NTIA-Report-82-108

Comparisons of Observed Propagation Loss with Predictions from Multiple Knife-Edge Attenuation

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U.S. DEPARTMENT OF COMMERCE
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for Communications and Information

October 1982

TABLE OF CONTENTS

COMPARISONS OF OBSERVED PROPAGATION LOSS WITH PREDICTIONS FROM MULTIPLE KNIFE-EDGE ATTENUATION

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Comparisons of theoretical attenuation based on multiple knife-edge diffraction with measured values of median propagation loss are presented for a number of different propagation paths. In general the knife-edge predictions tend to overestimate received signal strength with most of the differences between predicted and observed values lying in the range -12 to +7 dB. Use of a computerized topographic data base to generate path profiles for the knife-edge attenuation result in predicted/observed loss differences of about the same magnitude, although spurious results sometimes arise.

Key words: data comparisons; multiple knife-edge attenuation

1. INTRODUCTION

An expression for the attenuation of a plane wave diffracted by multiple knife-edges has been derived recently and a computer program developed that evaluates the result for an input of up to ten knife-edges (Vogler, 1981). Although actual radio propagation paths never consist strictly of knife-edges, many paths can be approximated as a sequence of knife-edges and an estimate of path attenuation obtained. This paper discusses the application of the multiple knife-edge (MKE) attenuation function to the prediction of propagation loss over irregular terrain.

Obvious limitations in the application of the MKE function to actual conditions are:

(1) the theoretical knife-edges are perfectly absorbing half-planes normal to the direction of propagation, whereas the corresponding terrain features are peaks or ridges of various orientations with a variety of electrical ground constants;

(2) terrain features characterized as "knife-edges" are actually rounded obstacles, and in most cases are only crude approximations to a true knife-edge; and

(3) intra knife-edge terrain reflections can affect signal levels.

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Despite these limitations, the MKE function should be able to provide useful information in the prediction of propagation loss. The accuracy of the estimate will, of course, depend on how closely the actual path approximates a knife-edge path.

Propagation paths can be categorized into three general types:

1. Line-of-sight (LOS) paths, in which the transmitter and receiver are within radio line-of-sight of each other.

2. Single horizon (SH) paths, in which a single obstacle acts as a common horizon for both the transmitter and receiver.

3. Double horizon (DH) paths, in which two separate obstacles act as horizons for the transmitter and for the receiver.

Propagation loss for an LOS path is usually somewhat near the free-space loss; however, if the tops of terrain features (or knife-edges) are close enough to the direct, line-of-sight ray, the signal attenuation can be significantly increased. Examples of this phenomenon are shown in some of the data comparisons given later. MKE diffraction losses of as much as 16 dB above free-space loss are indicated on some LOS paths.

SH paths are subject to the same circumstances along the two direct ray paths from the horizon to both antennas. In addition to the diffraction loss caused by the horizon obstacle (or knife-edge), further loss is incurred when intervening knife-edges approach the ray path.

In the case of DH paths the situation is further complicated by the fact that knife-edges between the horizons may completely obstruct the horizon-to-horizon direct ray path. The computer program used in the later comparisons always assumes that "obstructing" knife-edges (whether horizons or otherwise) are more significant than any others and -- up to a maximum of ten -- computes the propagation loss using the most significant knife-edges. If fewer than ten obstructing knife-edges are encountered, those knife-edges for which the tops most nearly approach any direct ray path are used. This criterion holds whether the path be LOS, SH, or DH.

In the following section, a number of propagation paths for which measured values of propagation loss are available are used to provide comparisons between observed and theoretically predicted losses. The paths and measurements were obtained from a report by Longley, Reasoner, and Fuller (1971) and include only those paths which can be designated as diffraction paths, i.e., tropospheric scatter paths are not considered. Also, profiles were chosen for which more than one set of measurements were available. Path profiles obtained by reading height versus distance values from contour maps are available for all the comparison paths and were used to select those terrain features read in as knife-edge inputs to the MKE attenuation subroutine. For any one path profile there can be a number of propagation paths, the latter being differentiated by different frequencies and/or antenna heights. The antenna height information is not given in this paper but may be found by referring to the appropriate path identification number in the Longley et al. report.

The observed loss, L_{bo}, used in the comparisons is the median or 50% observed loss tabulated in the data report. These observed losses come from distributions of hourly median values and usually represent many hours of measurement. At the time these measurements were made, antenna gain accuracies, power measurements, and calibration procedures limited measurement accuracies to the order of ± 1 dB (L. G. Hause, private communication). The predicted loss, L(MKE), is the sum of the free-space propagation loss, L_{fs}, and the diffraction loss (in dB), A(MKE), as obtained from the MKE attenuation function:

$$L(MKE) = L_{fs} + A(MKE) \quad , \tag{1}$$

where $$L_{fs} = 20 \log (d f_{MHz}) + 32.4478 \quad , \tag{2}$$

with d the path distance in km and f_{MHz} the radio frequency in megahertz.

The antenna and knife-edge heights used in the calculation of the MKE attenuation function are values measured from some common reference plane, while the height information from the path profile data are heights as measured from mean sea level (msl). Thus, the profile heights must be adjusted to account for the earth's curvature. Furthermore, atmospheric refraction will cause bending of the radio rays, whereas the geometric parameters of the MKE function require straight-line geometry.

The present computer program uses the concept of an effective earth's radius, a_e, to account (approximately) for atmospheric bending, and the following relationship adjusts for the earth's curvature:

$$h(x) = H(x) - x^2/2a_e \quad , \tag{3}$$

where H(x) is the profile height above msl of a terrain obstacle (considered as a knife-edge) at a distance, x, from the transmitter, and h(x) is the input height to the MKE function. The effective radius is given by (Rice et al., 1967)

$$a_e = 6370[1 - 0.04665 \exp(0.005577 N_s)]^{-1} \quad , \tag{4}$$

and the value of surface refractivity, N_s, for any particular propagation path is tabulated in the data report.

Finally, it should be pointed out that choosing knife-edges from a collection of profile points read from contour maps is a somewhat arbitrary process. To begin with, the points themselves are subjectively determined by the person reading the maps. Secondly, a particular point chosen as an MKE input might, in reality, be part of a "rounded" terrain feature which little resembles our concept of a knife-edge. These considerations will always be present when attempting to use knife-edge effects to estimate actual signal attenuation. Nevertheless, there are many paths for which the best method of predicting propagation loss would appear to be through the application of multiple knife-edge diffraction. The following section presents some comparisons of observed data with theoretical MKE attenuation.

2. COMPARISONS OF OBSERVED AND PREDICTED LOSS

Seventeen different profile paths, each containing a number of propagation paths, are presented in Table 1 to show comparisons of observed with predicted propagation loss. All three general types of paths (LOS, SH, and DH) are represented, there being

6 LOS profiles: profile nos. 1, 2, 3, 4, 7, and 10;

3 SH profiles: profile nos. 8, 12, and 15; and

8 DH profiles: profile nos. 5, 6, 9, 11, 13, 14, 16, and 17.

The order of the profiles is by path distance, d, and within each profile the propagation paths are arranged according to increasing frequency. If the same frequency appears more than once in a particular profile, the propagation paths have different transmitting or receiving antenna heights.

The column headed "Path #" contains the propagation path identification number used in Longley et al. (1971). Further information concerning the path can be found in that report.

Table 1. Comparison of Predicted and Observed Propagation Loss
$\Delta = L(MKE) - L(Observed)$

Path #	f_{MHz}	L(obs)	L_{fs}	A(MKE)	L(MKE)	Δ
Profile 1, Clausen Site - Eglin Main Base, FL d = 11.91 km						
187	40.5	94.4	86.12	- 1.83	84.29	-10.1
188	75.5	96.2	91.52	0.59	92.11	- 4.1
189	165.2	101.1	98.33	- 1.05	97.28	- 3.8
190	455	99.0	107.13	0.36	107.49	8.5
191	952	128.2	113.54	- 0.23	113.31	-14.9
Profile 2, Coupland Tower - Eglin Main Base, FL d = 18.59 km						
192	40.5	106.2	89.98	14.00	103.98	- 2.2
193	75.5	105.8	95.39	12.96	108.35	2.6
194	165.2	113.6	102.19	11.20	113.39	- 0.2
195	455	117.2	110.99	7.46	118.45	1.2
196	952	123.8	117.41	3.50	120.91	- 2.9
Profile 3, Wagner Site - Eglin Main Base, FL d = 27.50 km						
197	40.5	116.0	93.38	16.88	110.26	- 5.7
198	75.5	115.8	98.79	16.67	115.46	- 0.3
199	165.2	114.6	105.59	15.97	121.56	7.0
1800	455	122.8	114.39	14.32	128.71	5.9
1801	952	135.8	120.81	12.73	133.54	- 2.3
Profile 4, Cheyenne Mtn. S - Kendrick, CO d = 79.59 km						
250	100	131.4	110.46	9.05	119.51	-11.9
270	192.8	133.2	116.17	5.59	121.76	-11.4
290	230	128.6	117.70	4.87	122.57	- 6.0
310	1046	131.4	130.86	0.14	131.00	- 0.4

Table 1. (continued)

Path #	f_{MHz}	L(obs)	L_{fs}	A(MKE)	L(MKE)	Δ
Profile 5, Cheyenne Mtn. B - Kendrick, CO d = 79.73 km						
330	92	133.7	109.76	18.69	128.45	- 5.2
350	210.4	139.6	116.94	18.79	135.73	- 3.9
370	236	137.5	117.94	18.81	136.75	- 0.8
Profile 6, Rochester - Ithaca, NY d = 107.24 km						
1606	840	182.6	131.54	41.16	172.70	- 9.9
1609	2800	194.6	142.00	49.42	191.42	- 3.2
1610	9100	207.1	152.24	61.04	213.28	6.2
Profile 7, Cheyenne Mtn. S - Karval, CO d = 112.97 km						
252	100	135.0	113.51	10.90	124.41	-10.6
272	192.8	137.4	119.21	7.35	126.56	-10.8
292	230	135.1	120.74	6.48	127.22	- 7.9
297	751	135.0	131.02	3.93	134.95	0.0
266	1040.1	142.1	133.85	2.44	136.29	- 5.8
311	1046	150.1	133.90	3.04	136.94	-13.2
312	1046	134.5	133.90	- 0.30	133.60	- 0.9
313	1046	141.0	133.90	3.14	137.04	- 4.0
267	9250	153.9	152.83	0.12	152.95	- 1.0
268	9350	152.7	152.92	0.10	153.02	0.3
298	9361.3	154.0	152.93	0.04	152.97	- 1.0
Profile 8, Cheyenne Mtn. B - Karval, CO d = 113.32 km						
332	92	143.5	112.81	26.38	139.19	- 4.3
352	210.4	149.8	119.99	27.16	147.15	- 2.6
372	236	141.8	120.99	27.30	148.29	6.5

Table 1. (continued)

Path #	f_{MHz}	L(obs)	L_{fs}	A(MKE)	L(MKE)	Δ
Profile 9, San Antonio - Austin, TX d = 119.03 km						
21	101.5	168.1	114.09	48.17	162.26	- 5.8
22	101.5	164.7	114.09	47.93	162.02	- 2.7
23	101.5	167.8	114.09	48.84	162.93	- 4.9
Profile 10, Pikes Peak - Gun Barrel Hill, CO d = 139.09 km						
299	751	127.5	132.83	- 3.57	129.26	1.8
300	9361.3	158.5	154.74	2.46	157.20	- 1.3
Profile 11, Ft. Carson - Haswell, CO d = 150.95 km						
394	100	180.4	116.02	38.37	154.39	-26.0
389	1046	191.1	136.42	58.39	194.81	3.7
Profile 12, Cheyenne Mtn. S - Haswell, CO d = 156.00 km						
254	100	152.5	116.31	22.92	139.23	-13.3
274	192.8	157.2	122.01	22.16	144.17	-13.0
294	230	153.7	123.54	21.91	145.45	- 8.2
314	1046	164.5	136.70	17.25	153.95	-10.6
Profile 13, Cheyenne Mtn. B - Haswell, CO d = 156.12 km						
334	92	162.1	115.59	27.34	142.93	-19.2
354	210.4	172.4	122.78	31.01	153.79	-18.6
374	236	166.4	123.78	31.67	155.45	-11.0

Table 1. (continued)

Path #	f_{MHz}	L(obs)	L_{fs}	A(MKE)	L(MKE)	Δ
Profile 14, Blacktail Canyon - Eloy, AZ d = 167.79 km						
1702	880	205.2	135.83	52.66	188.49	-16.7
1703	950	205.3	136.50	53.01	189.51	-15.8
1713	1705	214.2	141.58	56.51	198.09	-16.1
1712	2345	218.8	144.35	60.48	204.83	-14.0
Profile 15, Beulah - Table Mesa, CO d = 223.56 km						
303	100	165.3	119.44	40.12	159.56	- 5.7
305	751	191.6	136.95	40.06	177.01	-14.6
319	751	197.3	136.95	44.60	181.55	-15.8
320	751	191.5	136.95	38.13	175.08	-16.4
321	9200.1	228.7	158.71	52.26	210.97	-17.7
Profile 16, Cheyenne Mtn. S - Sheridan Lake, CO d = 227.49 km						
262	100	163.4	119.59	36.55	156.14	- 7.3
302	230	164.4	126.82	41.34	168.16	3.8
322	1046	179.4	139.98	57.57	196.95	17.6
Profile 17, Pikes Peak - Sheridan Lake, CO d = 244.29 km						
425	1046	154.6	140.60	15.40	156.00	1.4

The column headed "Δ" shows the difference between the predicted and observed propagation loss, with Δ defined as

$$\Delta = L(MKE) - L_{bo} \quad . \tag{5}$$

Notice that a negative value of Δ indicates that more signal is predicted than is actually observed. There is a general tendency to underestimate the loss when considering only MKE attenuation, and this is reasonable since most terrain features are rounded obstacles rather than knife-edges.

Among the six LOS profiles, predicted loss is generally underestimated for the propagation paths of profiles 1 and 4. Profile 1 is a Florida path mainly over water and contains no terrain features that might be classified as knife-edges. Profile 4 extends over the eastern plains of Colorado and appears quite flat over that portion where the direct ray nears the earth's surface.

Predictions for the propagation paths of profiles 2, 3, and 10 are fairly close to observed values, and these profiles are more irregular than those of 1 and 4. An interesting observation concerning profiles 2 and 3 is that, although the knife-edges used in the predictions are all below the LOS direct ray, their configuration is such that as much as 17 dB attenuation is added to the free-space loss.

The predictions of profile 7 give varied results, although most of the Δ's are small. Path 311, at 1046 MHz, has the greatest discrepancy with a Δ of -13.2 dB; the other two paths at this frequency, nos. 312 and 313, show good predictions. The differences among these three paths are in the receiving antenna heights and the recording period of the observations. Path 312 was recorded for some 6000 hours, while 313 and 311 were recorded for about 400 and 600 hours, respectively.

The three SH profiles (nos. 8, 12, and 15) generally show much more predicted signal than is observed. Profile 15 is especially noteworthy because of Δ's as large as -18 dB, yet the terrain profile itself would appear to be a good example of a knife-edge path. The common horizon in this Colorado profile path (#15) is a peak of about 4300 meters above msl. At this altitude the actual radio ray path likely departs from the straight line geometry of the effective earth approximation, and the diffraction angle, θ, would be larger than the one used in the calculations. An effective radius based only on surface refractivity is probably too large for high altitude paths such as those in profile 15.

The DH paths have two profiles giving consistently large negative Δ's, nos. 13 and 14. Profile 14 (an Arizona path) appears to be reasonably well-approximated by knife-edges, but #13 (in eastern Colorado) is a smoother, more rounded profile.

Propagation path 394 in profile 11 shows the largest negative Δ in the table (-26 dB), while path 322 in profile 16 has the largest positive Δ (17.6 dB). No other Δ's are near these two values, and the measured losses, if correct, must be the result of unique effects. Predictions in the remaining 13 DH propagation paths agree fairly well with observations.

In summary it appears that propagation loss predictions based strictly on multiple knife-edge diffraction tend to provide estimates of signal power greater than that actually observed. Of the 66 paths in Table 1, there are:

(1) 13 paths with $10 > \Delta \geq 0$,

(2) 30 paths with $0 > \Delta > -10$, and

(3) 21 paths with $-10 > \Delta > 20$.

Only two paths have Δ's outside this range. Figure 1 gives a graphical representation of the information in Table 1. The figure is a plot of Δ versus distance, and it can be seen that most of the Δ's fall within the range from -12 to +7 dB. One reason for the tendency to underestimate the loss is probably that terrain obstacles usually have rounded tops. More comparisons of observations and predictions over paths with sharply irregular features would be helpful.

3. MKE ATTENUATION USING TOPO

MKE attenuations have also been evaluated for a few paths whose profiles have been obtained from a digitized topographic data base (TOPO) developed at ITS. The data base provides terrain elevations above mean sea level at every 30" of latitude and of longitude in the continental U.S. A complete description of TOPO can be found in Jennings and Paulson (1977).

TOPO terrain profiles are generated by designating the latitudes and longitudes of the transmitter and receiver locations, then calculating elevations along the propagation path by interpolating between grid points. A profile formed in this manner is not as accurate as one read from contour maps and can, in fact, occasionally result in spurious peaks or overlook actual ones.

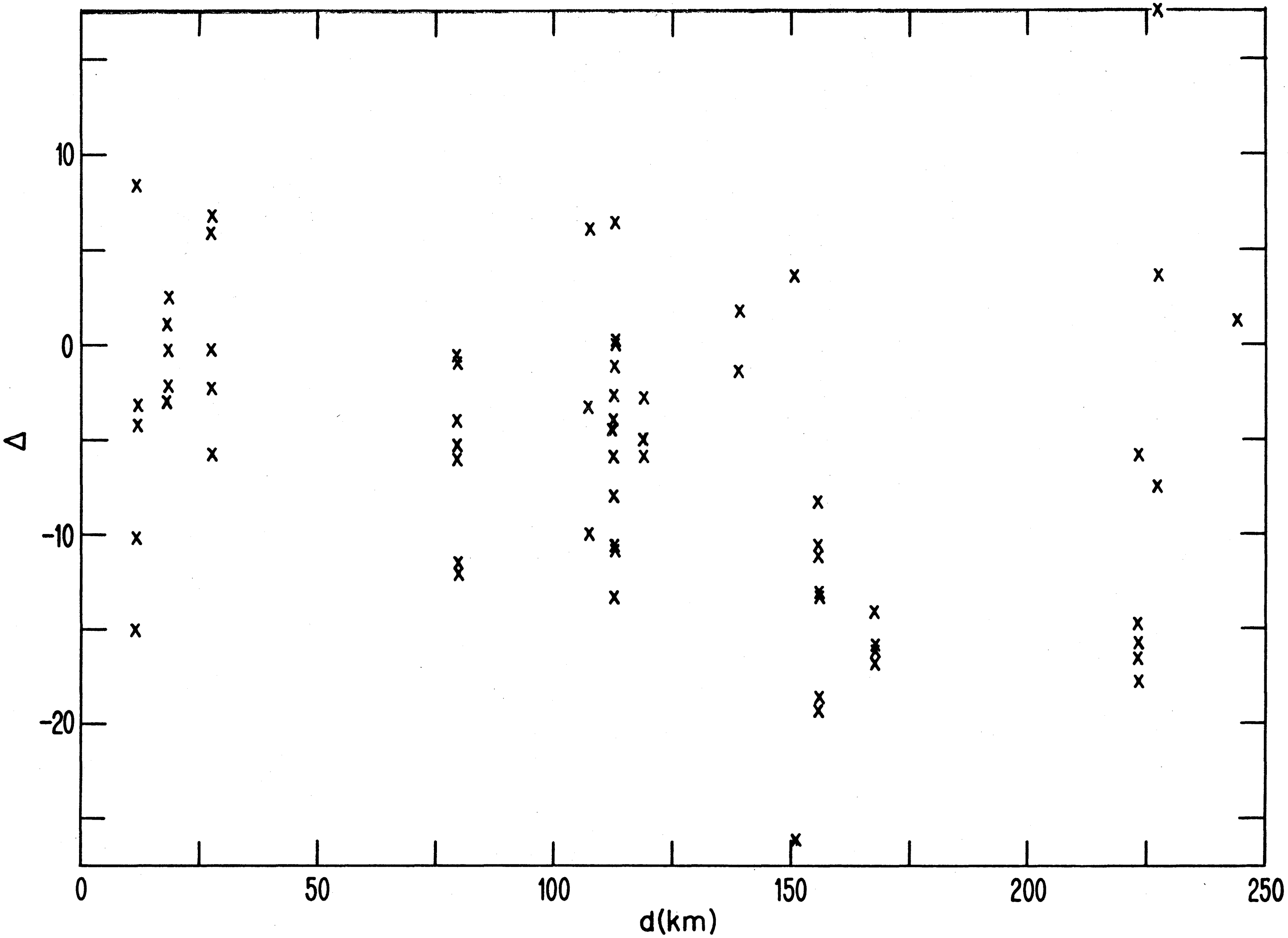

Figure 1. Δ versus distance from Table 1.

Profiles from contour maps are preferred in the calculation of MKE attenuation; however, the labor involved is much greater than when using TOPO. The attenuations will agree to the extent that the TOPO profile agrees with the map profile.

The propagation paths for which TOPO profiles were generated are listed in Table 2, along with the resulting Δ's. Path parameters are the same as in Table 1 except that path distances differ slightly because of the two profile-forming methods. It should also be remembered that ground elevations at the antennas in in the TOPO profiles usually differ from actual elevations, sometimes causing an antenna to be placed on a slope rather than a prominence.

There is, again, a predominance of negative Δ's indicating that the MKE attenuation predicts larger signal strengths than are observed. For two profiles, nos. 8 and 12, the TOPO profile gives a single horizon path rather than the double horizon path obtained from map reading. Apparently, one of the horizon obstacles has been reduced in height during the interpolation procedure.

An example of a spurious result caused by TOPO is probably propagation path #1610 which shows a Δ = 34.6 dB. The MKE attenuation was almost 30 dB larger than that calculated using the map profile. The main problem in applying TOPO is the inability to predict cases like this beforehand.

Topographic data bases with finer grids than TOPO are currently under development. When these are completed more accurate terrain profiles will be available and the problem of providing correct input information to the MKE propagation model will be greatly eased.

4. CONCLUSIONS

Comparisons of MKE diffraction loss with observed measurements have been made for over 60 propagation paths. The observed data represent median values of long-term measurements over paths of varying distances and frequencies. MKE predictions generally give higher signal levels than are actually observed, probably due to the fact that terrain features are usually more like rounded obstacles than true knife-edges. Two further papers which bear on this point are Nishikori et al. (1957) and Vigants (1981).

For the 66 paths analyzed, about 75% have Δ's lying within the range from -12 to +7 dB. All except two paths fall between the range -20 to +10 dB. Further

Table 2. Comparison of Predicted and Observed Propagation Loss Using Profiles from TOPO
Δ = L(MKE) - L(Observed)

Path #	L(obs)	L_{fs}	L(MKE)	Δ
Profile 6, Rochester - Ithaca, NY d = 107.05 km (from TOPO)				
1606	182.6	131.53	184.58	2.0
1609	194.6	141.98	209.56	15.0
1610	207.1	152.22	241.75	34.6
Profile 8, Cheyenne Mtn. B - Karval, CO d = 112.99 km (from TOPO)				
332	143.5	112.78	132.62	-10.9
352	149.8	119.97	141.40	- 8.4
372	141.8	120.97	142.69	0.9
Profile 12, Cheyenne Mtn. S - Haswell, CO d = 155.56 km (from TOPO)				
254	152.5	116.29	135.89	-16.6
274	157.2	121.99	142.26	-14.9
294	153.7	123.52	144.03	- 9.7
314	164.5	136.68	160.55	- 4.0
Profile 14, Blacktail Canyon - Eloy, AZ d = 167.90 km (from TOPO)				
1702	205.2	135.84	190.93	-14.3
1703	205.3	136.50	192.06	-13.2
1713	214.2	141.58	200.87	-13.3
1712	218.8	144.35	205.82	-13.0
Profile 15, Beulah - Table Mesa, CO d = 223.80 km (from TOPO)				
303	165.3	119.45	159.31	- 6.0
305	191.6	136.96	178.53	-13.1
319	197.3	136.96	183.81	-13.5
320	191.5	136.96	179.76	-11.7
321	228.7	158.72	217.88	-10.8

studies, using more measured data and a closer analysis of path profiles, might enable the development of an empirical correction factor to refine the MKE prediction model.

MKE predictions were also made on a few propagation paths for which the path profile was obtained from a topographic data base (TOPO). Again, comparisons with observed loss data indicate that MKE attenuation tends to overestimate signal strength. At present the elevation grid spacing in TOPO is too large to generate accurate path profiles in all cases, and spurious results are sometimes produced. The development of a finer grid spacing should overcome many of the difficulties now inherent in the application of TOPO to MKE attenuation modeling.

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FORM **NTIA-29**
(4-80)

U.S. DEPARTMENT OF COMMERCE
NAT'L. TELECOMMUNICATIONS AND INFORMATION ADMINISTRATION

BIBLIOGRAPHIC DATA SHEET

	1. PUBLICATION NO.	2. Gov't Accession No.	3. Recipient's Accession No.
	NTIA Report 82-108		

4. TITLE AND SUBTITLE

Comparisons of Observed Propagation Loss with Predictions from Multiple Knife-Edge Attenuation

5. Publication Date

October 1982

6. Performing Organization Code

NTIA/ITS-4

7. AUTHOR(S)

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9. Project/Task/Work Unit No.

8. PERFORMING ORGANIZATION NAME AND ADDRESS

U.S. Department of Commerce
NTIA/ITS-4
325 Broadway
Boulder, Colorado 80303

10. Contract/Grant No.

11. Sponsoring Organization Name and Address

National Telecommunications and Information Administration
Washington, DC

12. Type of Report and Period Covered

13.

14. SUPPLEMENTARY NOTES

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

Comparisons of theoretical attenuation based on multiple knife-edge diffraction with measured values of median propagation loss are presented for a number of different propagation paths. In general the knife-edge predictions tend to overestimate received signal strength with most of the differences between predicted and observed values lying in the range -12 to +7 dB. Use of a computerized topographic data base to generate path profiles for the knife-edge attenuation result in predicted/observed loss differences of about the same magnitude, although spurious results sometimes arise.

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

data comparisons; multiple knife-edge attenuation

17. AVAILABILITY STATEMENT	18. Security Class. *(This report)*	20. Number of pages
[X] UNLIMITED.	Unclassified	18
[ ] FOR OFFICIAL DISTRIBUTION.	19. Security Class. *(This page)* Unclassified	21. Price:

☆U.S. GOVERNMENT PRINTING OFFICE: 1982—676-772/38