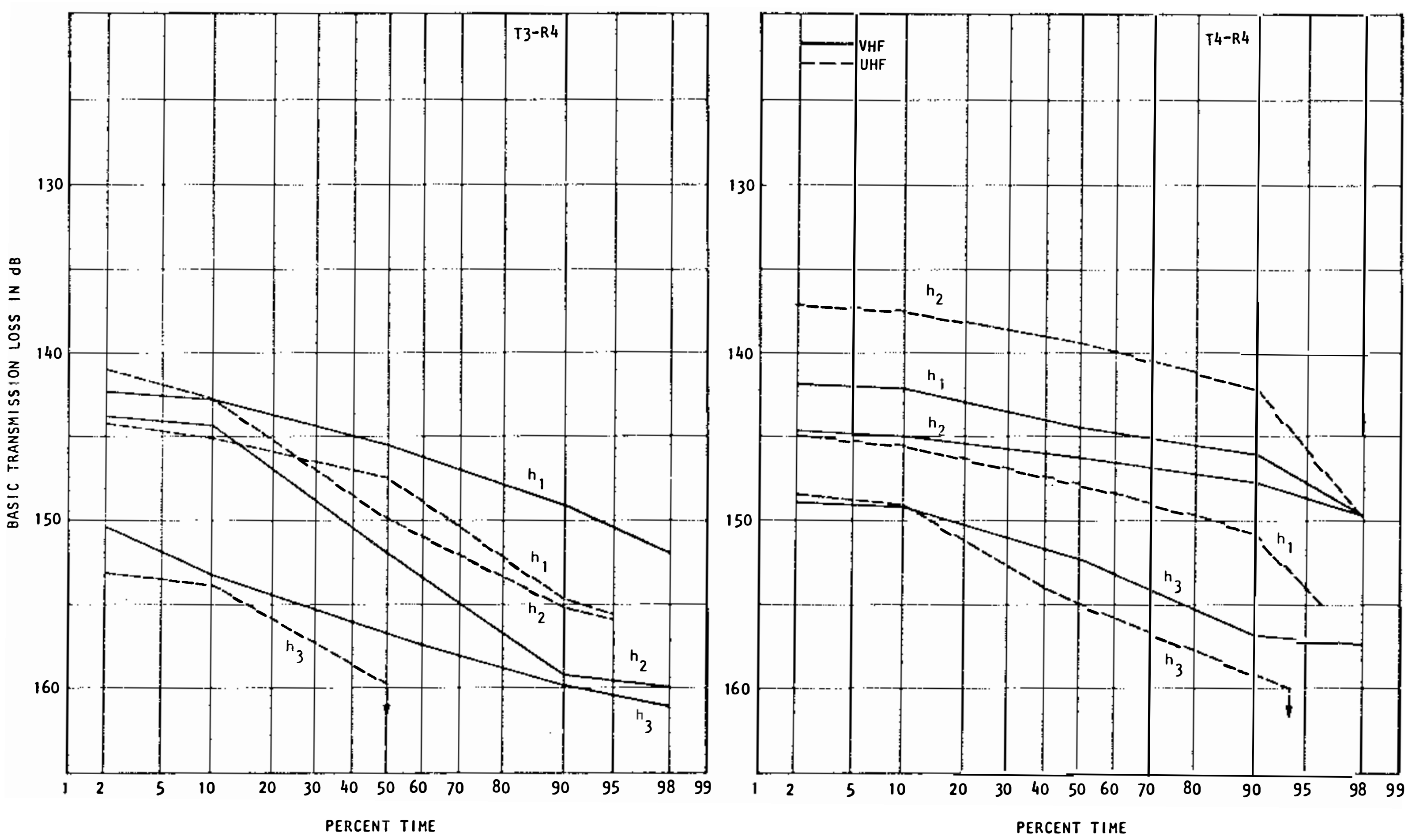

Figure GM30. Cumulative distributions of basic transmission loss recorded over paths T3-R4 and T4-R4, Graham Mountains.

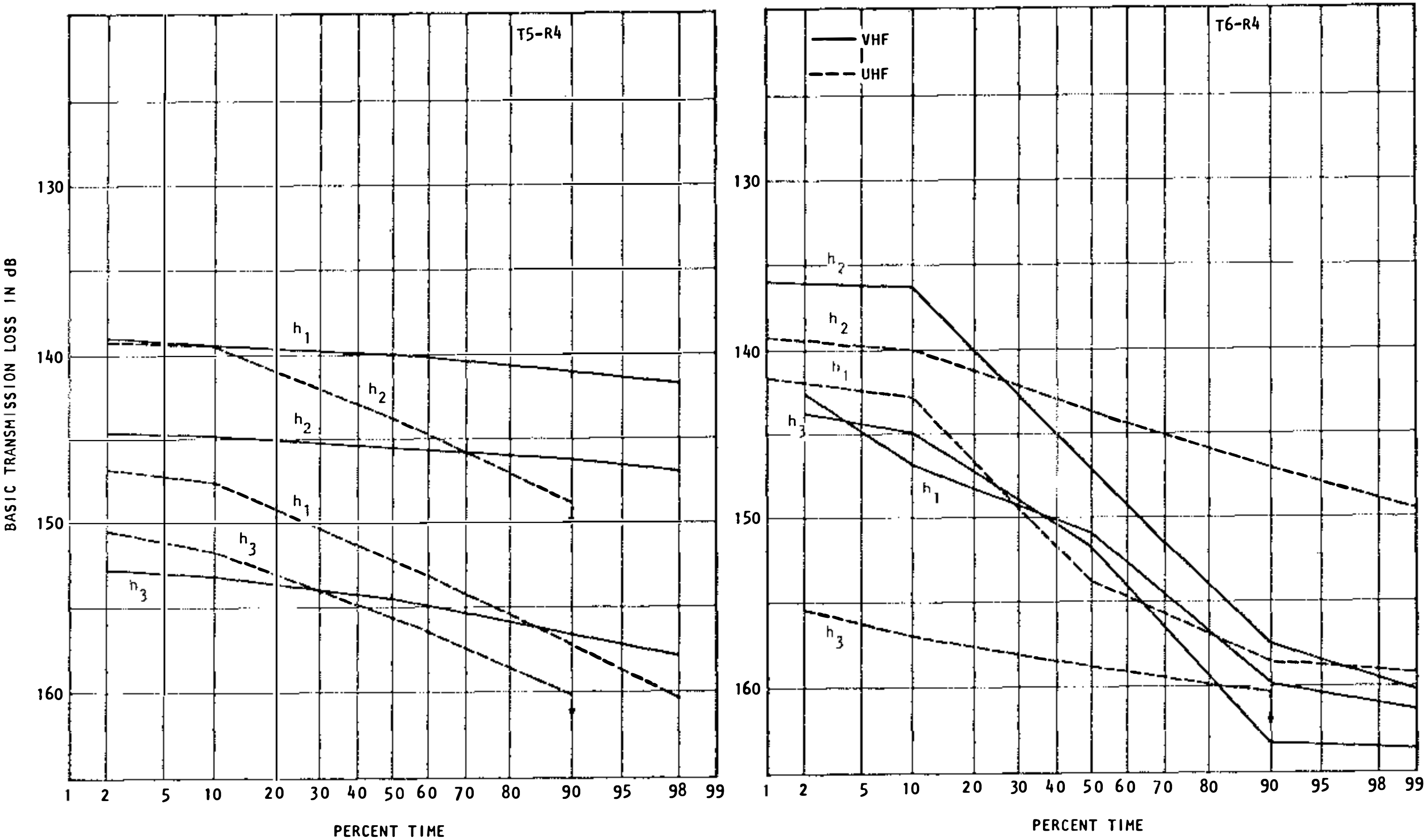

Figure GM31. Cumulative distributions of basic transmission loss recorded over paths T5-R4 and T6-R4, Graham Mountains.

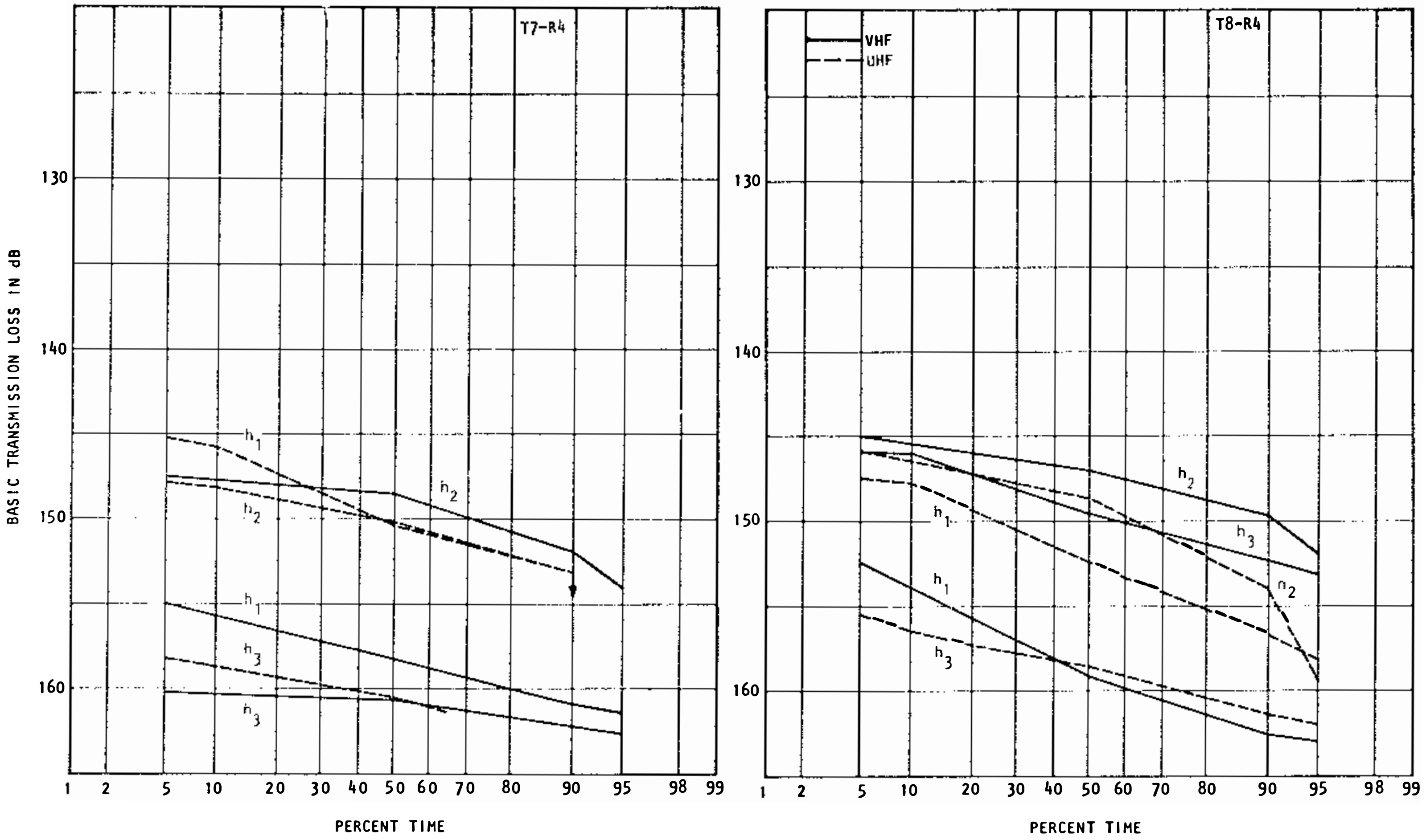

Figure GM32. Cumulative distributions of basic transmission loss recorded over paths T7-R4 and T8-R4, Graham Mountains.

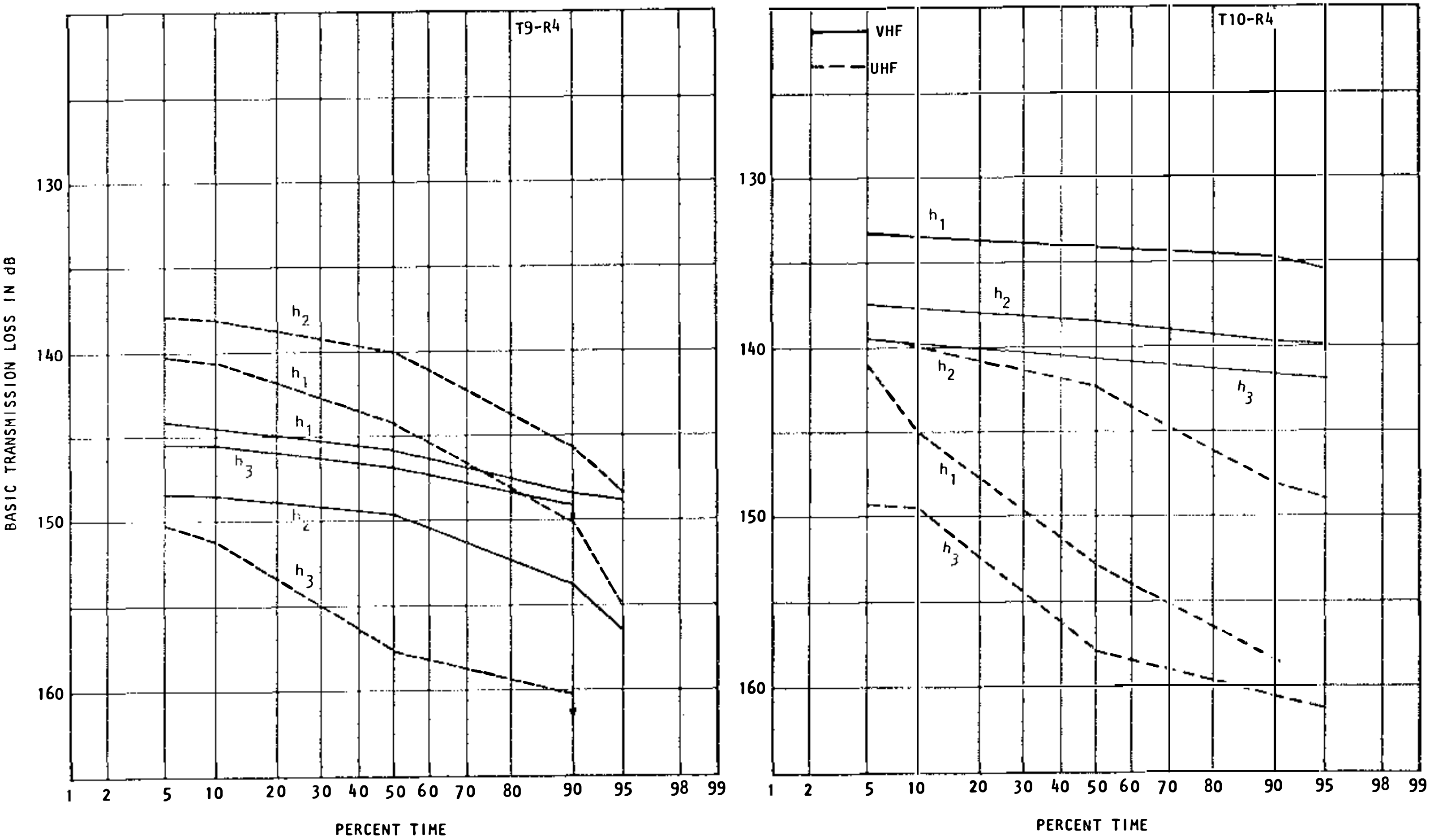

Figure GM33. Cumulative distributions of basic transmission loss recorded over paths T9-R4 and T10-R4, Graham Mountains.

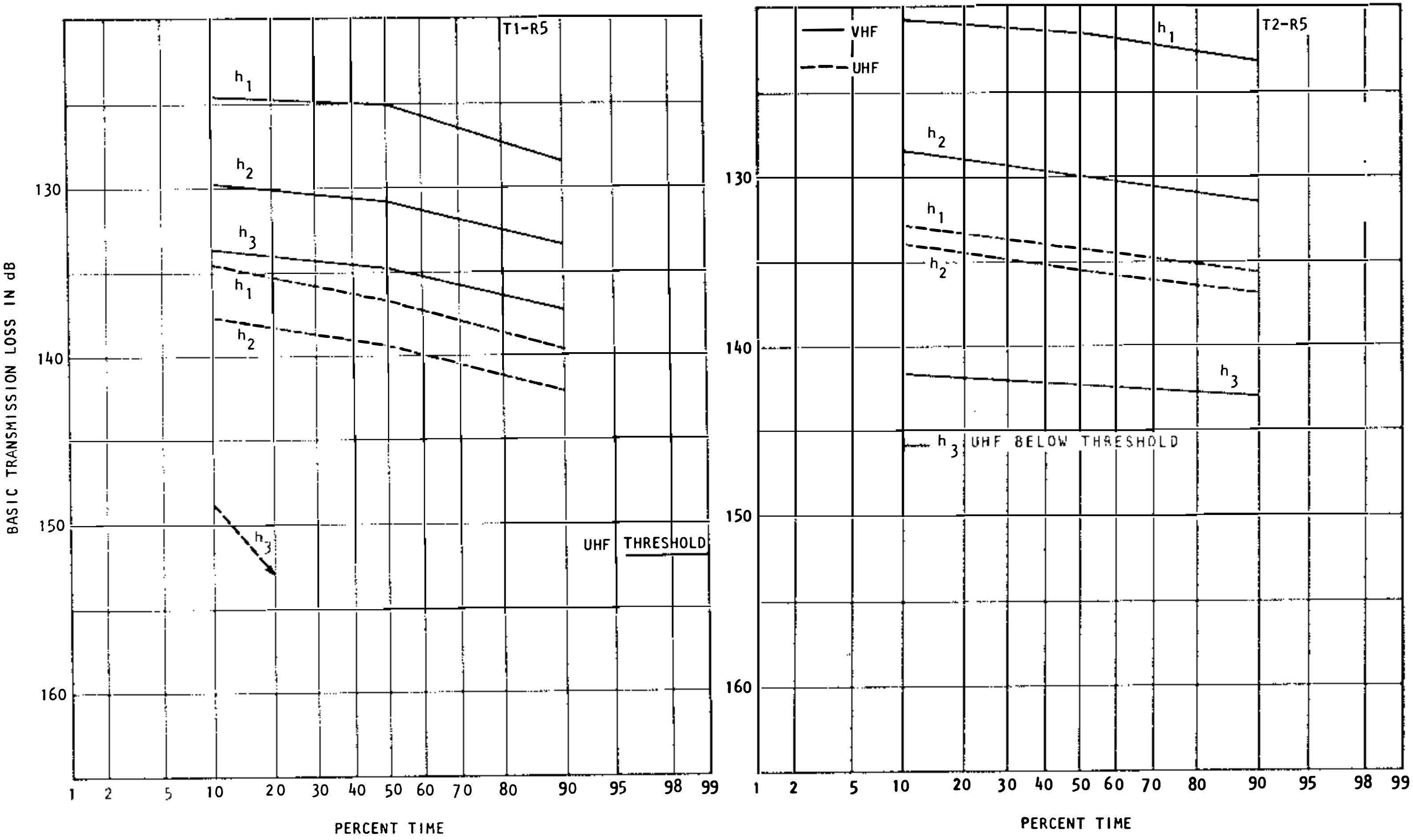

Figure GM34. Cumulative distributions of basic transmission loss recorded over paths T1-R5 and T2-R5, Graham Mountains.

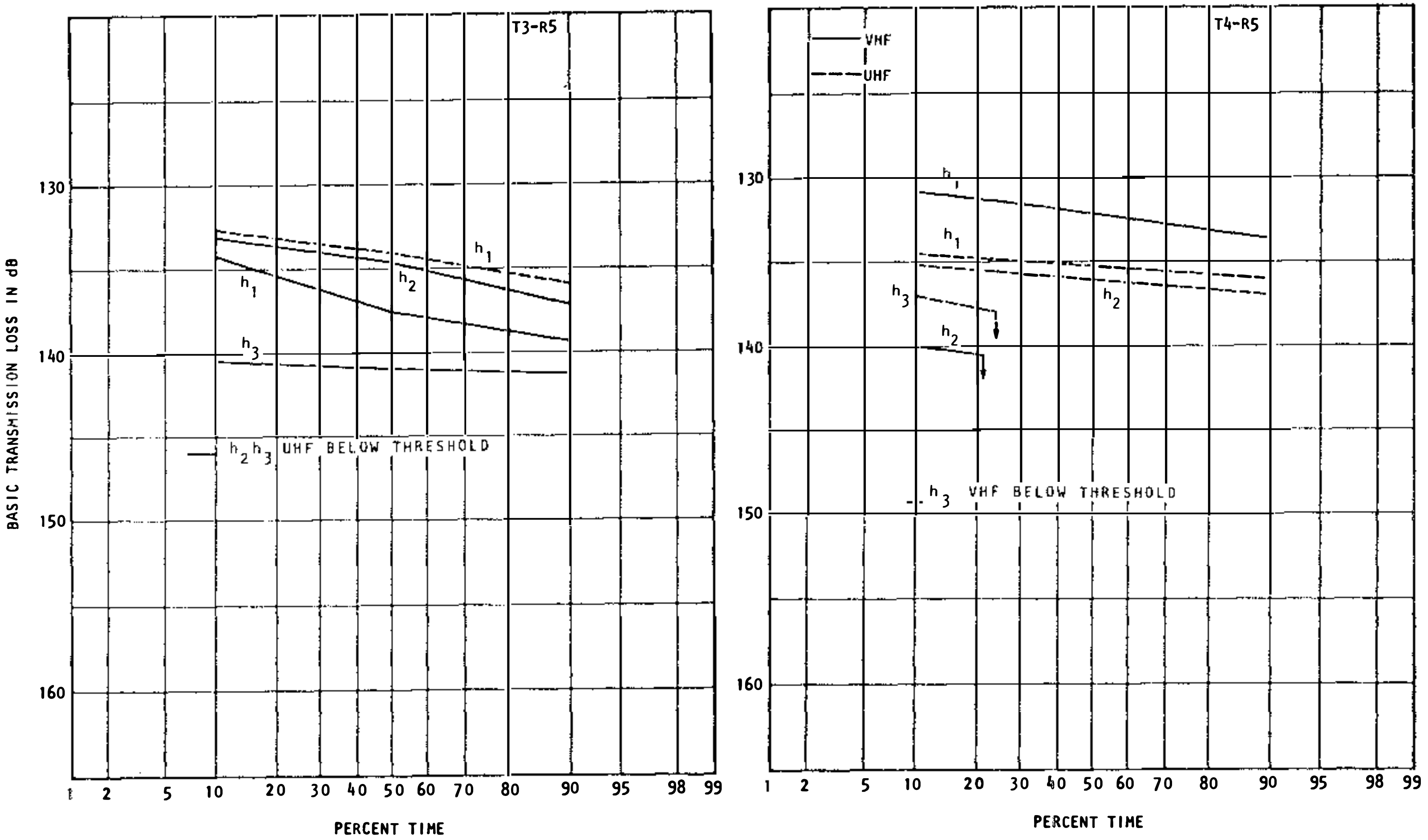

Figure GM35. Cumulative distributions of basic transmission loss recorded over paths T3-R5 and T4-R5, Graham Mountains.

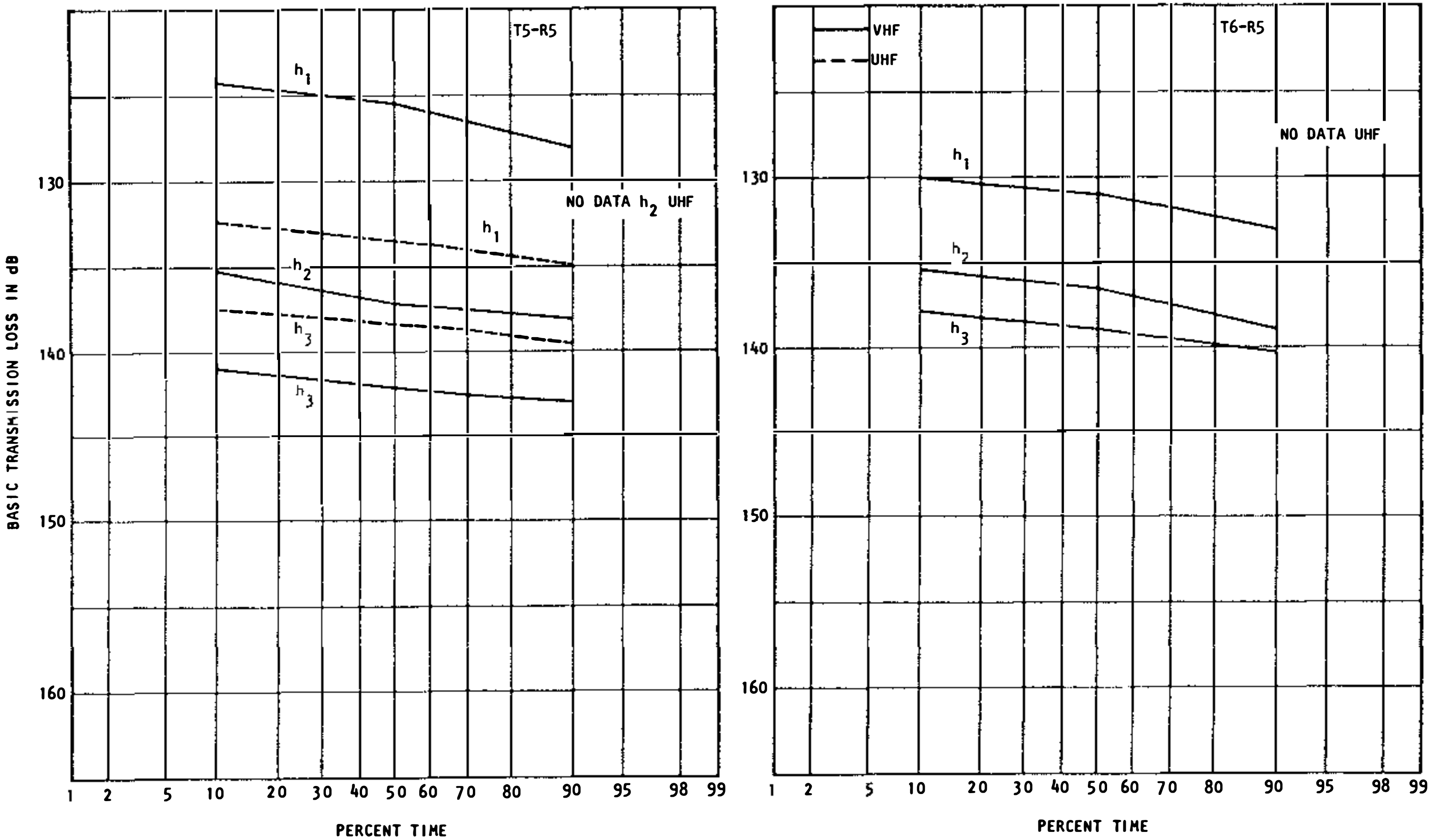

Figure GM36. Cumulative distributions of basic transmission loss recorded over paths T5-R5 and T6-R5, Graham Mountains.

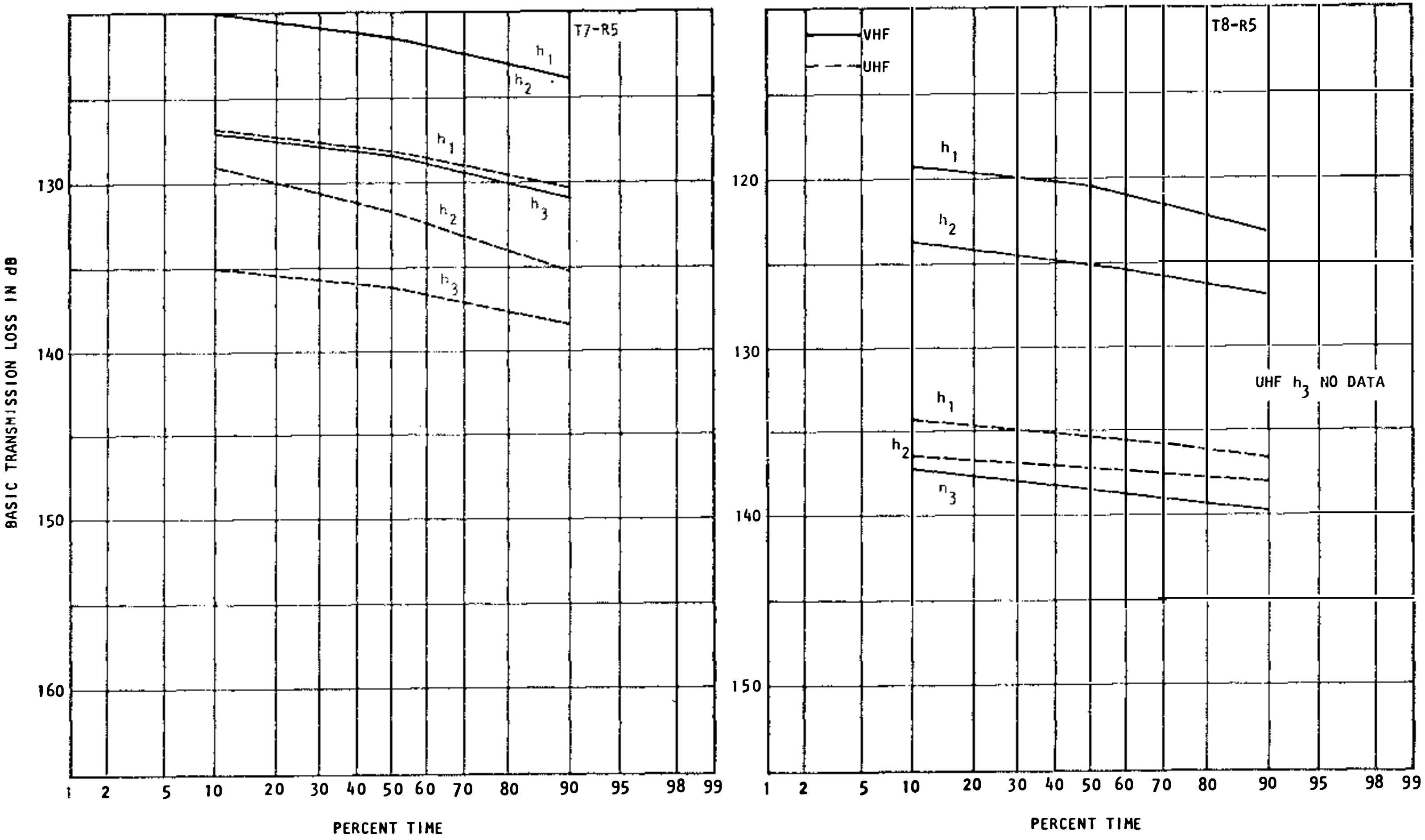

Figure GM37. Cumulative distributions of basic transmission loss recorded over paths T7-R5 and T8-R5, Graham Mountains.

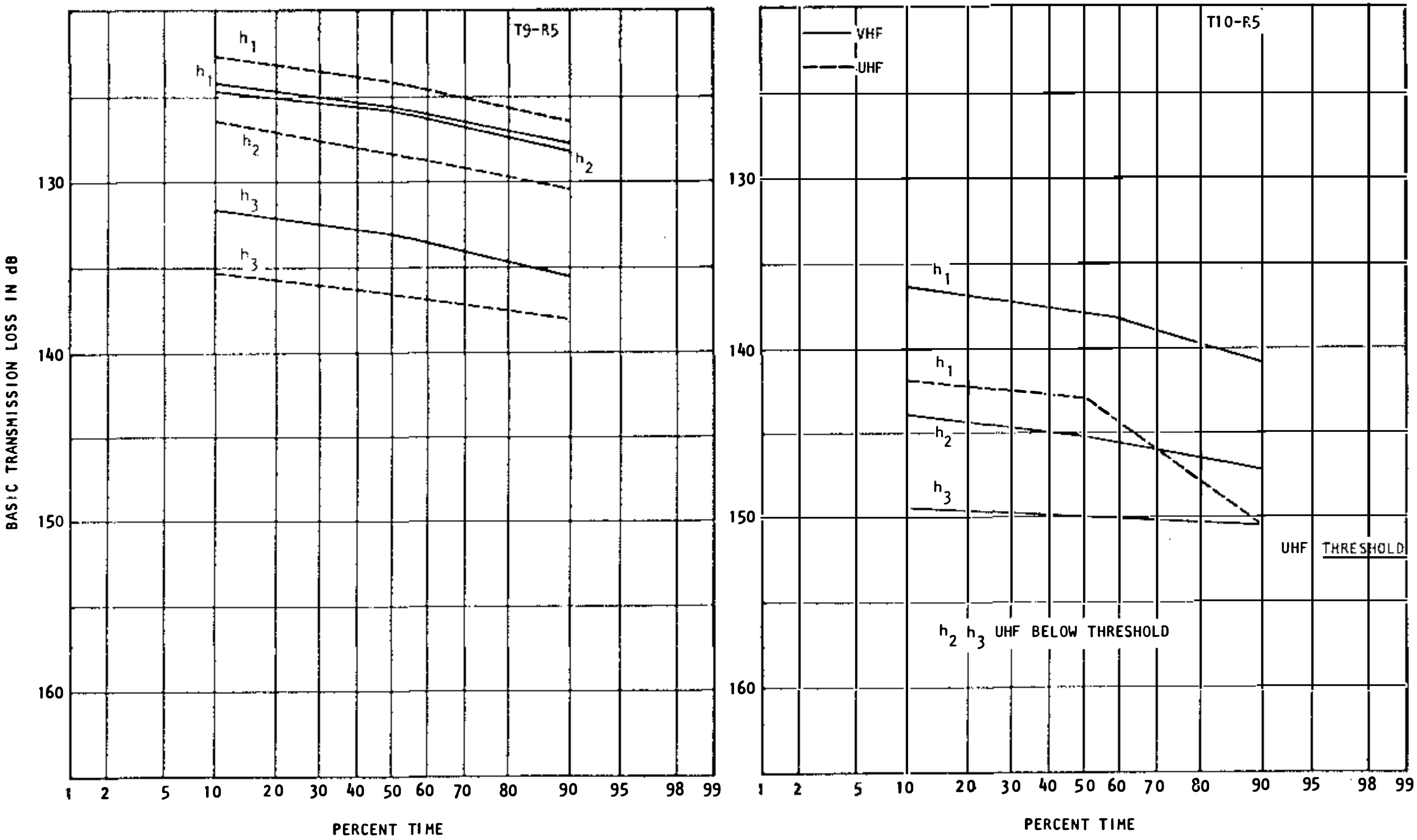

Figure GM38. Cumulative distributions of basic transmission loss recorded over paths T9-R5 and T10-R5, Graham Mountains.

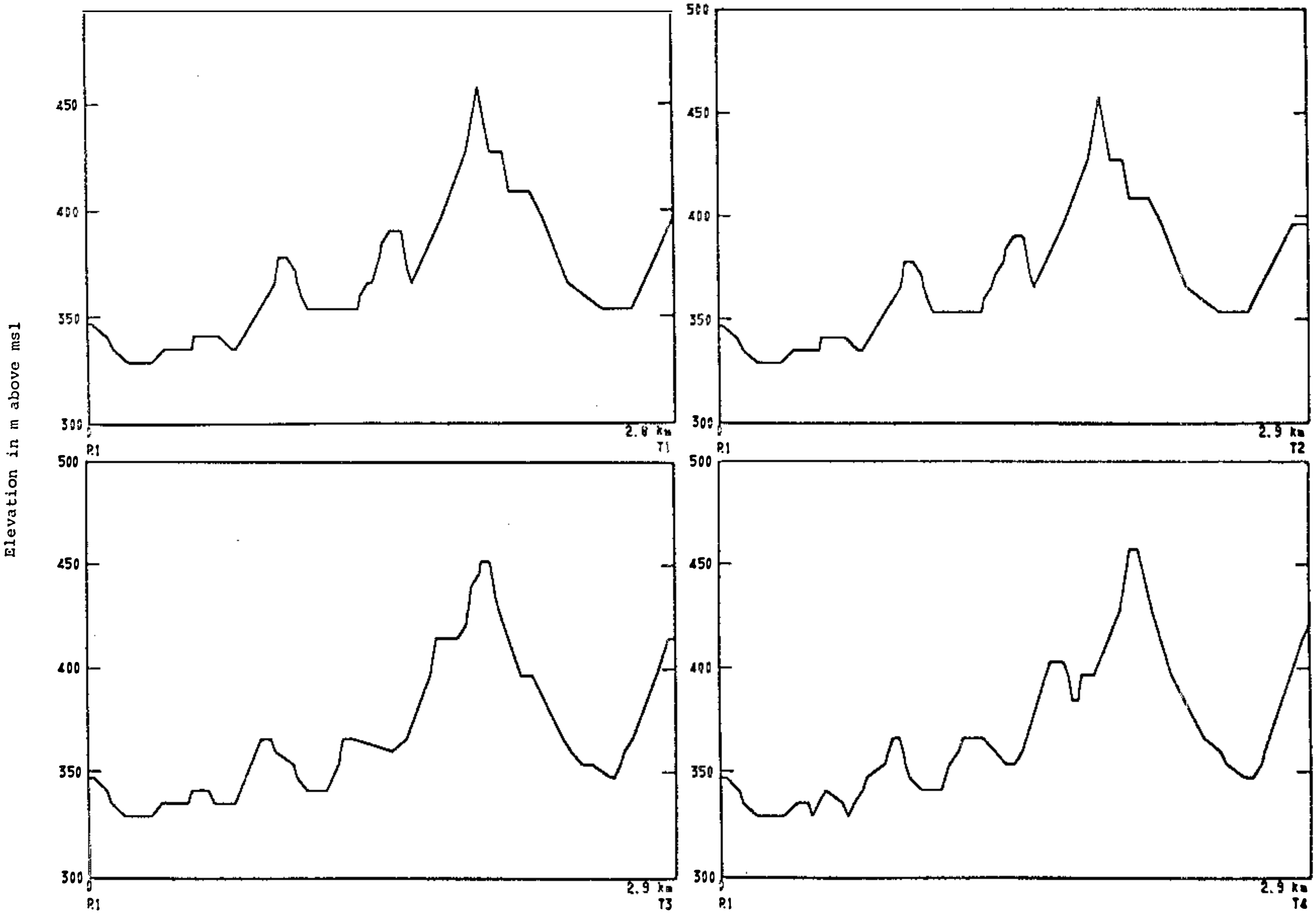

Figure HL1. Terrain profiles from transmitter sites T1, T2, T3, and T4 to receiver site R1, Hunter Liggett.

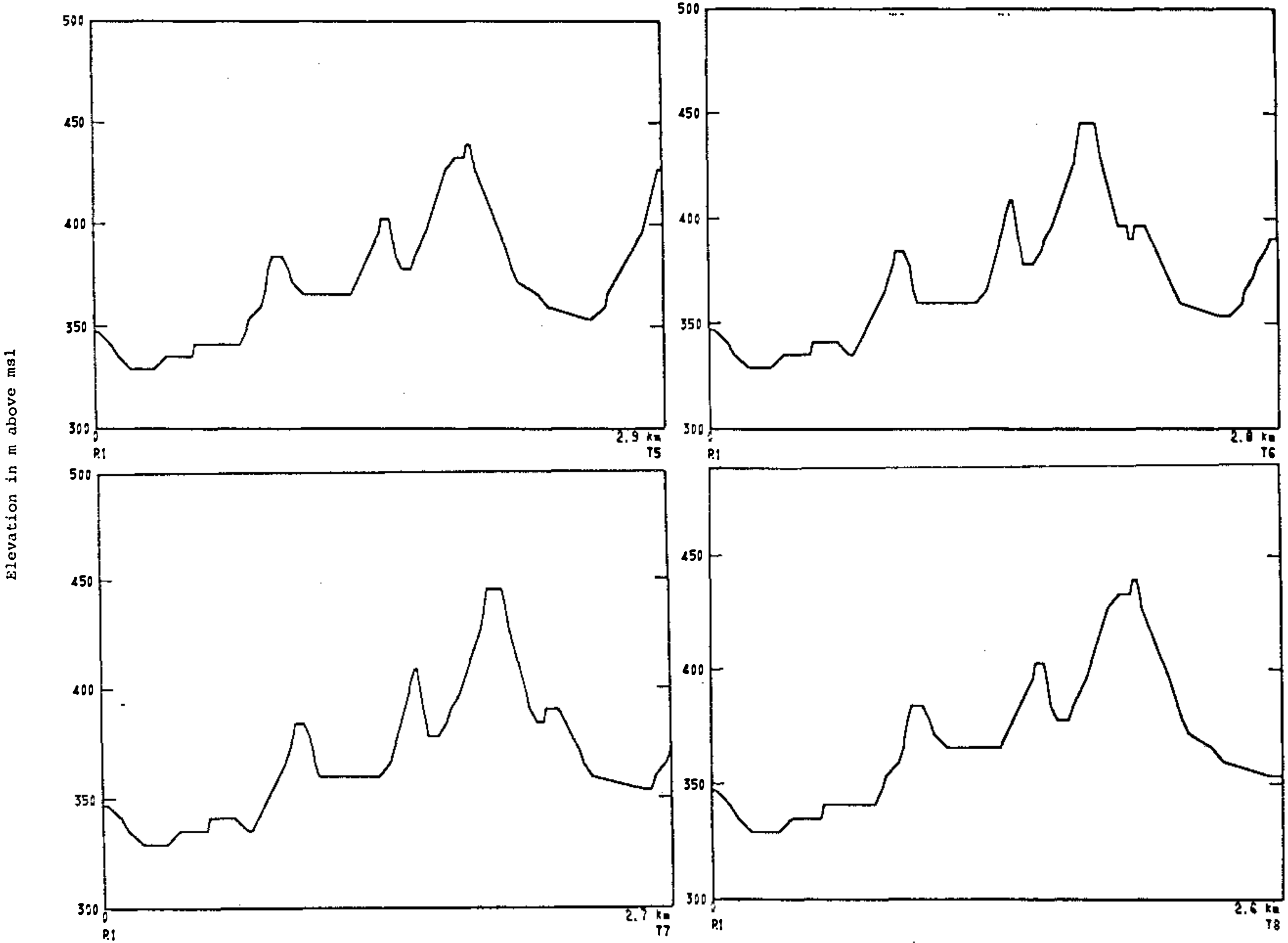

Figure HL2. Terrain profiles from transmitter sites T5, T6, T7, and T8 to receiver site R1, Hunter Liggett.

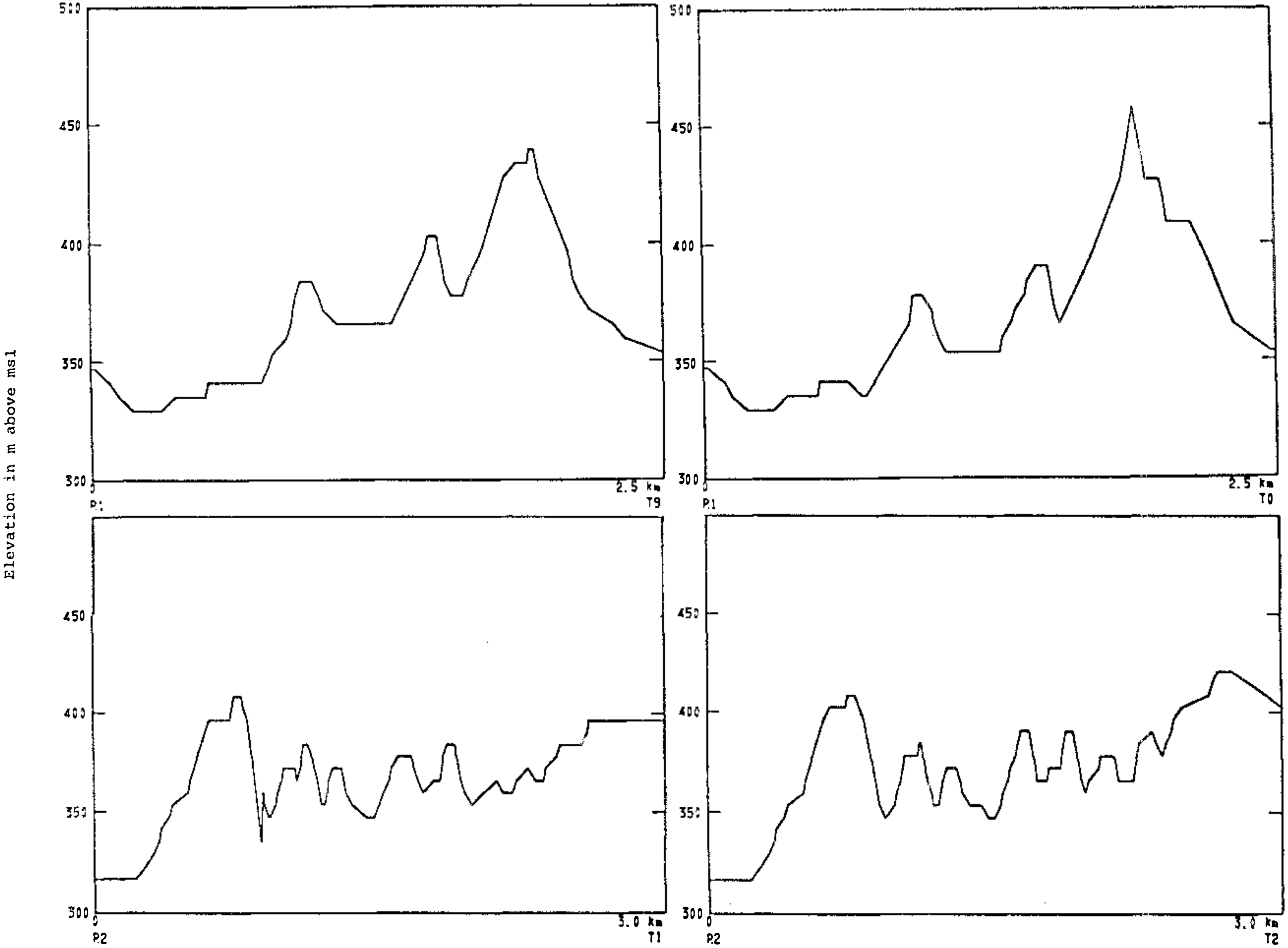

Figure HL3. Terrain profiles from T9 and T10 to R1, and from T1 and T2 to R2, Hunter Liggett.

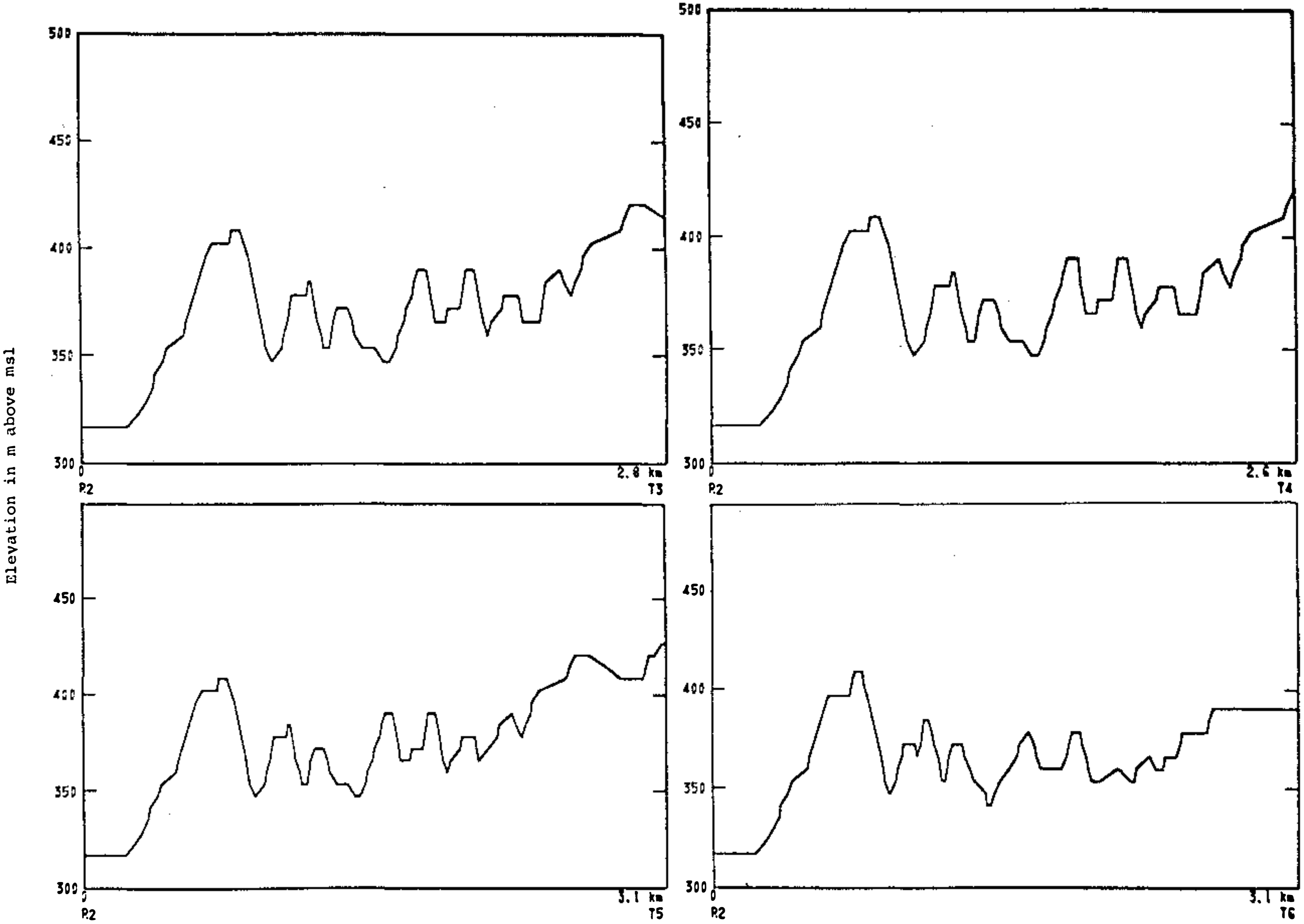

Figure HL4. Terrain profiles from transmitter sites T3, T4, T5, and T6 to receiver site R2, Hunter Liggett.

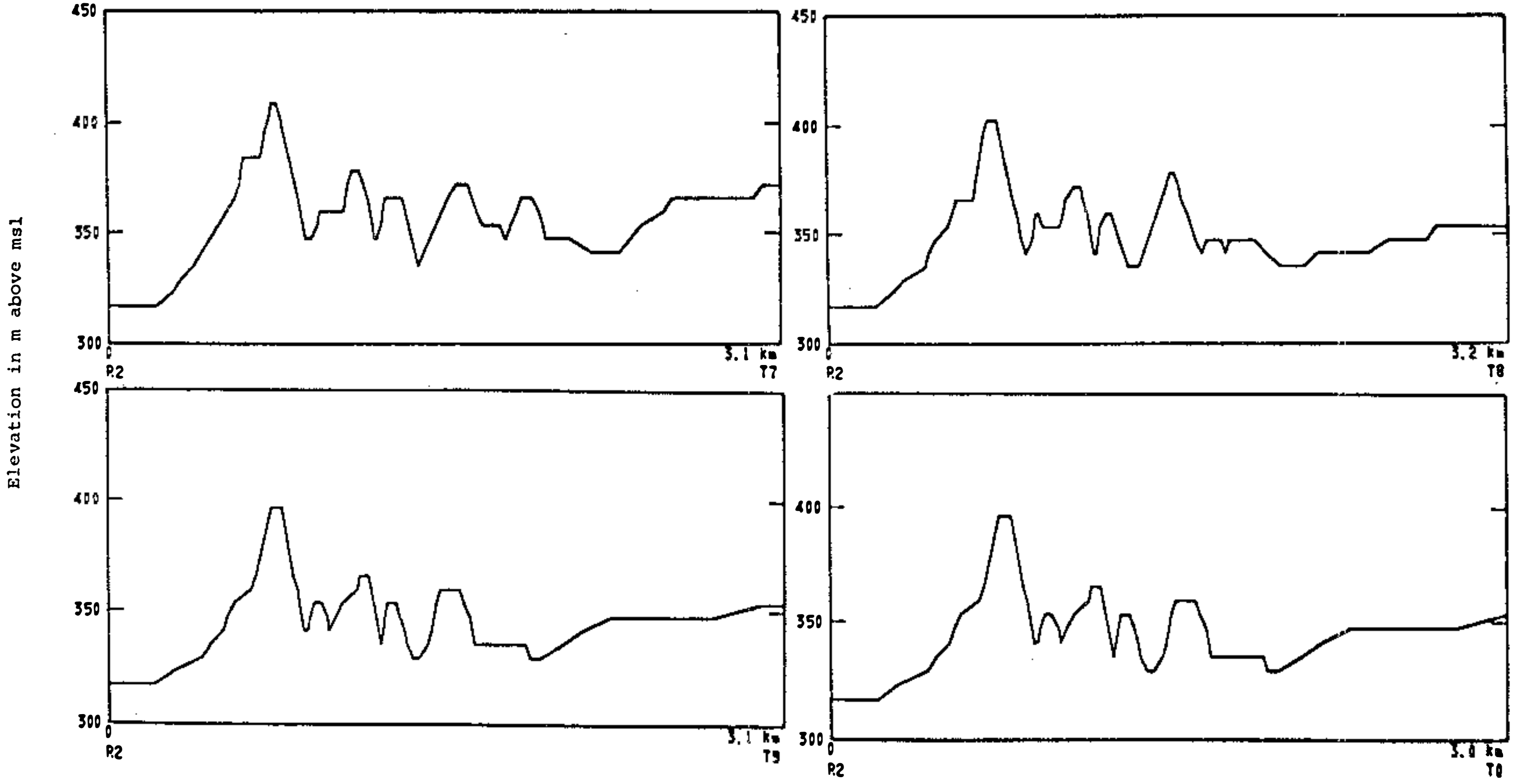

Figure HL5. Terrain profiles from transmitter sites T7, T8, T9, and T10 to receiver site R2, Hunter Liggett.

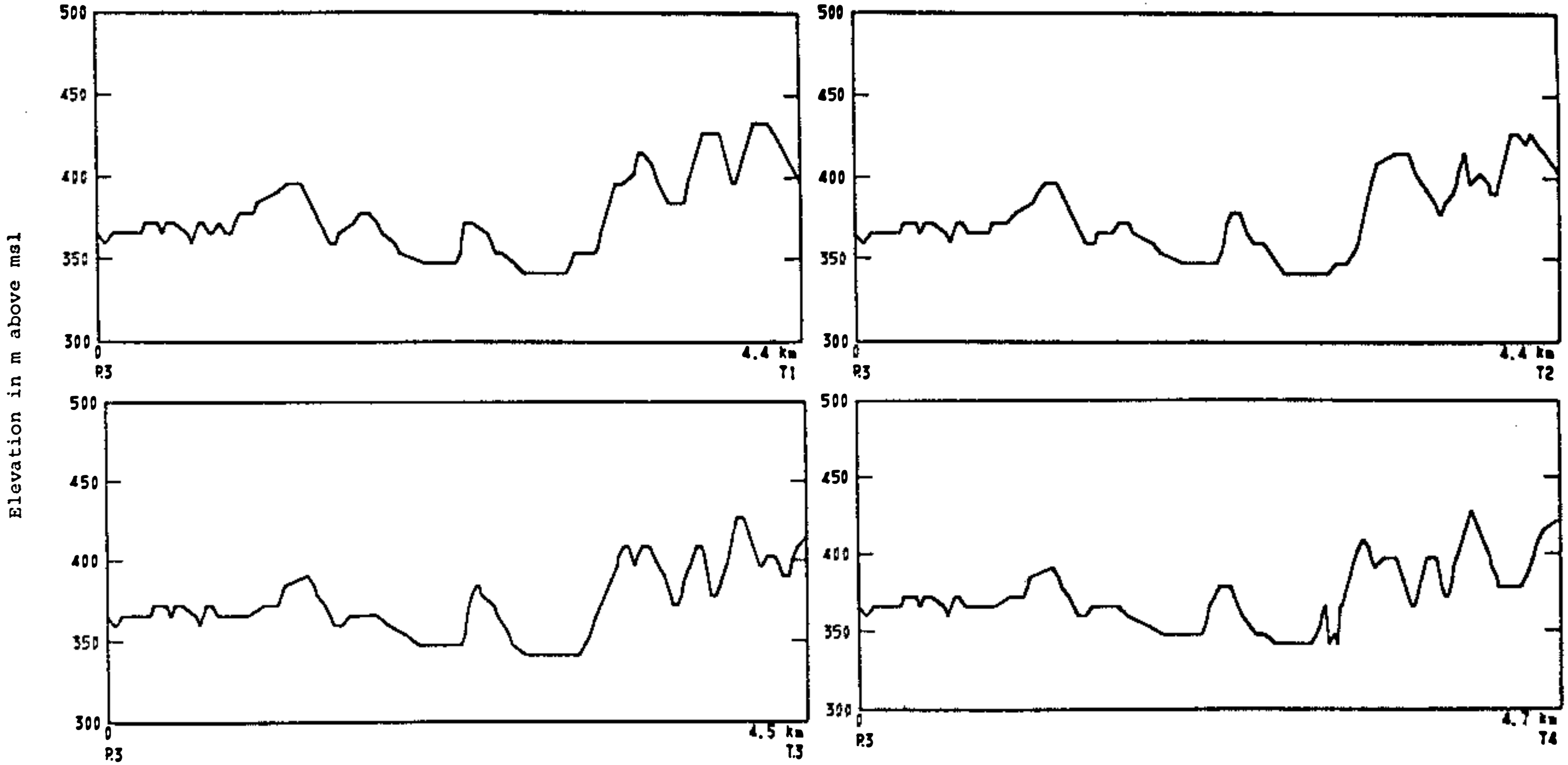

Figure HL6. Terrain profiles from transmitter sites T1, T2, T3, and T4 to receiver site R3, Hunter Liggett.

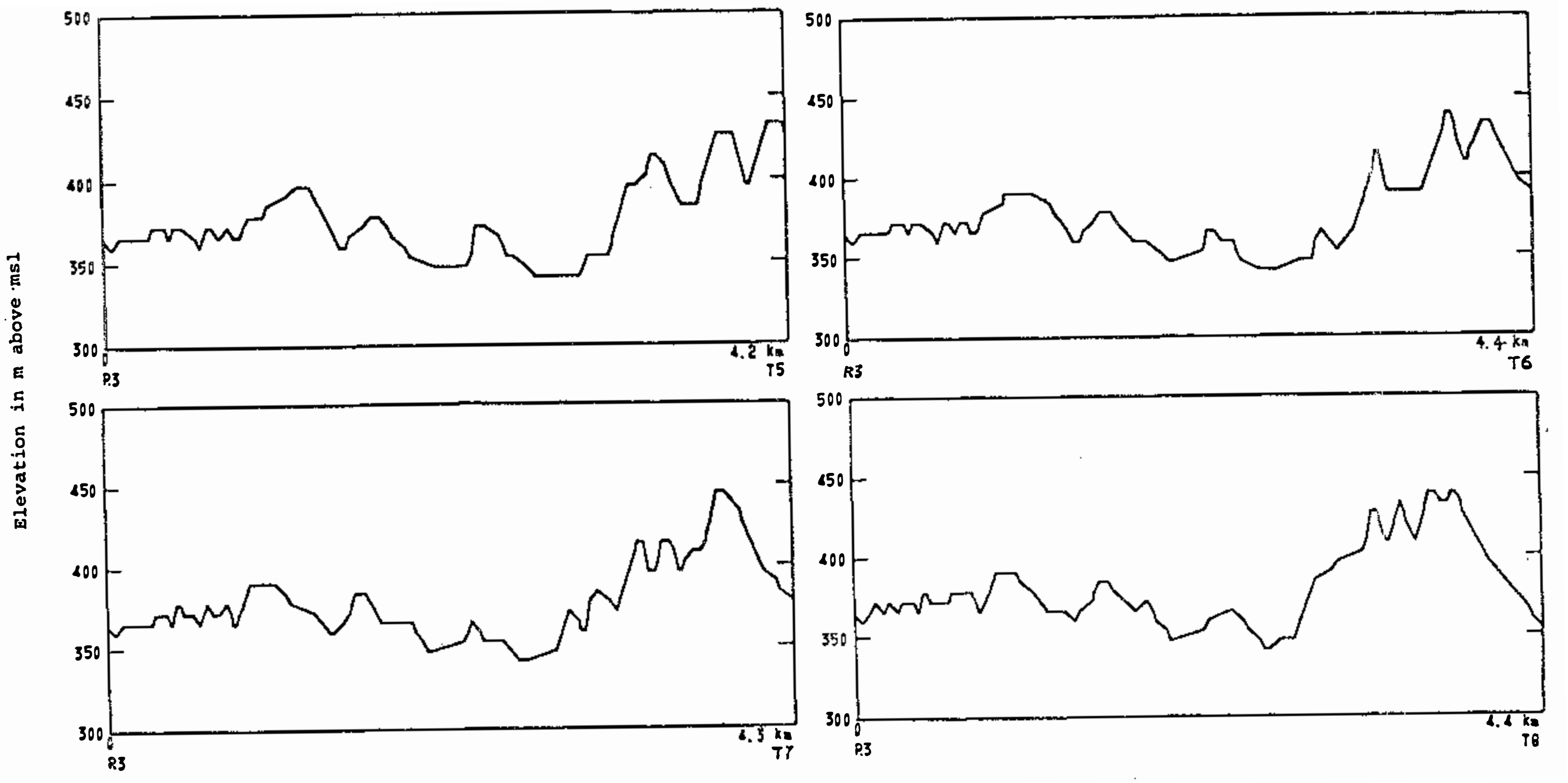

Figure HL7. Terrain profiles from transmitter sites T5, T6, T7, and T8 to receiver site R3, Hunter Liggett.

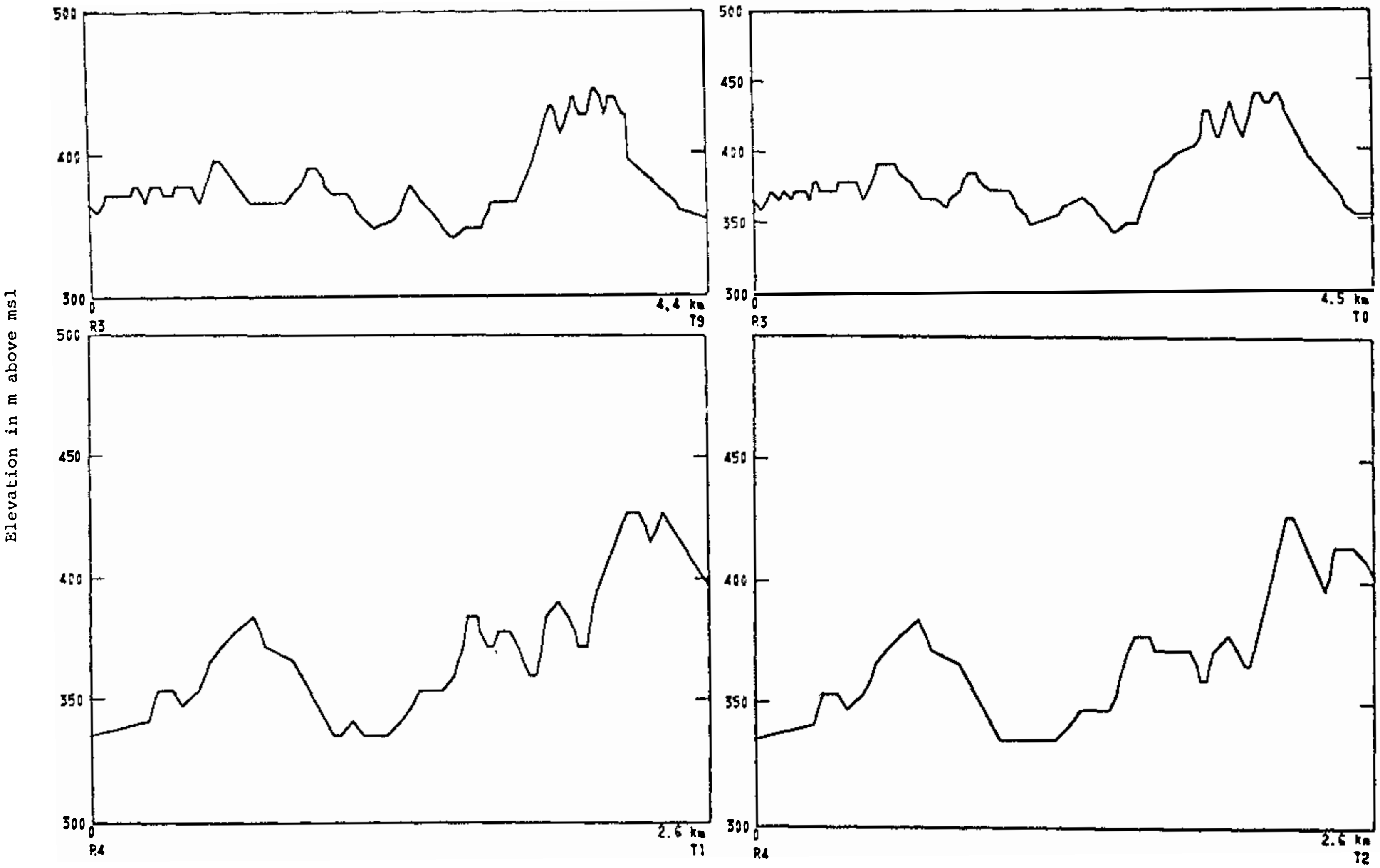

Figure HL8. Terrain profiles from T9 and T10 to R3, and from T1 and T2 to R4, Hunter Liggett.

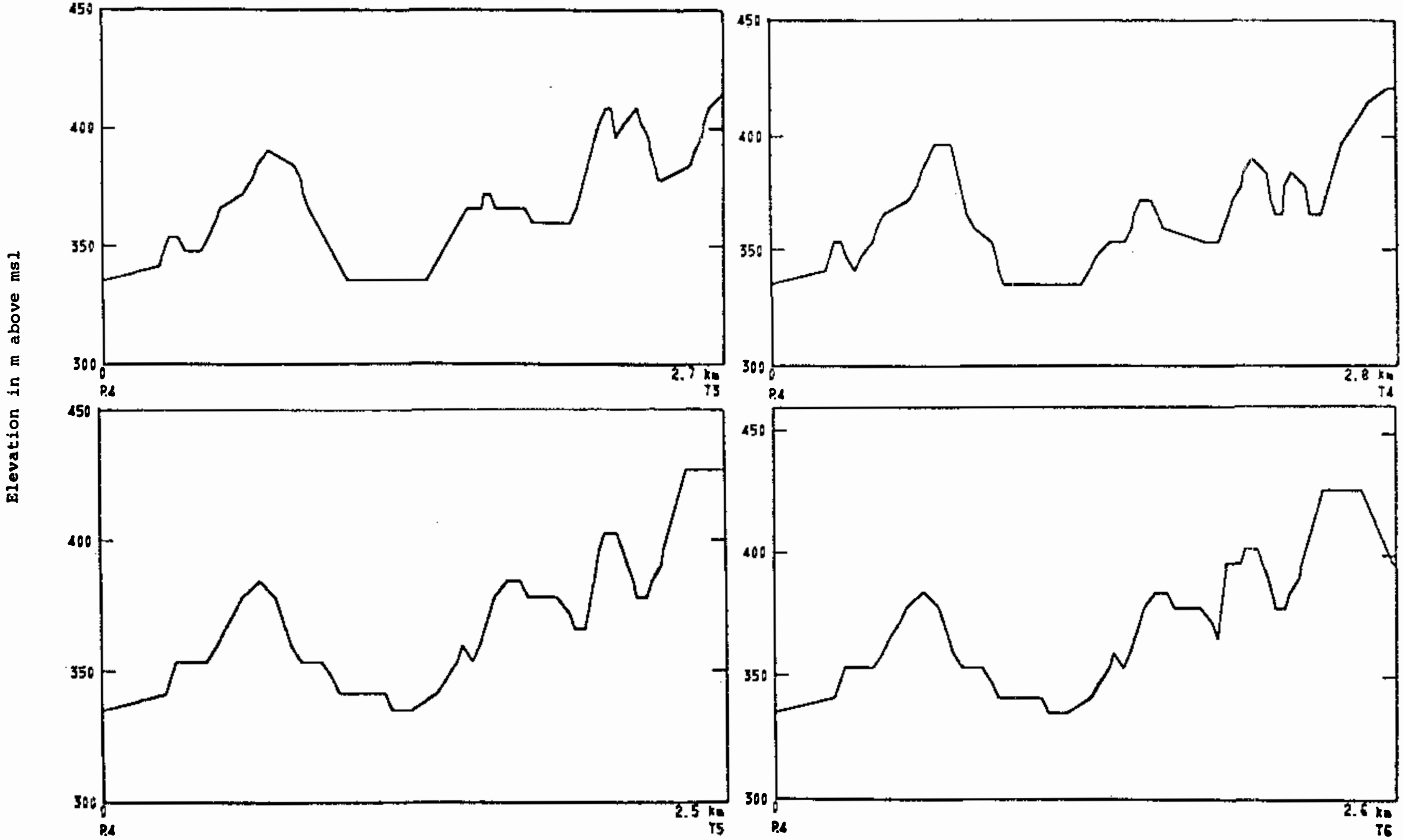

Figure HL9. Terrain profiles from transmitter sites T3, T4, T5, and T6 to receiver site R4, Hunter Liggett.

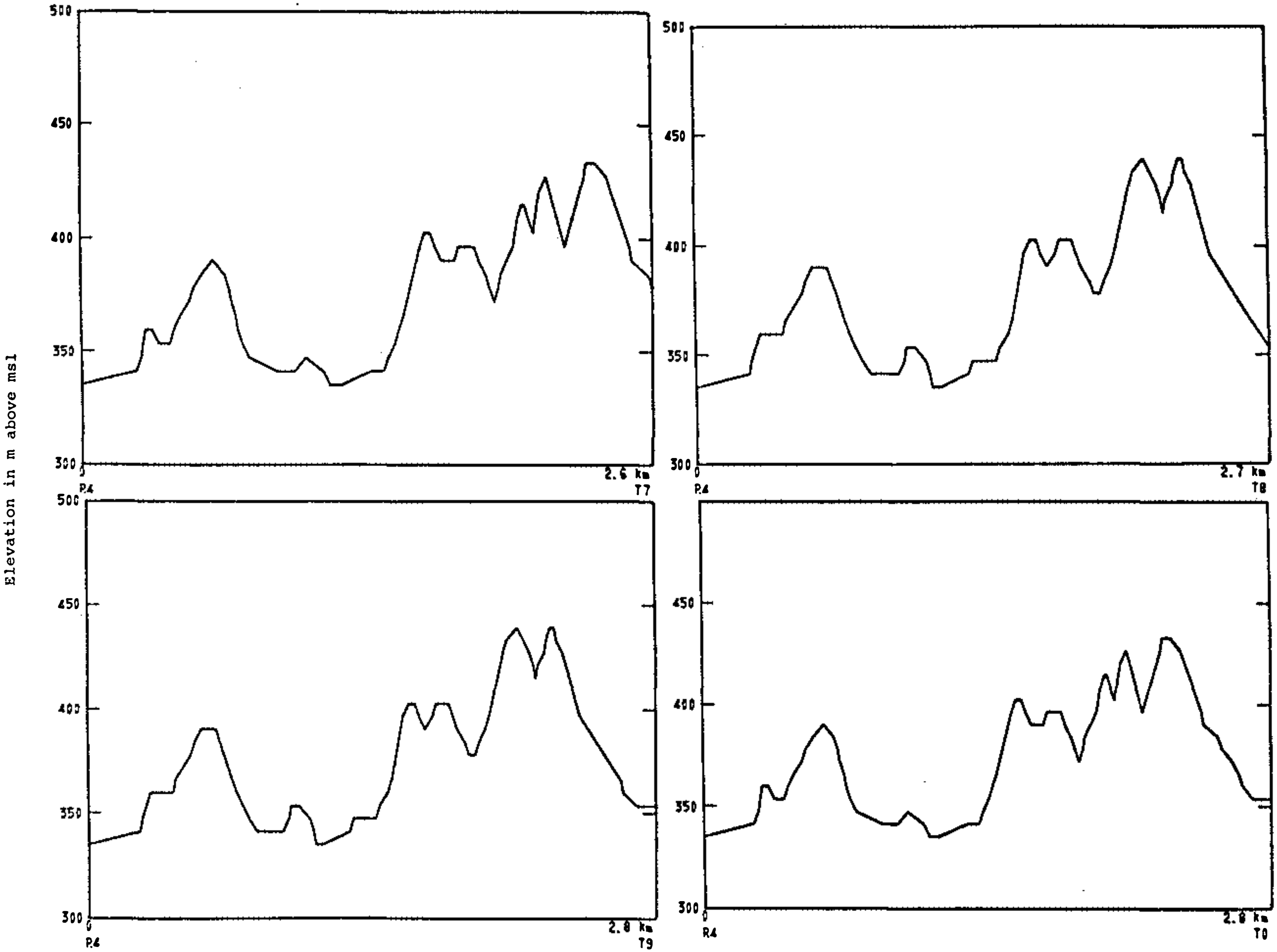

Figure HL10. Terrain profiles from transmitter sites T7, T8, and T9, and T10 to receiver site R4, Hunter Liggett.

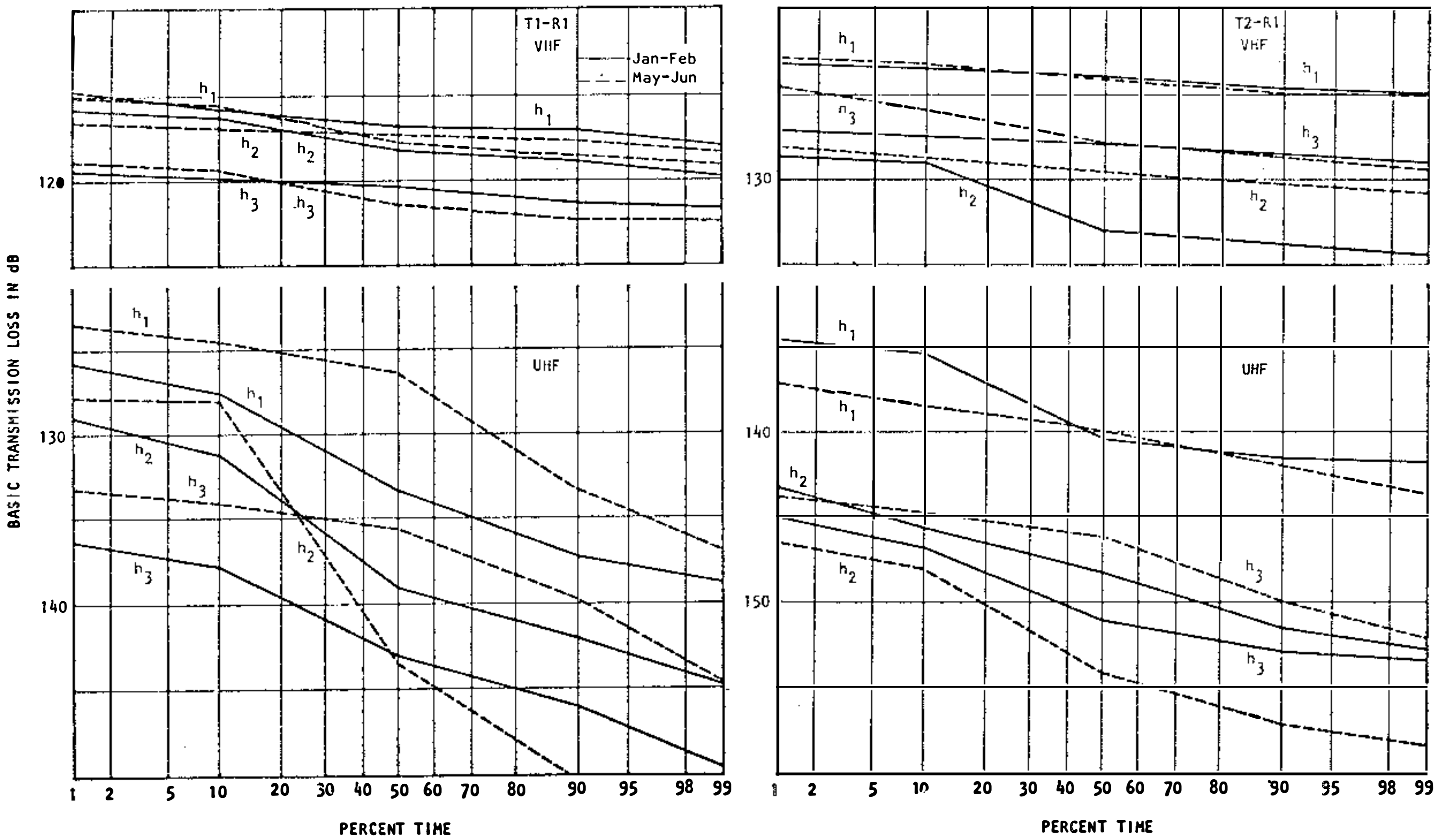

Figure HL11. Cumulative distributions of basic transmission loss recorded over paths T1-R1, and T2-R1, Hunter Liggett.

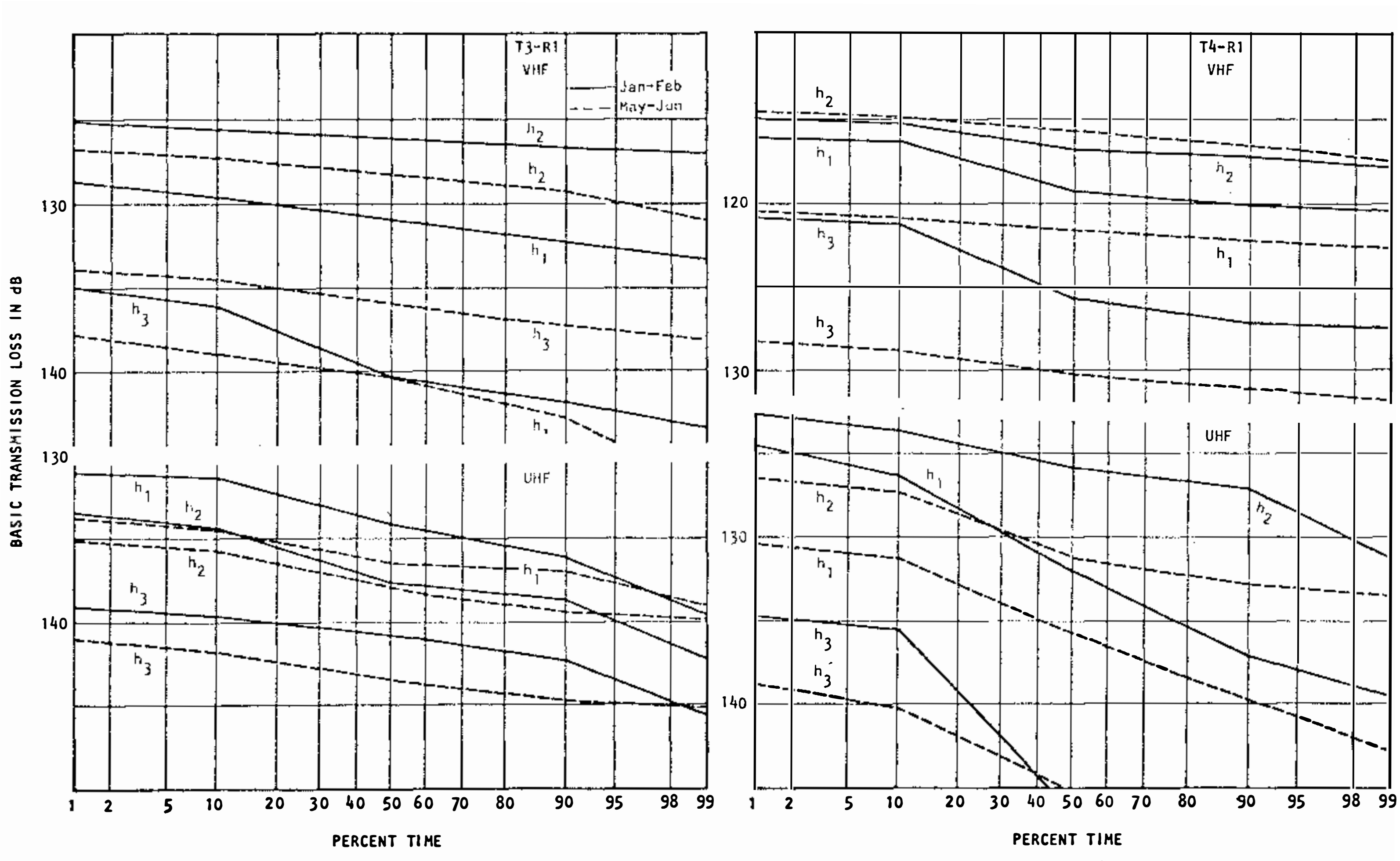

Figure HL12. Cumulative distributions of basic transmission loss recorded over paths T3-R1, and T4-R1, Hunter Liggett.

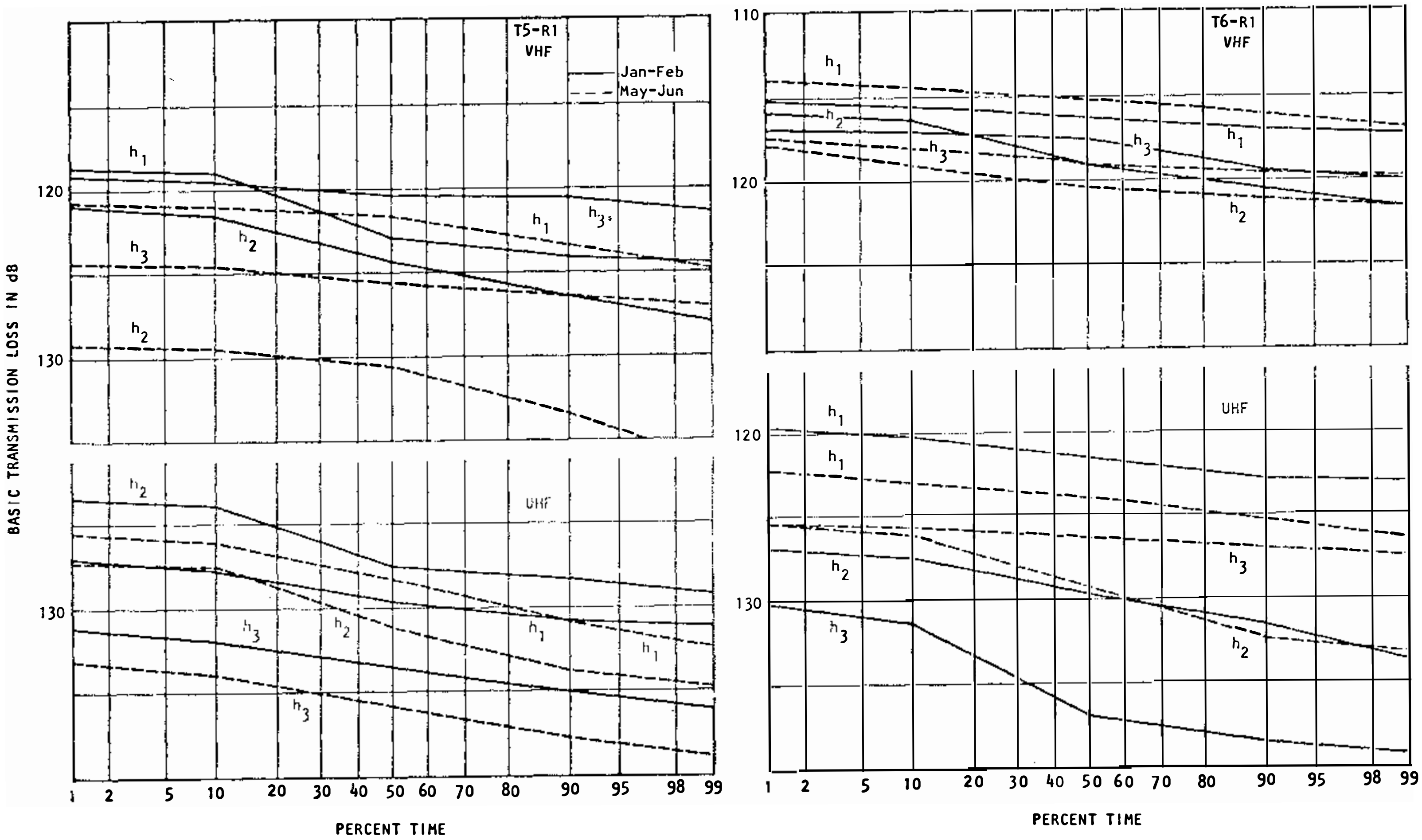

Figure HL13. Cumulative distributions of basic transmission loss recorded over paths T5-R1, and T6-R1, Hunter Liggett.

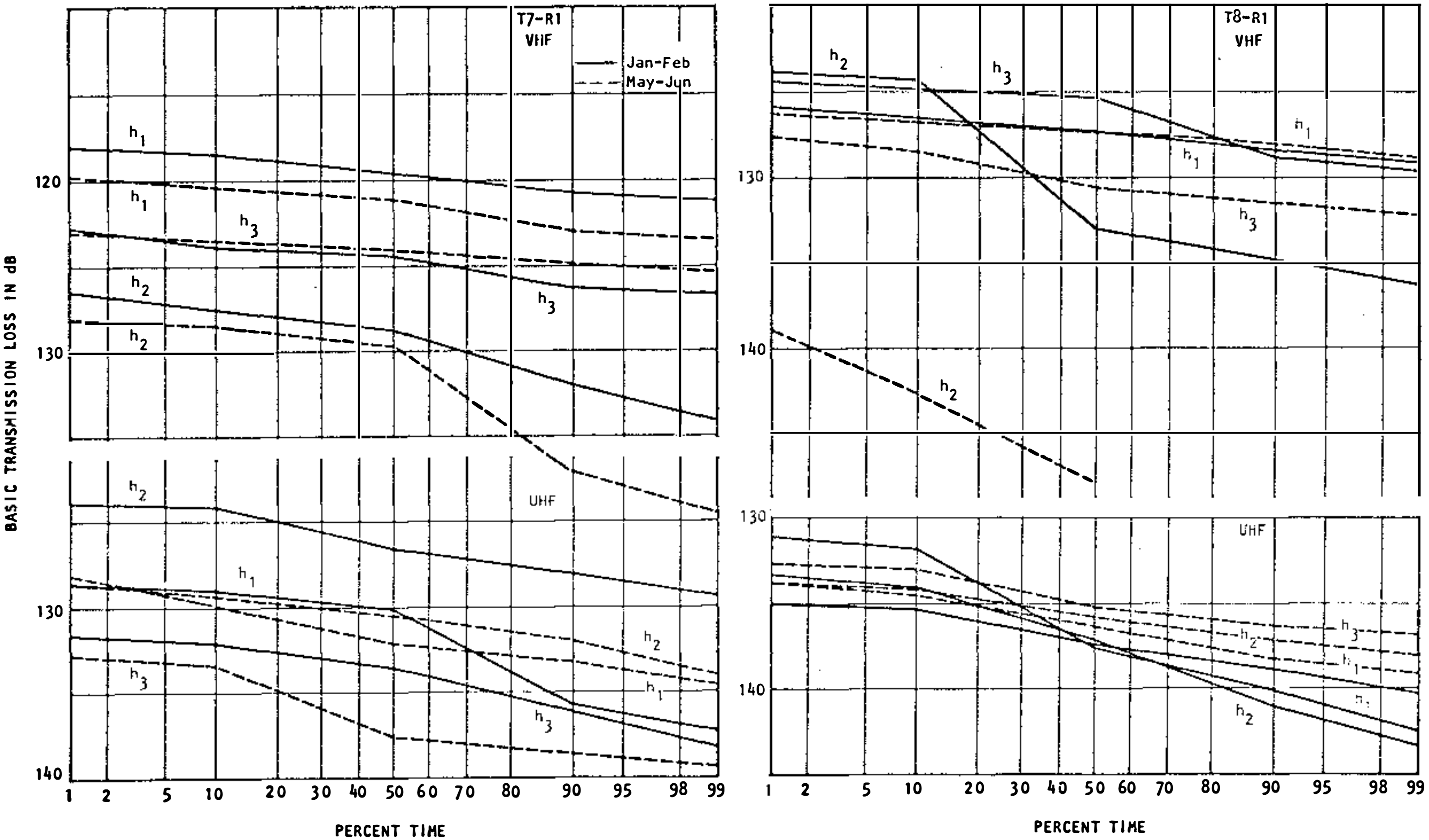

Figure HL14. Cumulative distributions of basic transmission loss recorded over paths T7-R1, and T8-R1, Hunter Liggett.

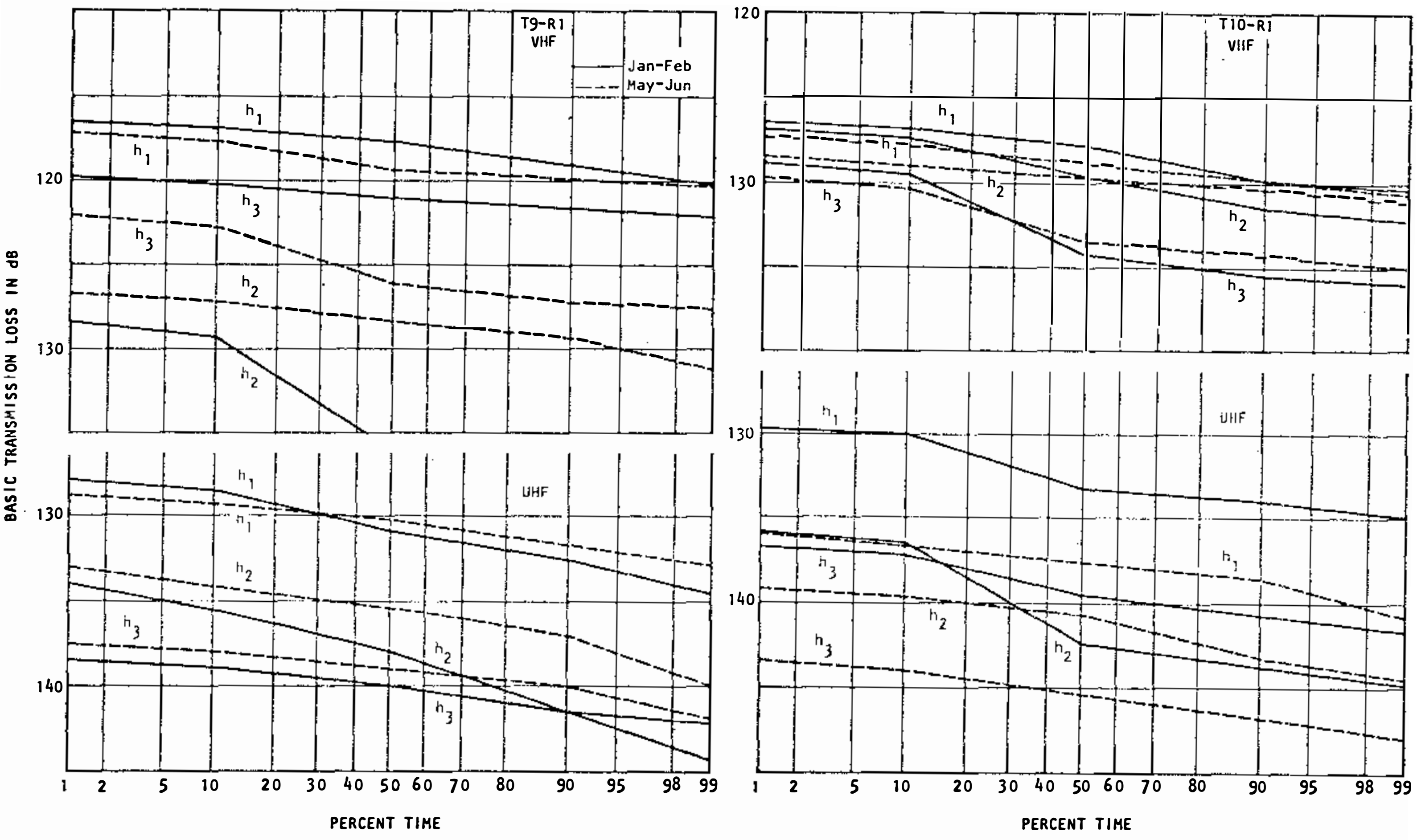

Figure HL15. Cumulative distributions of basic transmission loss recorded over paths T9-R1, and T10-R1, Hunter Liggett.

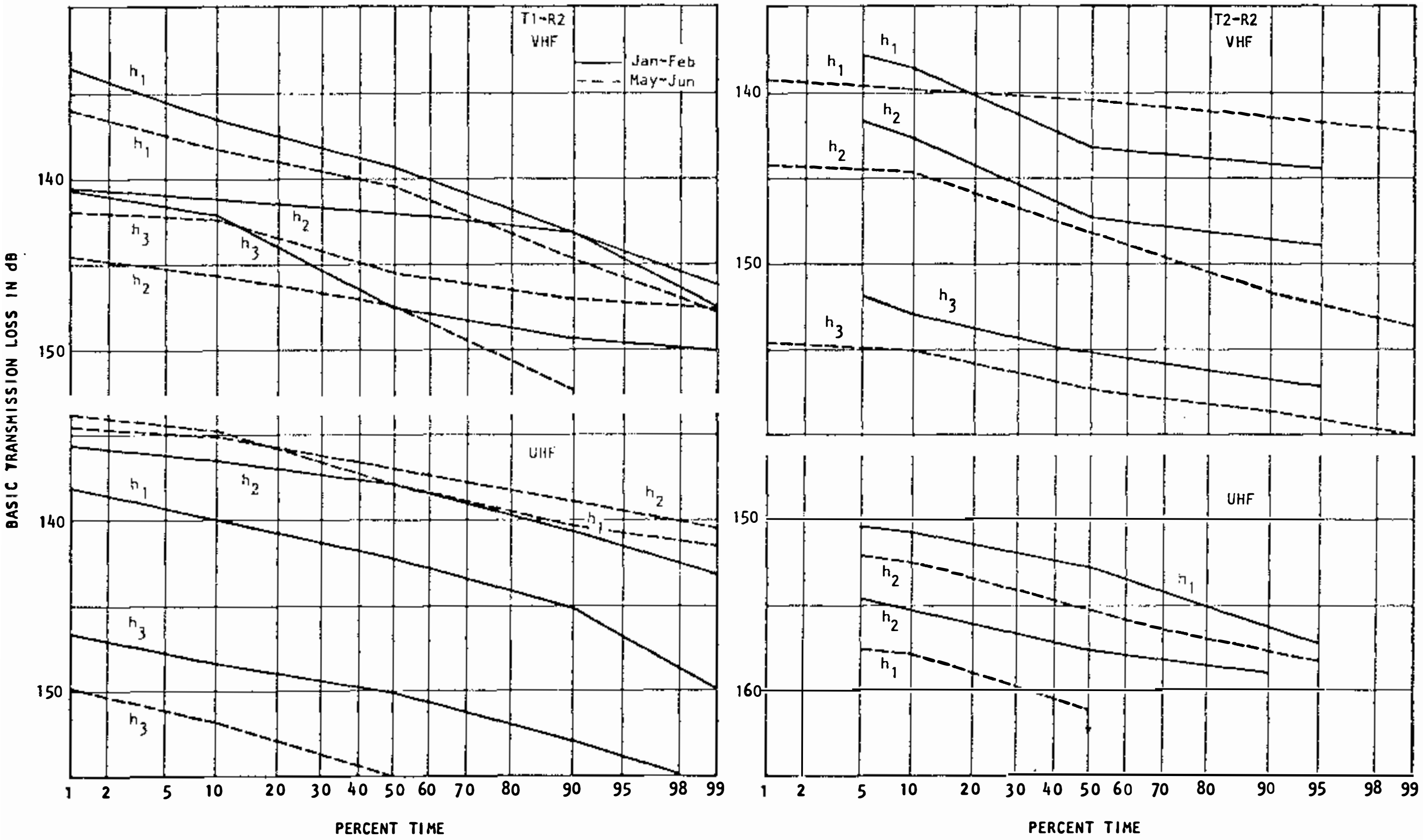

Figure HL16. Cumulative distributions of basic transmission loss recorded over paths T1-R2, and T2-R2, Hunter Liggett.

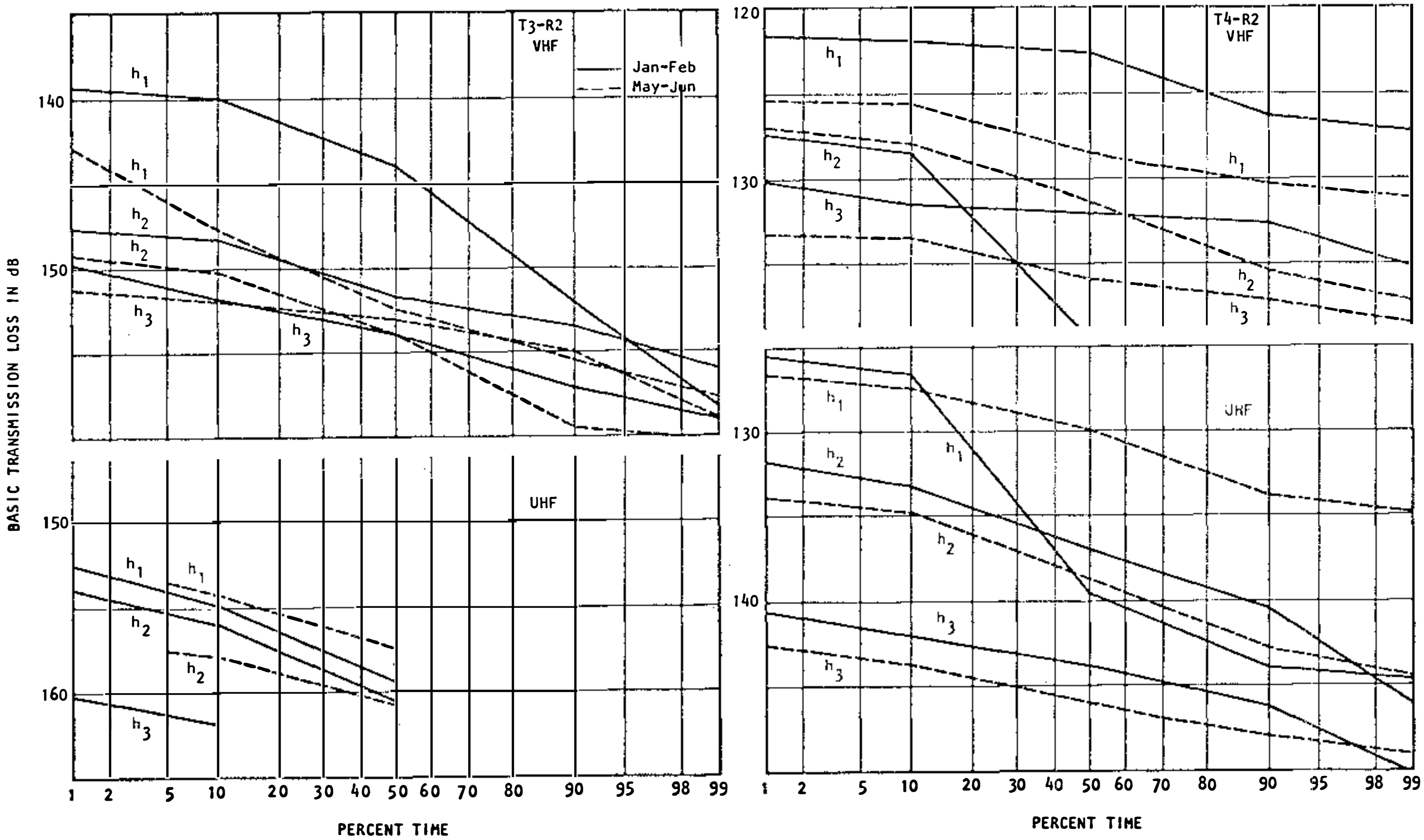

Figure HL17. Cumulative distributions of basic transmission loss recorded over paths T3-R2, and T4-R2, Hunter Liggett.

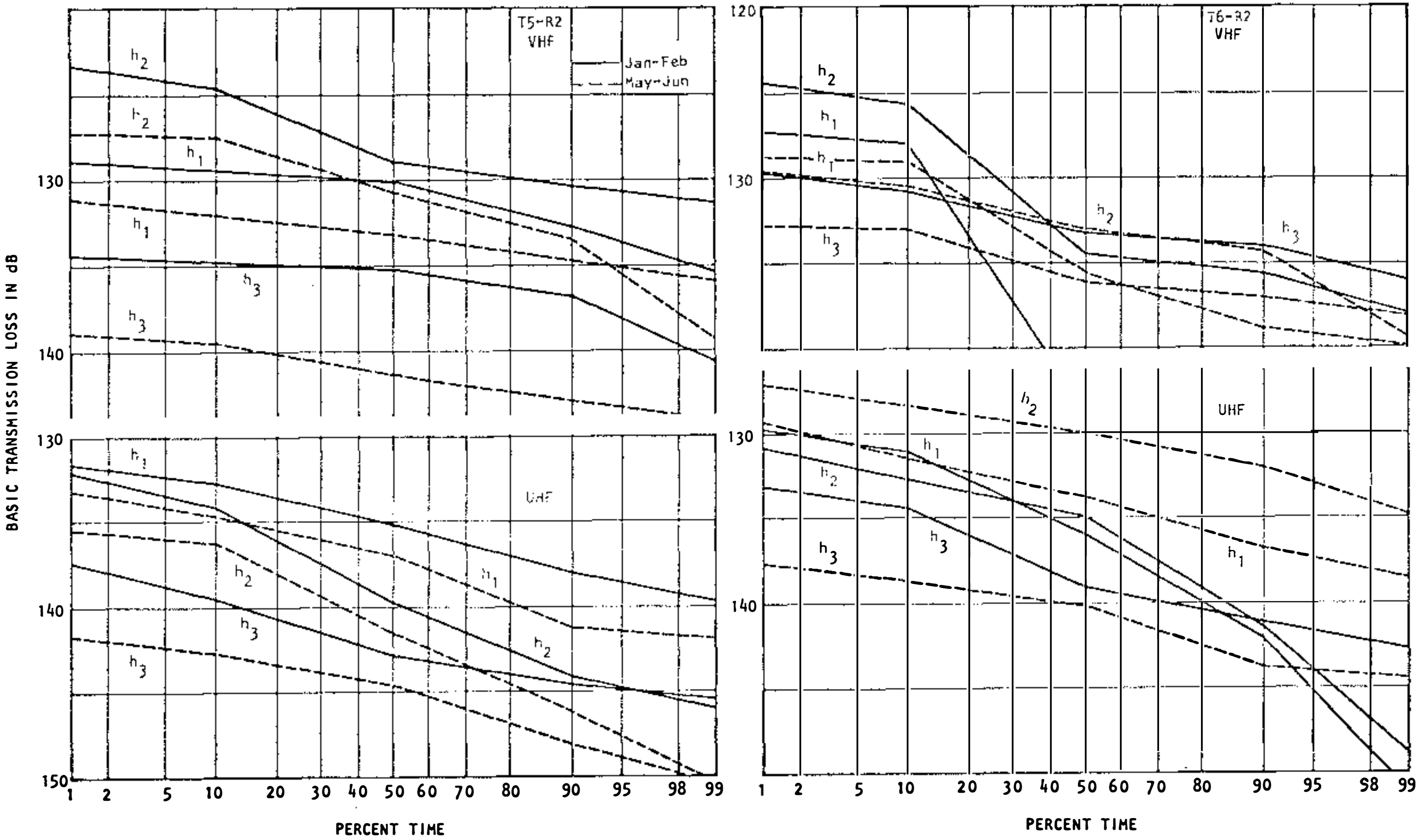

Figure HL18. Cumulative distributions of basic transmission loss recorded over paths T5-R2, and T6-R2, Hunter Liggett.

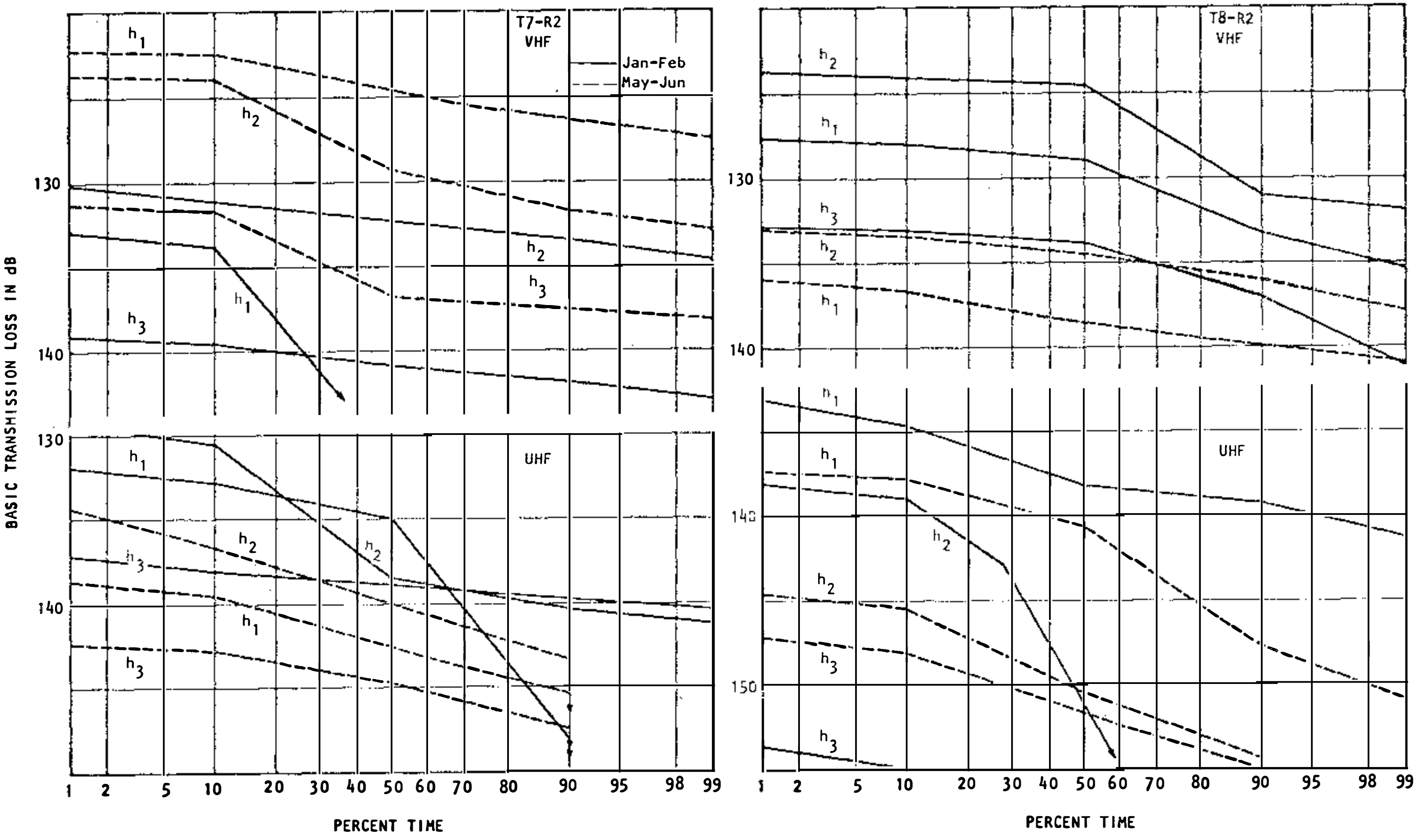

Figure HL19. Cumulative distributions of basic transmission loss recorded over paths T7-R2, and T8-R2, Hunter Liggett.

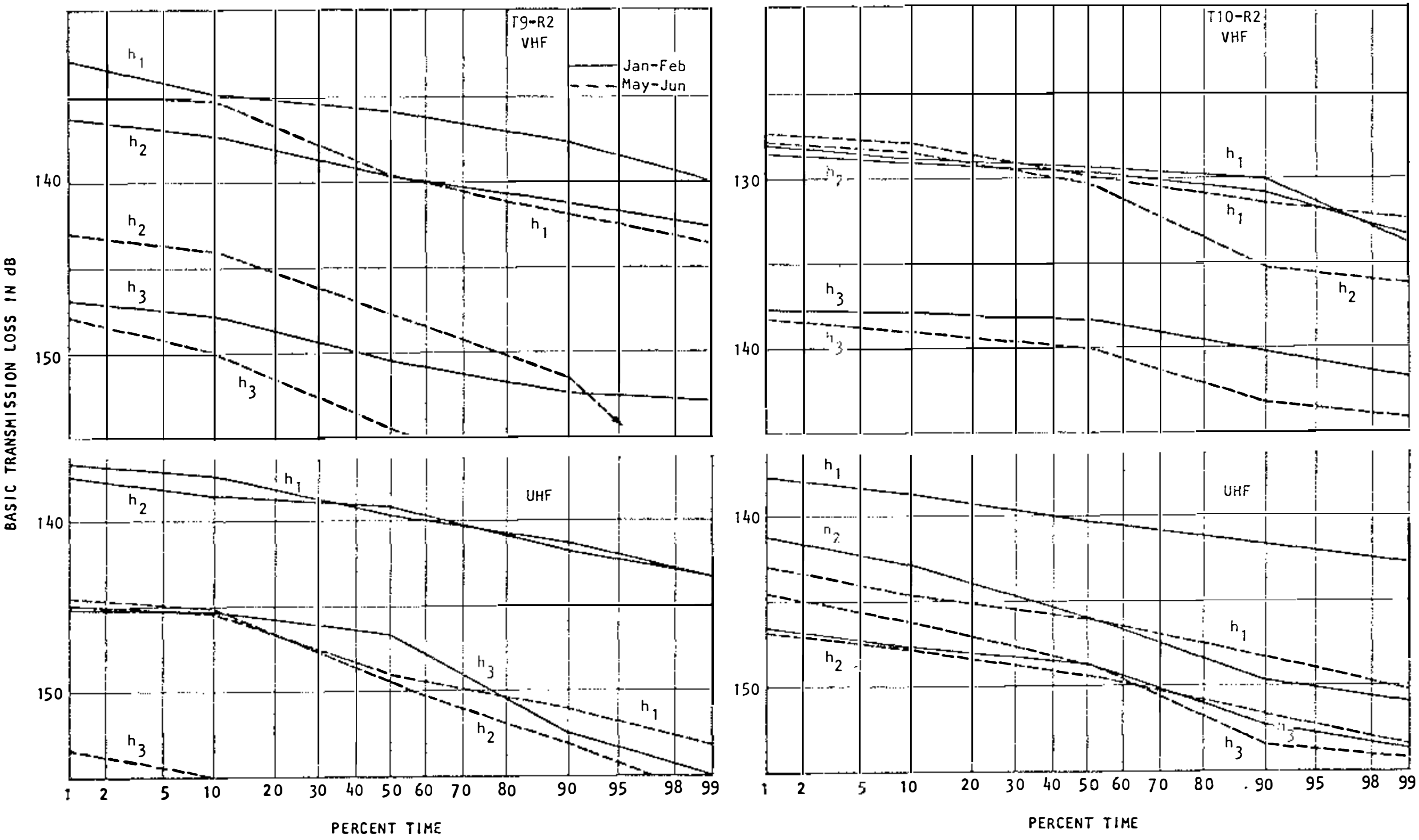

Figure HL20. Cumulative distributions of basic transmission loss recorded over paths T9-R2, and T10-R2, Hunter Liggett.

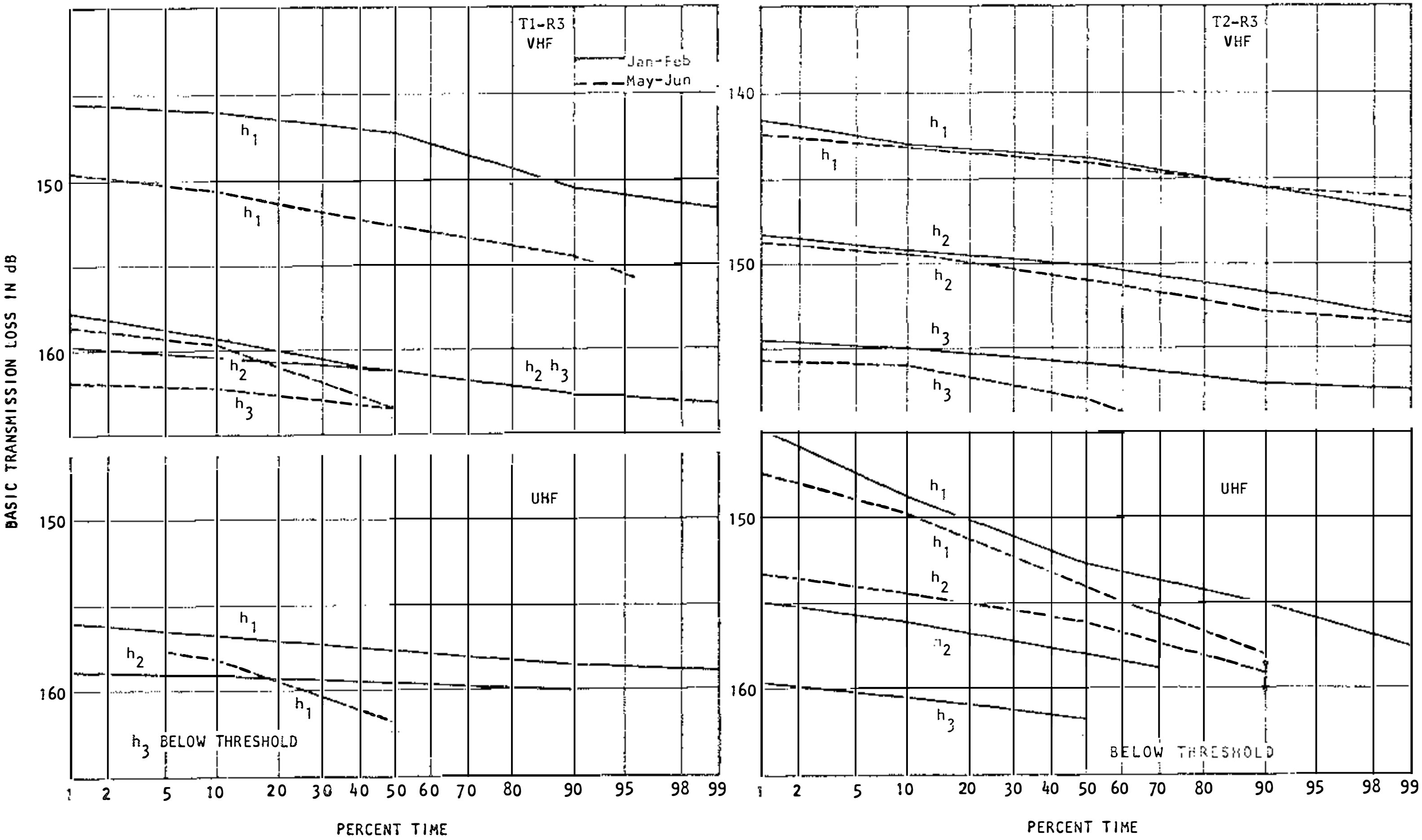

Figure HL21. Cumulative distributions of basic transmission loss recorded over paths T1-R3, and T2-R3, Hunter Liggett.

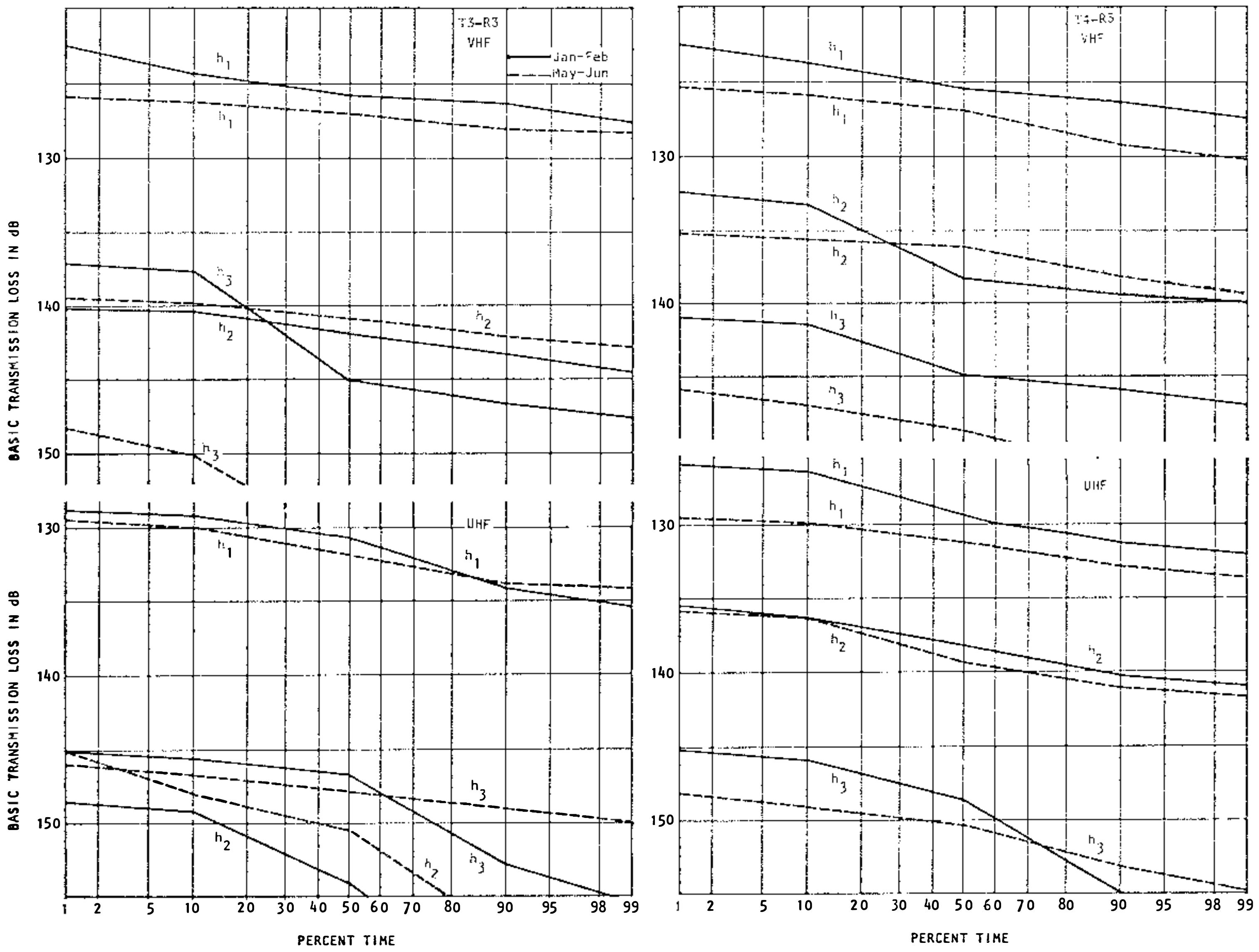

Figure HL22. Cumulative distributions of basic transmission loss recorded over paths T3-R3, and T4-R3, Hunter Liggett.

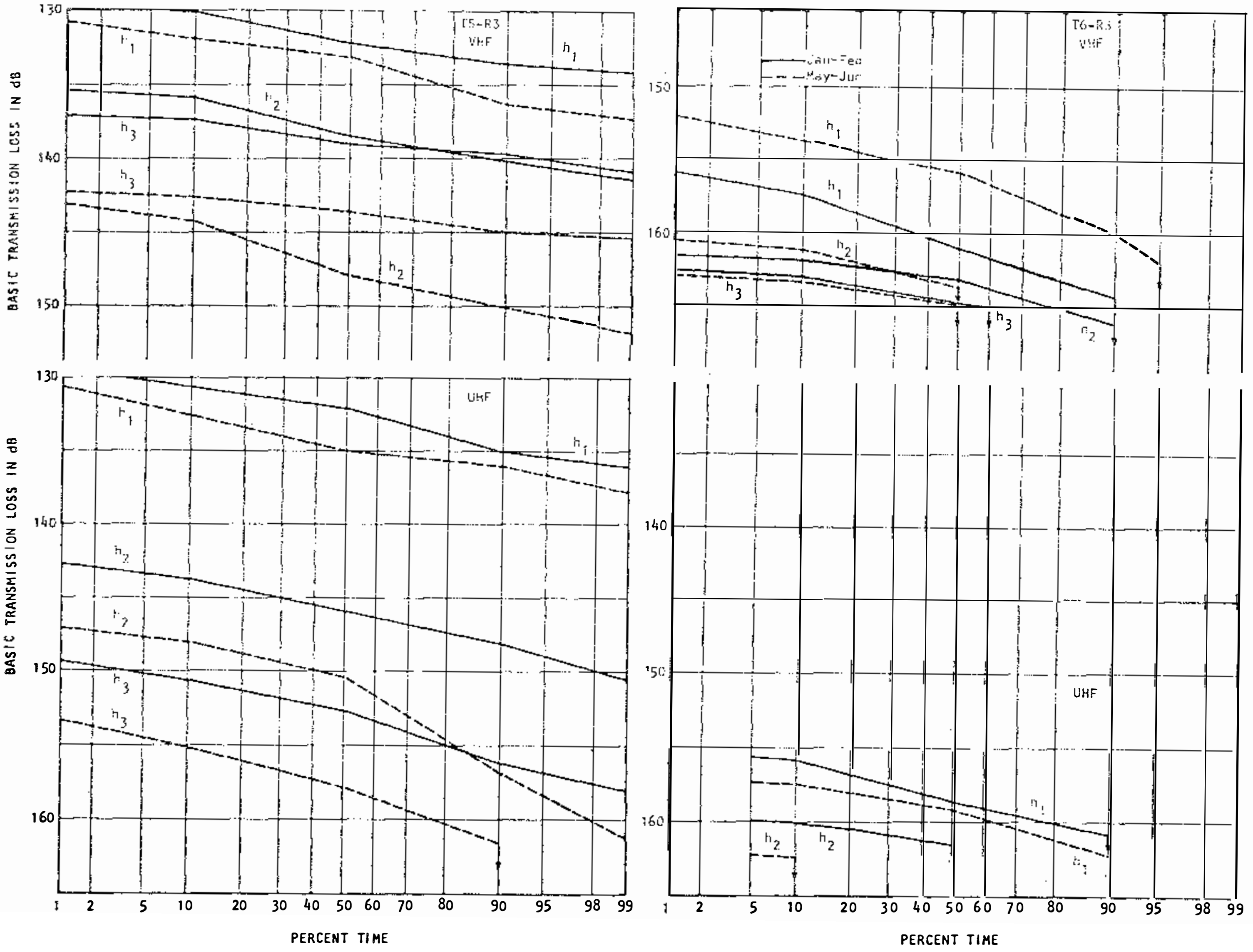

Figure HL23. Cumulative distributions of basic transmission loss recorded over paths T5-R3, and T6-R3, Hunter Liggett.

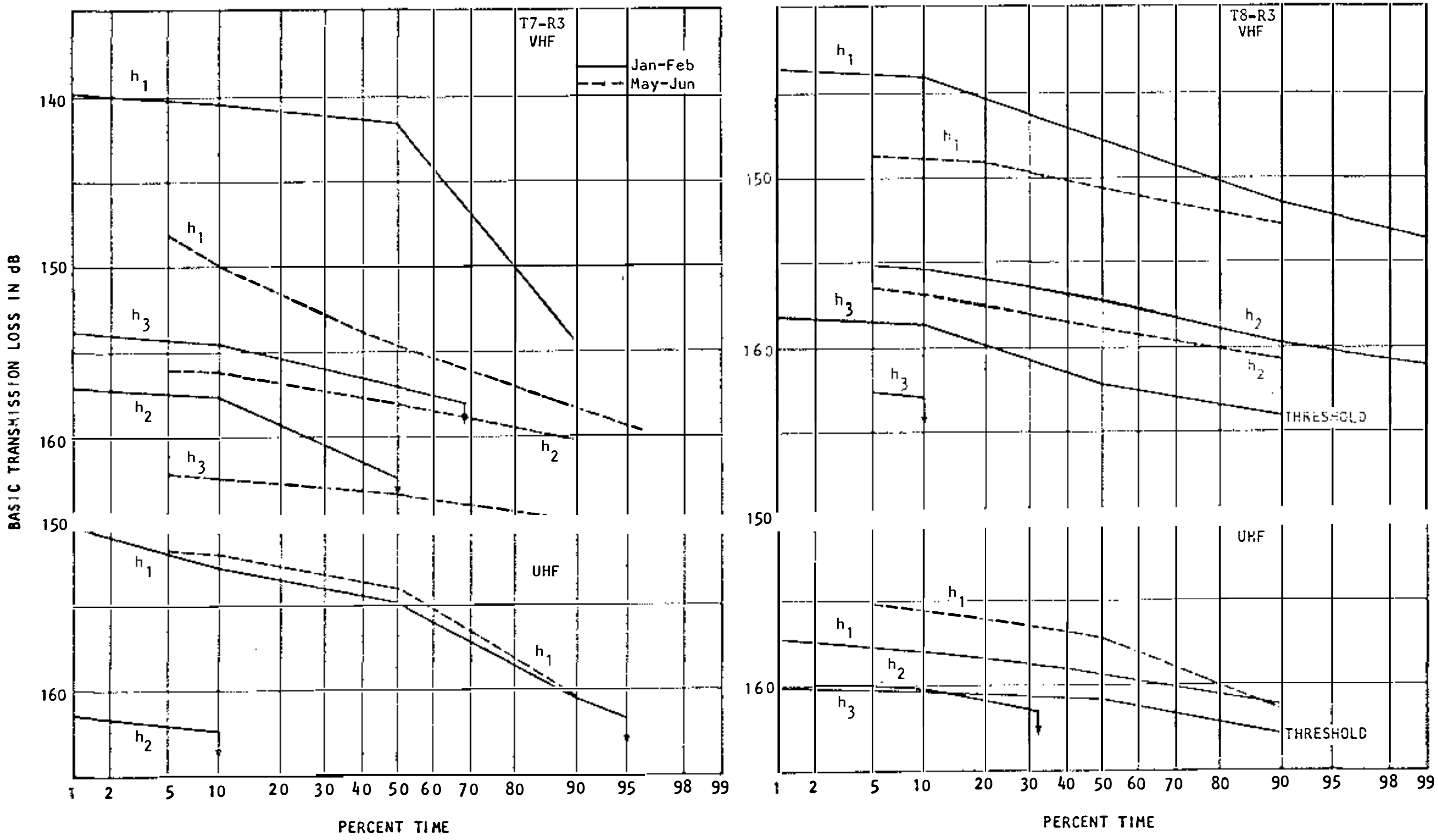

Figure HL24. Cumulative distributions of basic transmission loss recorded over paths T7-R3, and T8-R3, Hunter Liggett.

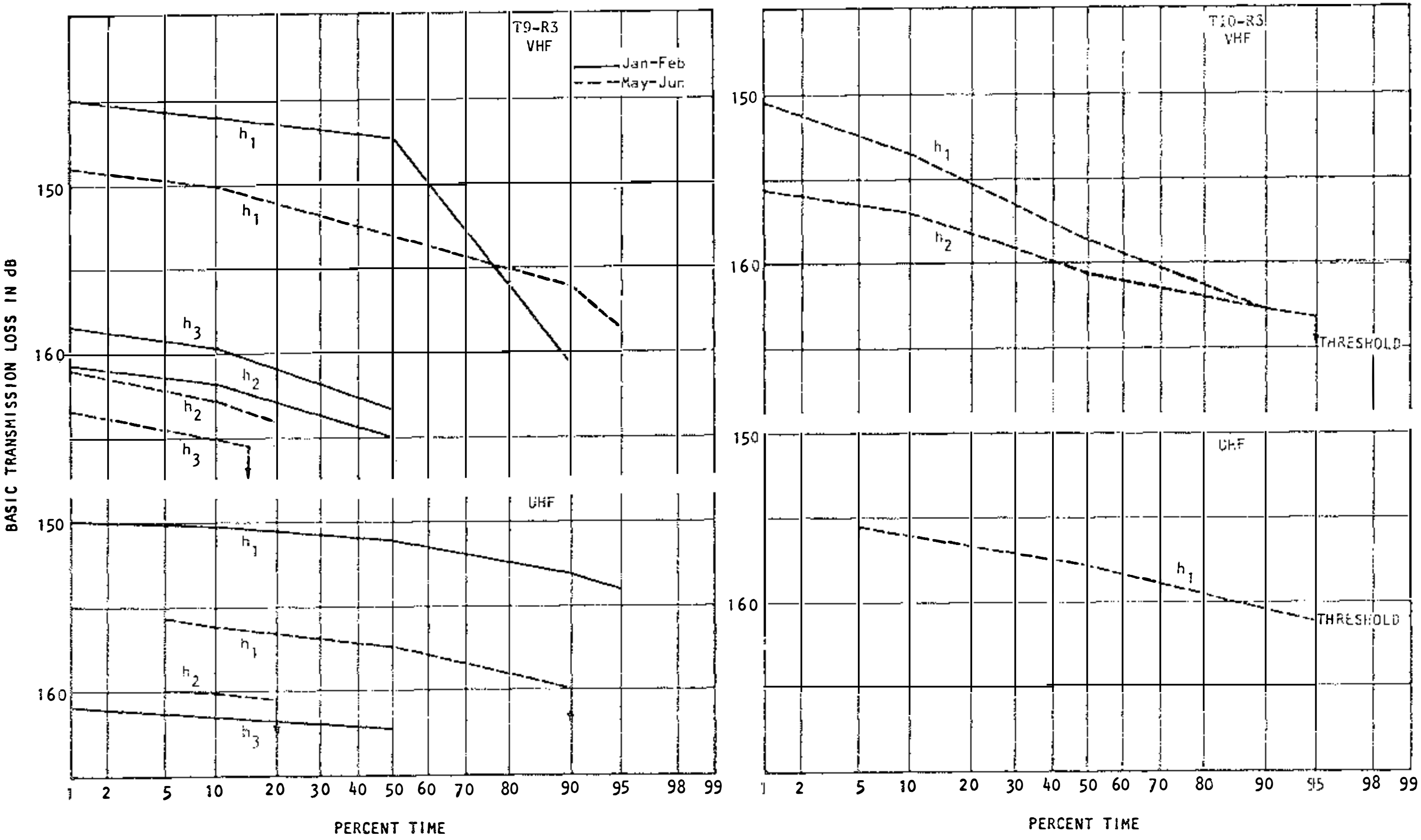

Figure HL25. Cumulative distributions of basic transmission loss recorded over paths T9-R3, and T10-R3, Hunter Liggett.

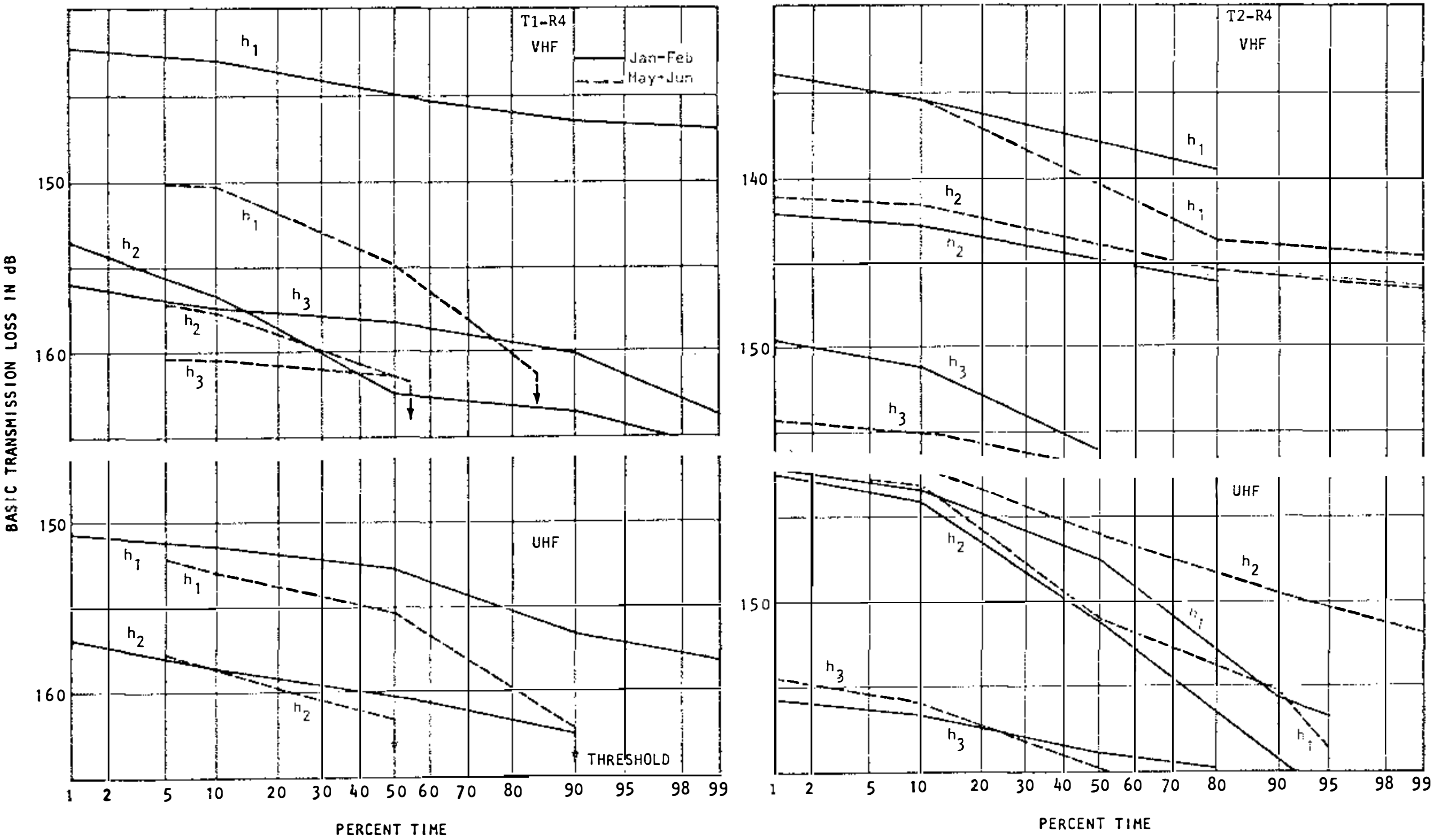

Figure HL26. Cumulative distributions of basic transmission loss recorded over paths T1-R4, and T2-R4, Hunter Liggett.

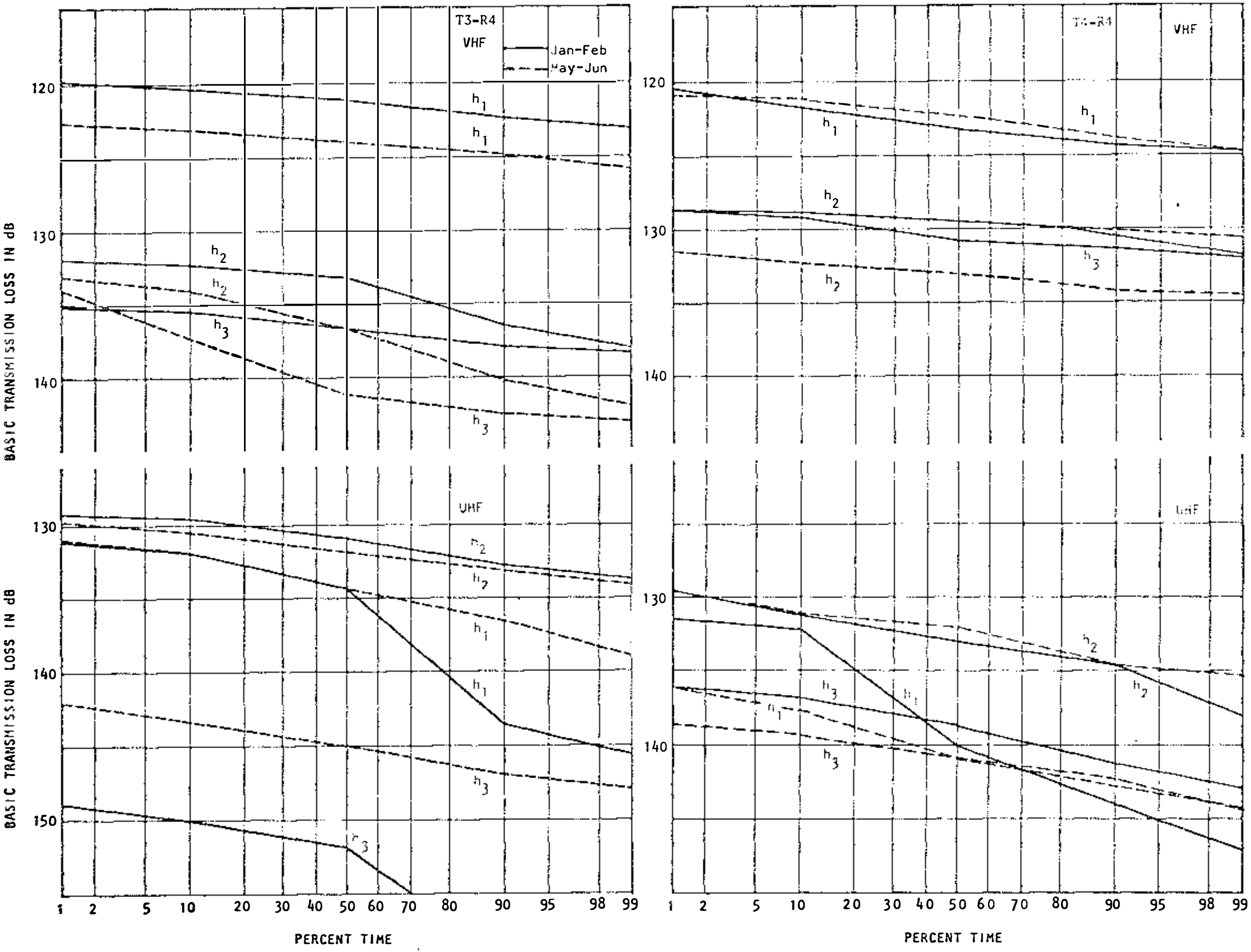

Figure HL27. Cumulative distributions of basic transmission loss recorded over paths T3-R4, and T4-R4, Hunter Liggett.

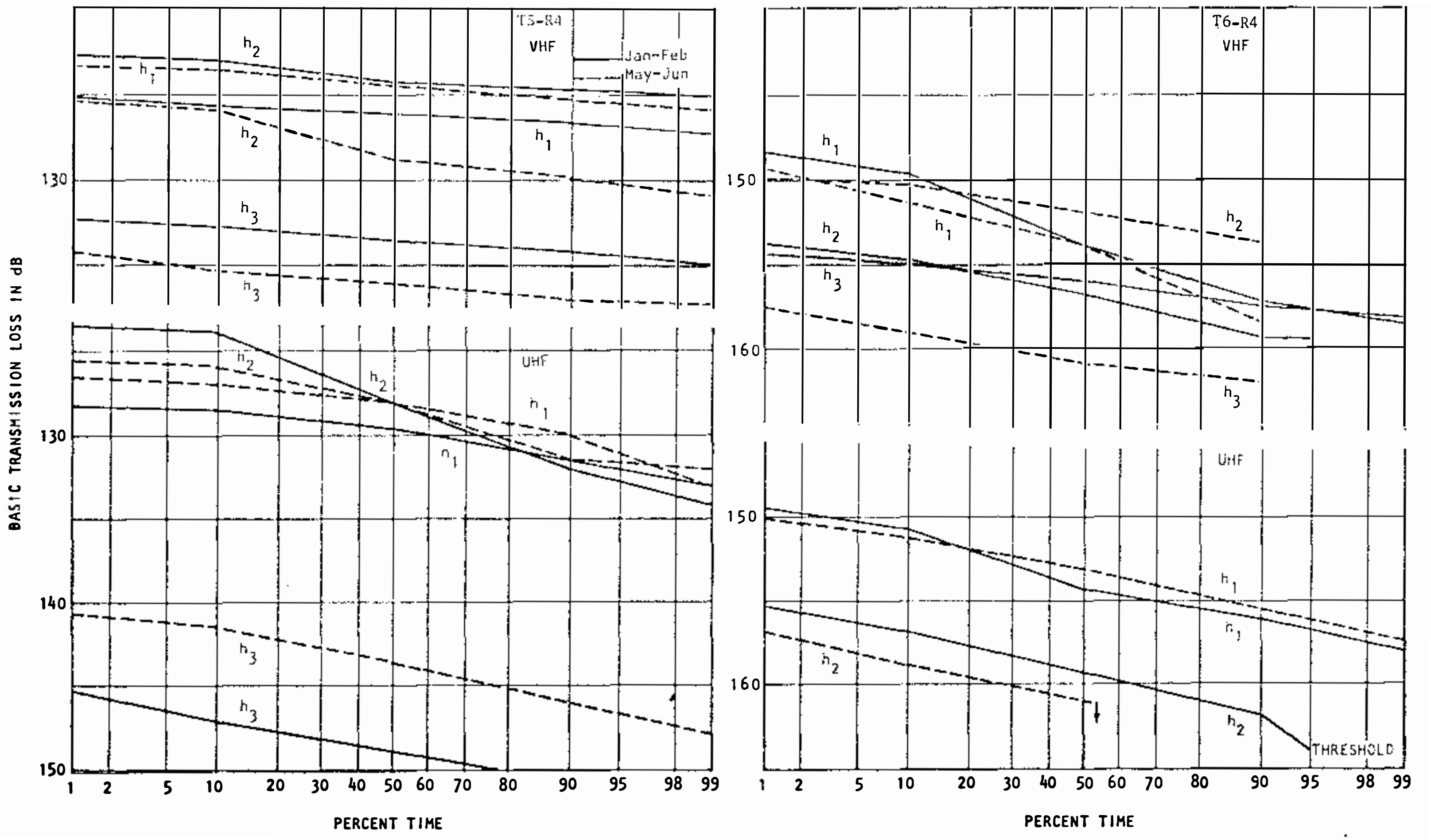

Figure HL28. Cumulative distributions of basic transmission loss recorded over paths T5-R4, and T6-R4, Hunter Liggett.

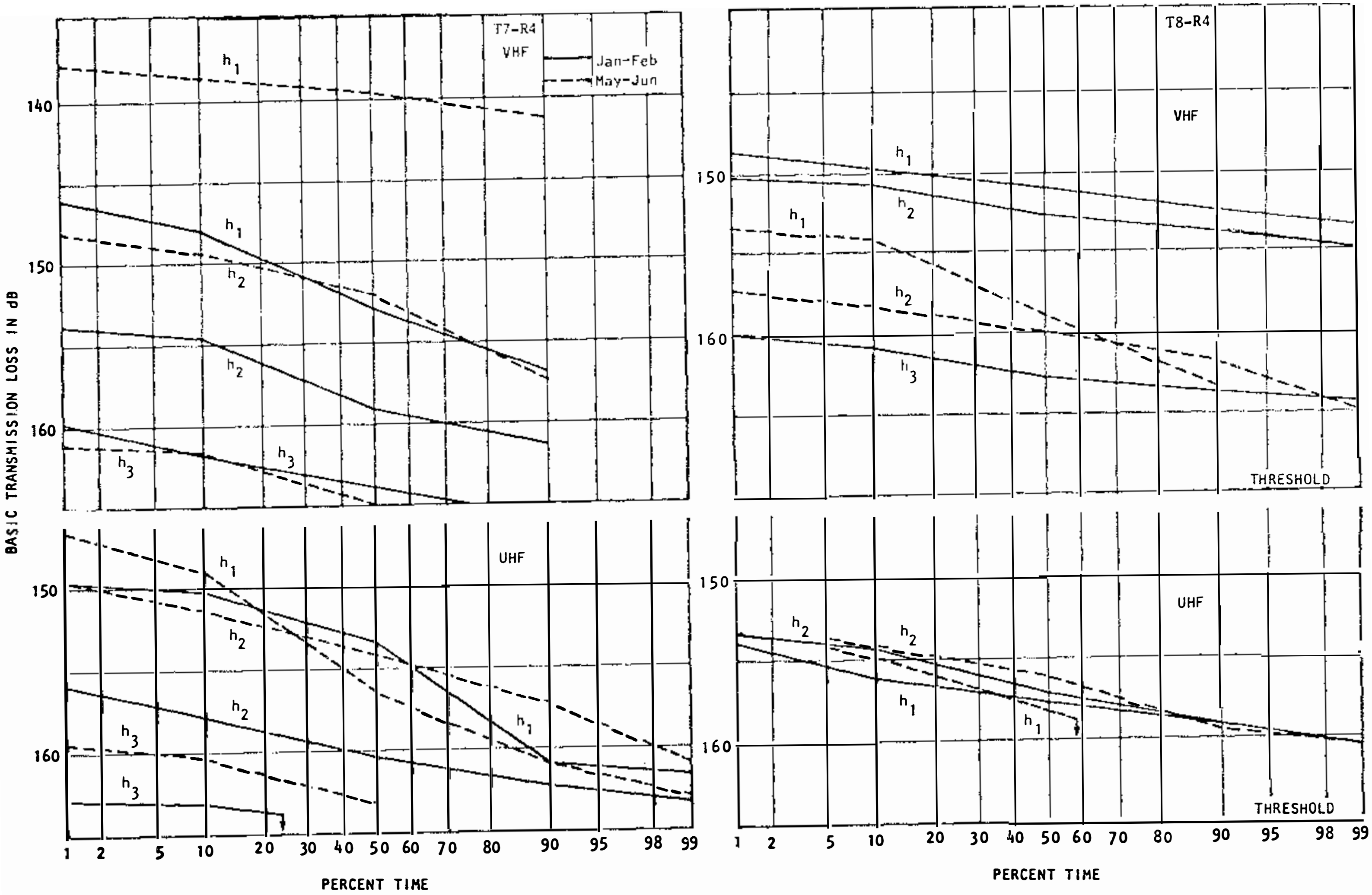

Figure HL29. Cumulative distributions of basic transmission loss recorded over paths T7-R4, and T8-R4, Hunter Liggett.

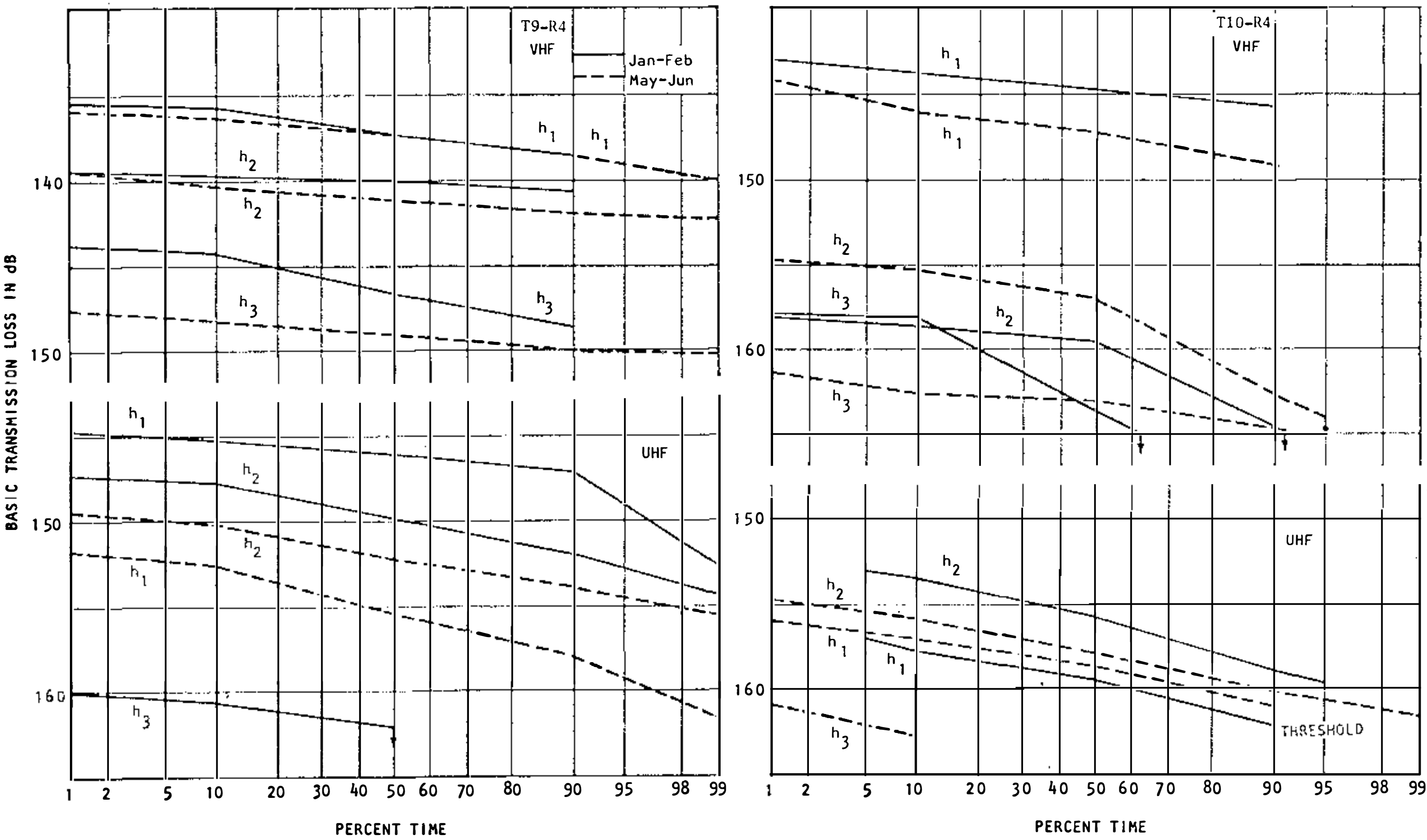

Figure HL30. Cumulative distributions of basic transmission loss recorded over paths T9-R4, and T10-R4, Hunter Liggett.

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

The data from a large measurement program at VHF and UHF are carefully evaluated, summarized and compared with values predicted from models of radio propagation over irregular terrain. Particular problems of low antennas and the effects of vegetation are considered. Modifications in prediction models are suggested for particular application to sensor systems.

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

Irregular terrain; low antennas; path loss; radio propagation; sensor communication; vegetation effects.

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