NTIA-REPORT-78-10

Earth-Space Attenuation Predictions for Geostationary Satellite Links in the U.S.A.

E. J. Dutton

U.S. DEPARTMENT OF COMMERCE
Juanita M. Kreps, Secretary

Henry Geller, Assistant Secretary
for Communications and Information

October 1978

PREFACE

The study presented in this report was partially supported by the Advanced Mail Systems Directorate of the U.S. Postal Service, Rockville, MD 20852, under Agreement Number 104230-78-T-0681. The U.S.P.S. technical monitor for the program was Mr. Ralph Marcotte of the Systems Division. The program director at the Institute for Telecommunication Sciences was Dr. Peter McManamon.

The opinions expressed herein are those of the author and are not to be construed as representing policies or doctrines of the U.S.P.S.

TABLE OF CONTENTS

LIST OF FIGURES

List of Figures (Continued)

LIST OF TABLES

Earth-Space Attenuation Predictions for Geostationary Satellite Links in the U.S.A.

E. J. Dutton*

ABSTRACT

The previously developed Rice-Holmberg (RH) rain-rate model and the Dutton-Dougherty (DD) attenuation model for earth-space links, and their subsequent modifications, are reviewed. Predictions are compared with data observed both from the Communications Technology Satellite (CTS) and from radiometric measurements. Then predictions are made at 12.2 and 14.5 GHz for 75 possible U.S.A.-based earth stations pointing to several potential geostationary satellite locations.

Key words: attenuation distributions, earth-space attenuation, microwave frequencies, prediction confidence limits, rain-rate distributions, satellite-earth communication links.

1. INTRODUCTION AND BACKGROUND

An earlier report (Dutton, 1977a) discussed the development of a model for the prediction of earth-space attenuation, principally due to rain, at 4 to 16 GHz. This model was applied to earth-space communications systems for time-availabilities of 99% or more. As this report showed, the rain attenuation problem was much more substantial for systems using the 12 to 14 GHz frequency band than for systems using the 4 to 6 GHz band. Hence, this report will concentrate on the earth-satellite attenuation in the 12 to 14 GHz band.

As was discussed in Dutton (1977a), precipitation-caused attenuation has been traditionally linked to a difficult-to-measure parameter, "one-minute rain rate",** R_o, at the earth's surface. This tradition has been maintained in Dutton (1977a), but the relationship between R_o and attenuation has been

---

*The author is with the Institute for Telecommunication Sciences, National Telecommunications and Information Administration, U. S. Department of Commerce, Boulder, CO 80303.

**or simply "rain rate".

significantly altered from the classic Ryde (1946) relationship, for use on earth-space links. It has been found helpful to model (rather than measure) the distribution of mean R_o, $\overline{R}_o$, (or "rain rate expected during an *average* year") and the variance S_R^2 of R_o for a particular percentile on the distribution, in order to describe the distribution of rain rate at a given location. This was achieved in Dutton (1977a) by use of a modification to the Rice-Holmberg, RH, (Rice and Holmberg, 1973) model.

The RH model expresses the percent of time, $P(\overline{R}_o)$, that the mean rain rate, $\overline{R}_o$, is exceeded during a year. This is expressed mathematically as

$$P(\overline{R}_o) = kT_{11} \exp(-\overline{R}_o/\overline{R}_{11}) + .35kT_{21} \exp(-.453074\overline{R}_o/\overline{R}_{21})$$

$$+ .65\, kT_{21} \exp(-2.857143\, \overline{R}_o/\overline{R}_{21}) \ . \qquad (1)$$

A fast and accurate interative-recursive technique for large-scale computers has made it desirable to solve (1) for $\overline{R}_o$, rather than use the less-accurate modified RH model to estimate R_o, given $P(\overline{R}_o)$ (Dutton, 1977b). The basic meteorological parameters used in (1) are M, the average annual precipitation at a location of interest; M_m, the greatest monthly precipitation in 30 consecutive record years; D, the average annual number of days with precipitation ≥0.25 mm; and U, the average annual number of days with thunderstorms. In (1), $\overline{R}_{11}$, $\overline{R}_{21}$, T_{11}, and T_{21} are functions of M_m, M, D, and U; and k = 0.01141, a conversion from hours/year to percent of a year (see also Appendix A). There are two types of rainstorms considered by Rice and Holmberg (1973), whence the "1" and "2" subscripts on the various parameters in (1). The second subscript (always a "1") refers to "one-minute rain rates". Another important variable used in connection with the RH model is β, the ratio of precipitation associated with thunderstorms to the total precipitation for an average year. The parameter β can be expressed in terms of M, M_m, and U as

$$\beta = \beta_o \left\{ 0.25 + 2 \exp\left[\frac{-0.35(1+0.125M)}{U}\right] \right\} , \qquad (2)$$

where

$$\beta_o = 0.03 + 0.97\ [-5 \exp(-0.004M_m)] \ . \qquad (3)$$

Expressions (2) and (3) are empirical relationships. Based upon M and β for 305 first-order U.S. Weather Service locations, the United States of America was divided into 19 telecommunication-oriented, rainfall zones in Dutton (1977b). Each zone presumably represented a region in which rainfall patterns are similar, and by pooling raw data within a given zone, zone-wide S_R^2 values were obtained for application at any particular location within that zone. This approach, however proved less than optimum for many zones. For this and other reasons discussed in Appendix A of this report, the zonal concept has been discontinued so far as this report is concerned.

The variance of attenuation, S_τ^2, about a mean value, $\bar{\tau}$, predicted for a given percent of a year, was handled in Dutton (1977a) by simply assuming <u>all</u> the attenuation model's variability was due to S_R^2. This gave a restricted (upper and lower bounds) range of attenuation variability. In Section 2, recent data from the CTS satellite observations at 11.7 GHz have been compared with this approach, in a further effort to assess the model's meaningfulness. This is in addition to the data-model comparisons made in Dutton (1977a). In Section 3, results using this model are given at 12.2 and 14.5 GHz.

Figure 1 shows an example of geostationary satellite-earth attenuation and a relationship between mean satellite suborbital longitude for Washington, DC, at 12.2 GHz. Three separate curves are displayed that are parametric in percent of a year that the attenuation is expected. Attenuation values are those expected for an <u>average</u> year. This relationship is derived in detail in Appendix A.

2. COMPARISON OF OBSERVATIONS AND MODELING

Recently, much attenuation data from the Communications Technology Satellite (CTS) taken at 11.7 GHz have become available for various locations throughout the U.S.A. Most of these data are presented in a cumulative distribution format, which facilitates their comparison with the Dutton-Dougherty (DD) model (Dutton, 1977a). The DD model, however, is, at this stage, still a model which predicts <u>annual</u> distributions of earth-space attenuation, only, and does so only as low as 0.01 percent of a year. Much of the data examined to date (Vogel and Straiton, 1977; Bostian et al., 1977, 1978) covers a period of time much less than a year; e.g., a summer. There are various ways that both this kind of data or the DD model can be manipulated to accommodate these

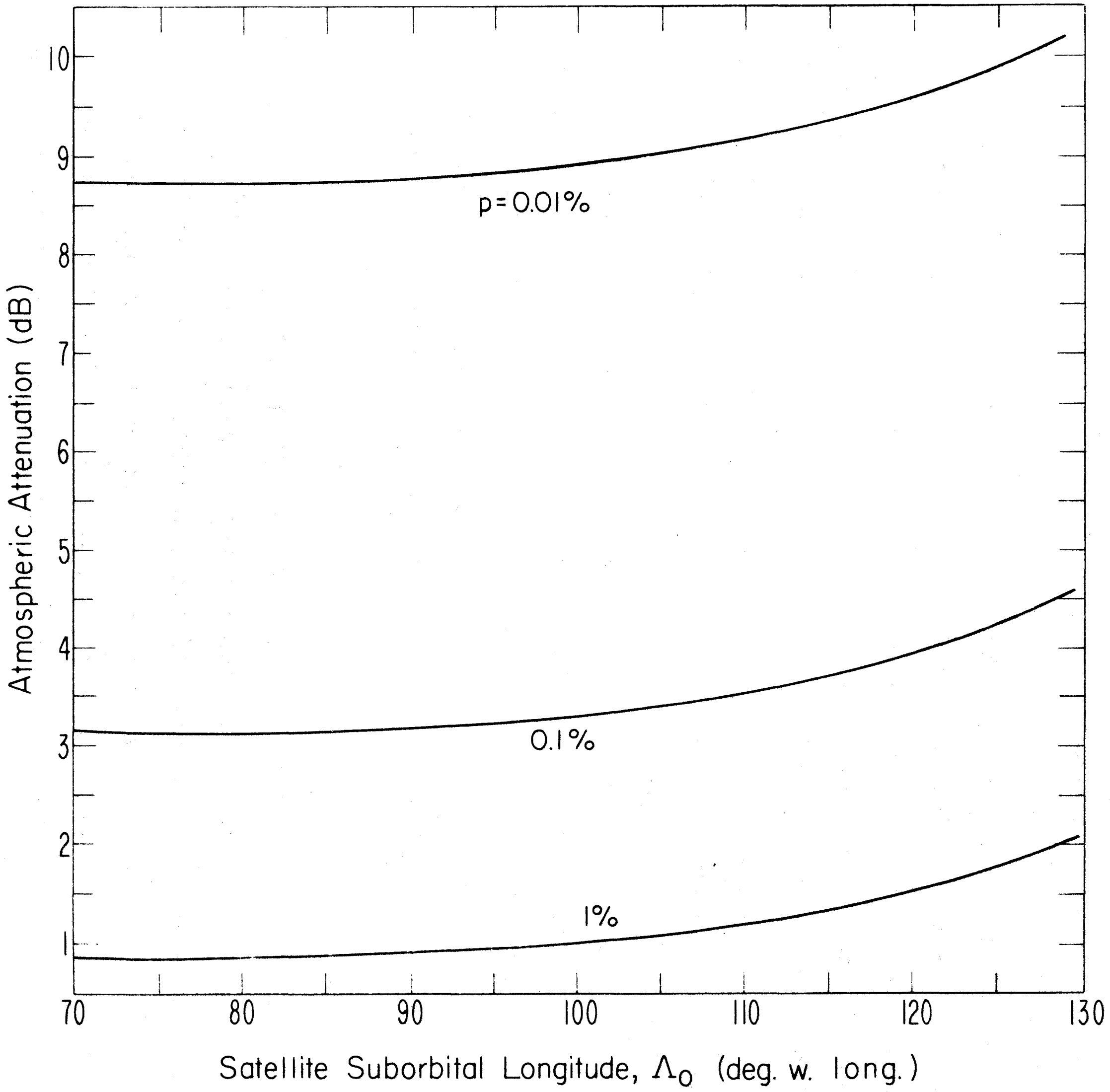

Figure 1. Mean atmospheric attenuation expected at a Washington, DC earth terminal at 12.2 GHz as a function of geostationary satellite position.

intervals of less than a year. However, in view of the facts that there are sufficient other data, both radiometric and CTS, available for at least a year in duration, and that manipulation of the data and/or model lends considerably less credence to the results, no data of less than one year in extent has been used for comparison with DD model predictions herein. Nonetheless some accommodations for this kind of data are considered in Appendix B. Data presented in Dutton (1977a) will not be repeated here. Thus the comparisons are essentially new.

Figures 2 and 3 show the comparison of the DD model with the CTS data presented by Ippolito (1978). The data used in figure 2 were taken at the NASA Goddard Space Flight Center, Greenbelt, MD, for the year from June 1, 1976 to May 31, 1977. The data results were observed at 11.7 GHz for an elevation angle $\theta_o = 29°$. The data included 96.7% of the rain events for that period. The data as presented by Ippolito (1978) did not include clear-air attenuation, so that attenuation (approximately 1 dB) was added to the data presented in Figure 2. In all cases that follow (except Figure 4, where there are several "nearby" stations), the nearest first-order U.S. Weather Service station was used for prediction comparison with the data. In some cases these "nearby" stations are 30 or 40 miles away, which can introduce some skepticism as to the validity of any such comparisons. However, no meteorological data with which to make predictions were available (to this author) closer, and, additionally, such comparisons are in keeping with similar comparisons (Dutton, 1977a, Rustako, 1978) elsewhere. In Figure 2, however, the prediction comparison site, Washington, DC, is relatively close (about 15 mi) to Greenbelt, MD.

The predicted attenuation distributions are for the same frequency and θ_o as the data, and there are five prediction curves in Figure 2, and subsequent figures. Proceeding from left to right on the figure as it faces the reader, these curves correspond to the predicted 0.5 and 5 percent confidence limits, the mean prediction, and the 95 and 99.5 percent confidence limits respectively.

Figure 3 shows a comparison of CTS data also reported by Ippolito (1978). These data, however, were observed by NASA at Rosman, NC at 11.7 GHz and $\theta_o = 33°$ for the period from June 1, 1976 to June 30, 1977. The predicted attenuation distributions were determined from data at Asheville, NC, which is located roughly 35 mi from Rosman. Again, as in Figure 2, the predicted

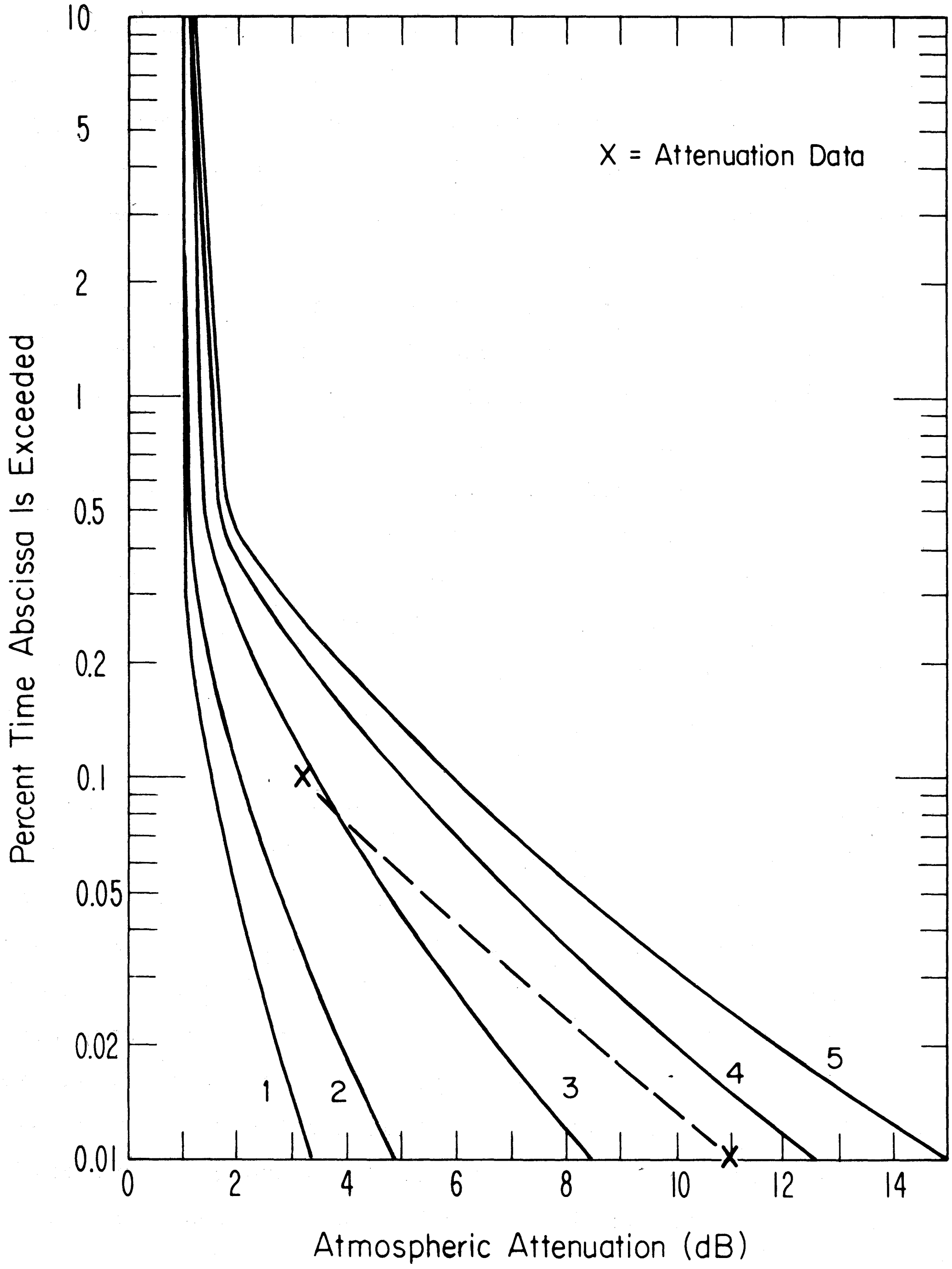

Figure 2. Comparison of CTS data from Greenbelt, MD, and predictions for Washington, DC, for 11.7 GHz at an elevation angle of 29 degrees, data period is June 1, 1976 to May 31, 1977.
Curve 1 represents the 0.5 percent confidence limit;
Curve 2 represents the 5 percent confidence limit;
Curve 3 represents the mean prediction;
Curve 4 represents the 95 percent confidence limit; and
Curve 5 represents the 99.5 percent confidence limit.

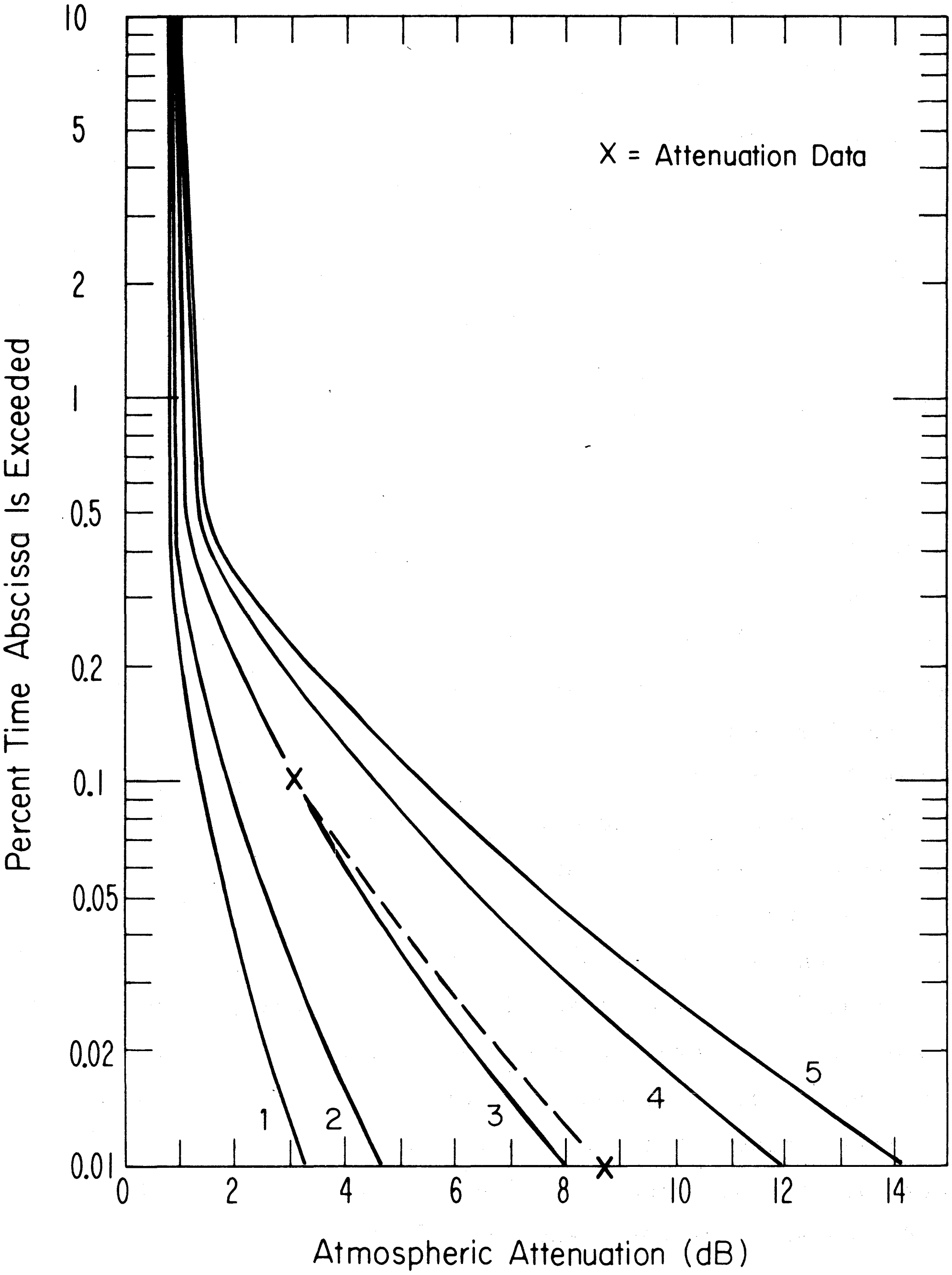

Figure 3. Comparison of CTS data from Rosman, NC, and predictions for Asheville, NC, for 11.7 GHz at an elevation angle of 33 degrees. Data period is June 1, 1976 to June 30, 1977. See Figure 2 for definition of curves 1 to 5.

clear-air attenuation at Asheville was added to the Rosman data for more accurate comparability with the predictions.

Figures 4, 5, and 6 involve attenuation data from CTS at 11.7 GHz and $\theta_o = 27°$, taken at Holmdel, NJ, by Bell Laboratories during the period April 26, 1976 to April 26, 1977. These data are presented by Rustako (1978). The data plus 0.3 dB clear-air attenuation (Rustako's value) are presented in figures 4, 5, and 6 for comparison with attenuation distribution predictions made at 3 locations: Trenton, NJ (Figure 4), Newark, NJ (Figure 5), and New York City, Central Park, NY (Figure 6). The reason that three locations were compared is that all 3 are approximately equidistant (30 to 35 mi. away) from Holmdel, NJ. Climatologically speaking, however, Trenton, NJ, would seem the least likely station to be comparable to Holmdel, since it is much farther inland than Newark or New York City. However, since Rustako (1978) uses his Trenton prediction methodology for comparison purposes, this author feels obliged to do the same, for consistency.

CTS data are being observed at the Ohio State University in Columbus, OH, at the University of Texas in Austin, TX, and at the Virginia Polytechnic Institute in Blacksburg, VA. Unfortunately, as of this writing, only data for short segments of a year were available to this author from the latter two of these locations (see Appendix B). No full-year data were available to his knowledge. It would have been helpful to have a year's worth of data from locations such as Austin, TX, because it would have given a comparison with an entirely different area of the country than was contained in Figures 2 through 6. Since attenuation predictions have been made for the entire conterminous U.S.A. in the next section (Section 3), such a direct-observation data distribution as the Texas data would have been highly desirable for comparison with prediction. There are, however, some indirect observations of satellite-to-ground attenuation, made by radiometer, for locations more geographically diverse throughout the U.S.A. than those for the CTS. These radiometric observations are also of at least a year's length, and are shown in figures 7, 8, and 9. They were taken by Bell Labs and presented by Bergmann (1977). As discussed in Dutton (1977a), most radiometric data, when interpreted as attenuation, cannot be trusted above about 10 dB. For values below 10 dB, however, radiometric data should be nearly as reliable as direct observations.

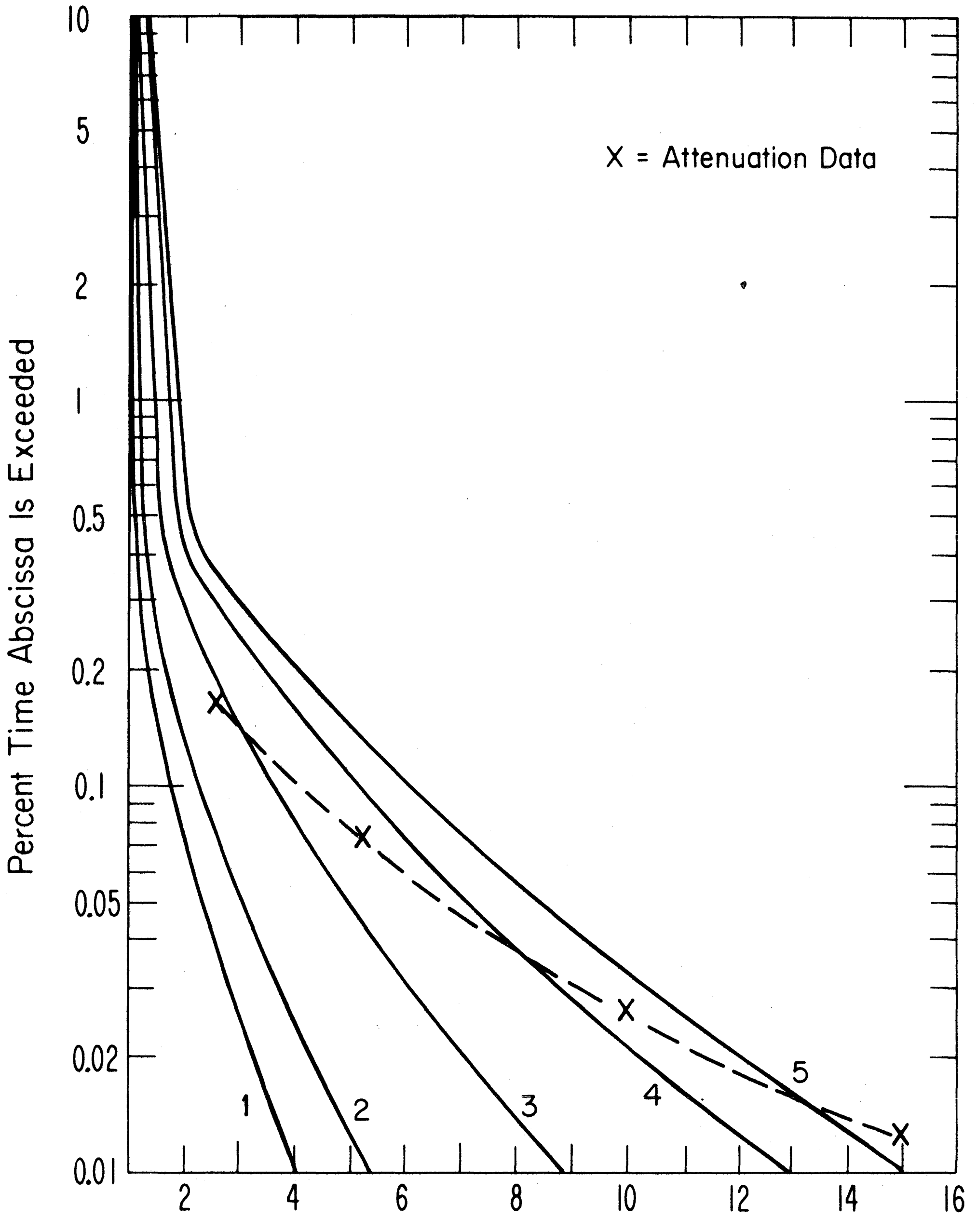

Figure 4. Comparison of CTS data from Holmdel, NJ, and predictions for Trenton, NJ, for 11.7 GHz at an elevation angle of 27 degrees. Data period is April 26, 1976 to April 26, 1977. See Figure 2 for definition of curves 1 to 5.

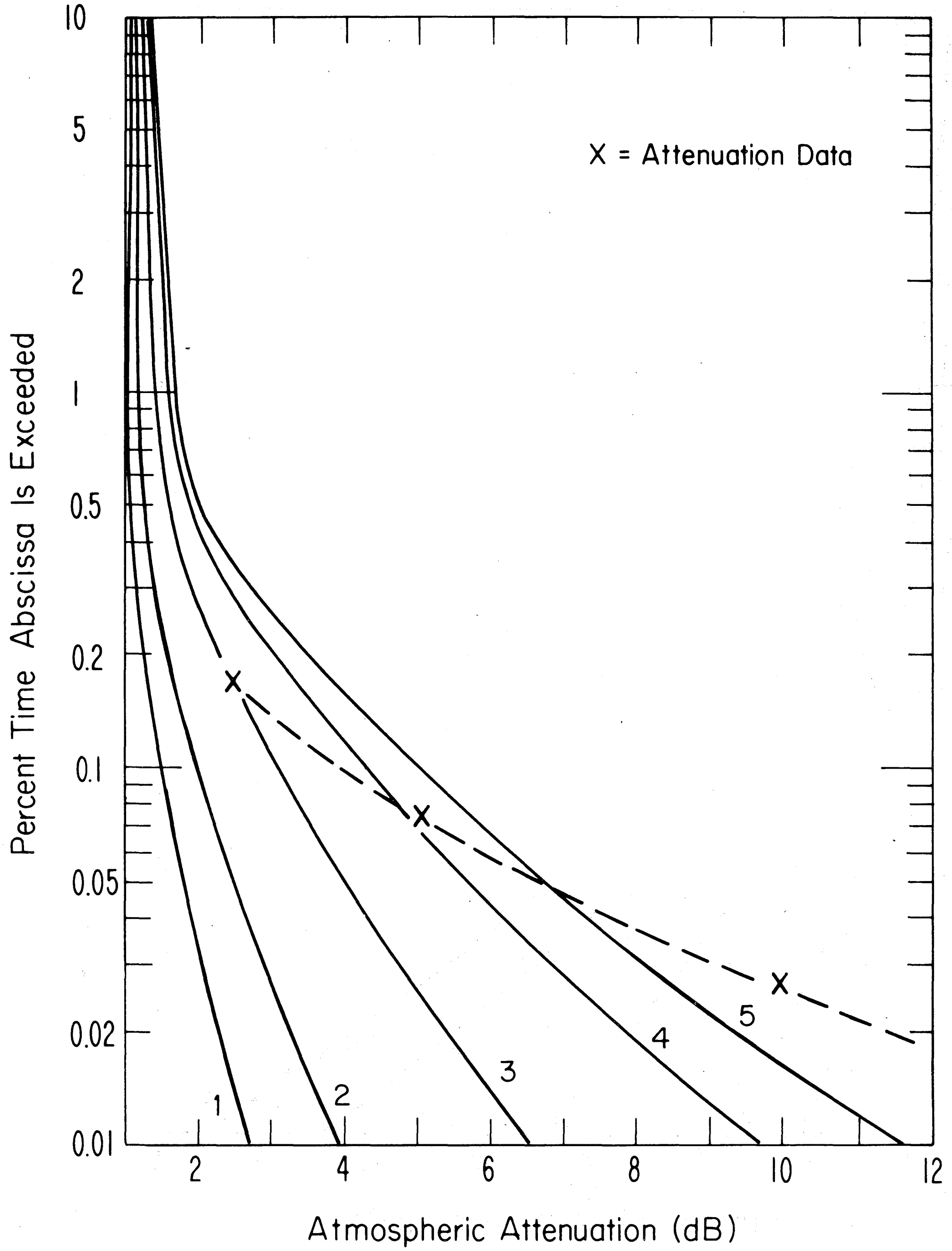

Figure 5. Comparison of CTS data from Holmdel, NJ, and predictions for Newark, NJ, for 11.7 GHz at an elevation angle of 27 degrees. Data period is April 26, 1976 to April 26, 1977. See Figure 2 for definition of curves 1 to 5.

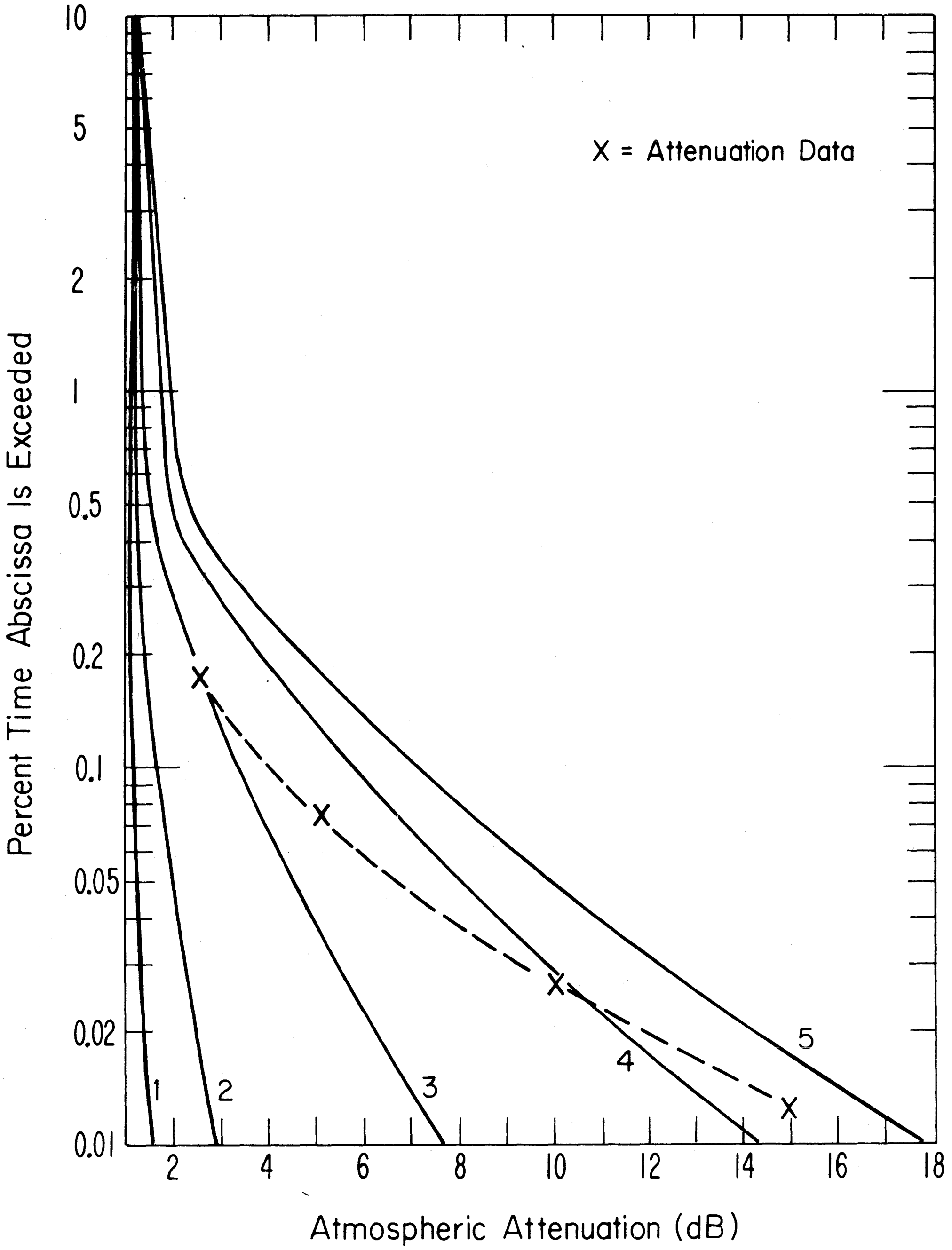

Figure 6. Comparison of CTS data from Holmdel, NJ, and predictions for New York City, Central Park, NY, for 11.7 GHz at an elevation angle of 27 degrees. Data period is April 26, 1976 to April 26, 1977. See Figure 2 for definition of curves 1 to 5.

Figure 7 shows radiometric observations made at 13.6 GHz for $\theta_o = 38.2°$ at Palmetto, GA, during the period June 1973-June 1975. Radiometric observations inherently include clear air attenuation; therefore, it is presumed to be included in the data of the following figures. The comparative attenuation distribution predictions have been made for Atlanta, GA, a location roughly 15 mi. from Palmetto.

Figure 8 shows radiometric observations made at 13.6 GHz for $\theta_o = 27.3°$ at Grant Park, IL, during the period July 1976 to June 1977. These data are compared with predictions of attenuation distributions for Chicago, IL, which is approximately 40 mi. north of Grant Park. Figure 9 shows radiometric observations made at 13.6 GHz for $\theta_o = 42.6°$ at Longmont, CO, during the two-year period June 1973 to July 1975. These data are plotted on the figure along with the attenuation distribution prediction curves for Denver, CO, approximately 40 mi. to the south of Longmont.

In general, the comparison of data and predictions in Figures 2 through 9 appears to be relatively good. Of all the figures, however, probably the set (Figs. 4, 5, and 6) that compare the Holmdel, NJ, CTS data with predictions for 3 different locations is the most exemplary of the type of frustration likely to result when using predictions. In Dutton (1977a), it was indicated that, even in a small subzone of stations on the east coast with fundamentally similar climatologies, sizable differences in earth-space attenuation predictions to the same satellite were possible. Basically, this means that the meteorological data for one station theoretically should not be used to predict results for potential earth-terminal sites even a few miles away. Yet this kind of situation is likely to arise, since terminals will probably be remote from urban, interference-producing, areas, but U.S. Weather Service stations are either downtown or at the local airport. Figures 5 and 6 illustrate the problem clearly. The Newark, NJ, and New York City, Central Park, NY, stations are both in urbanized locations, about 10 mi. apart. Yet the Newark predictions compare rather poorly with the Holmdel CTS data, whereas the Central Park predictions compare rather well with the Holmdel CTS data. Both stations are about 30 mi. from Holmdel. More data in the southern, western, and midwestern U.S.A. is clearly needed for comparison purposes-especially data observed directly from geostationary satellites in the 12 to 14 GHz frequency band.

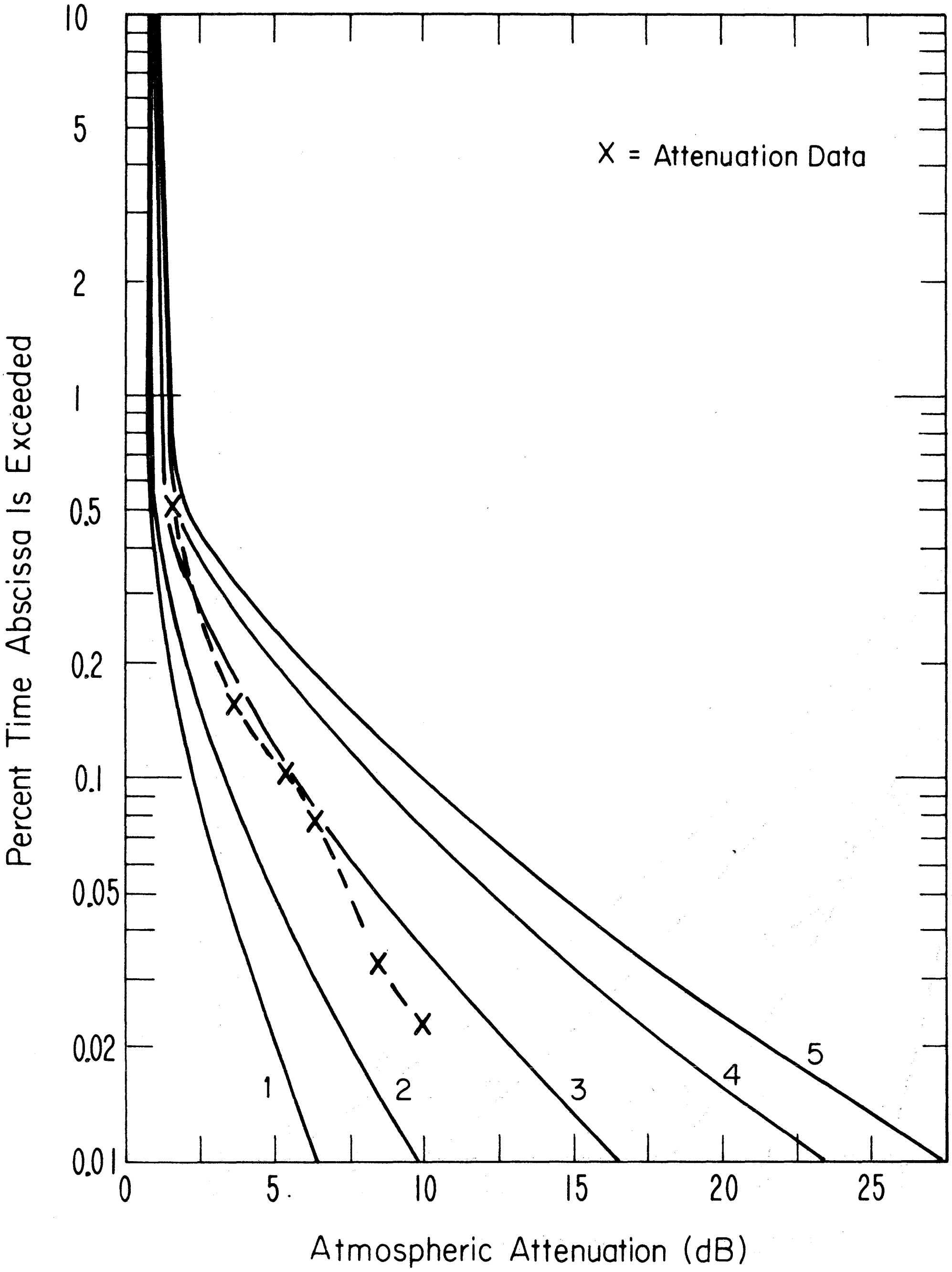

Figure 7. Comparison of radiometric data from Palmetto, GA, and predictions for Atlanta, GA, for 13.6 GHz at an elevation angle of 38.2 degrees. Data period is June, 1973 to June 1975. See Figure 2 for definition of curves 1 to 5.

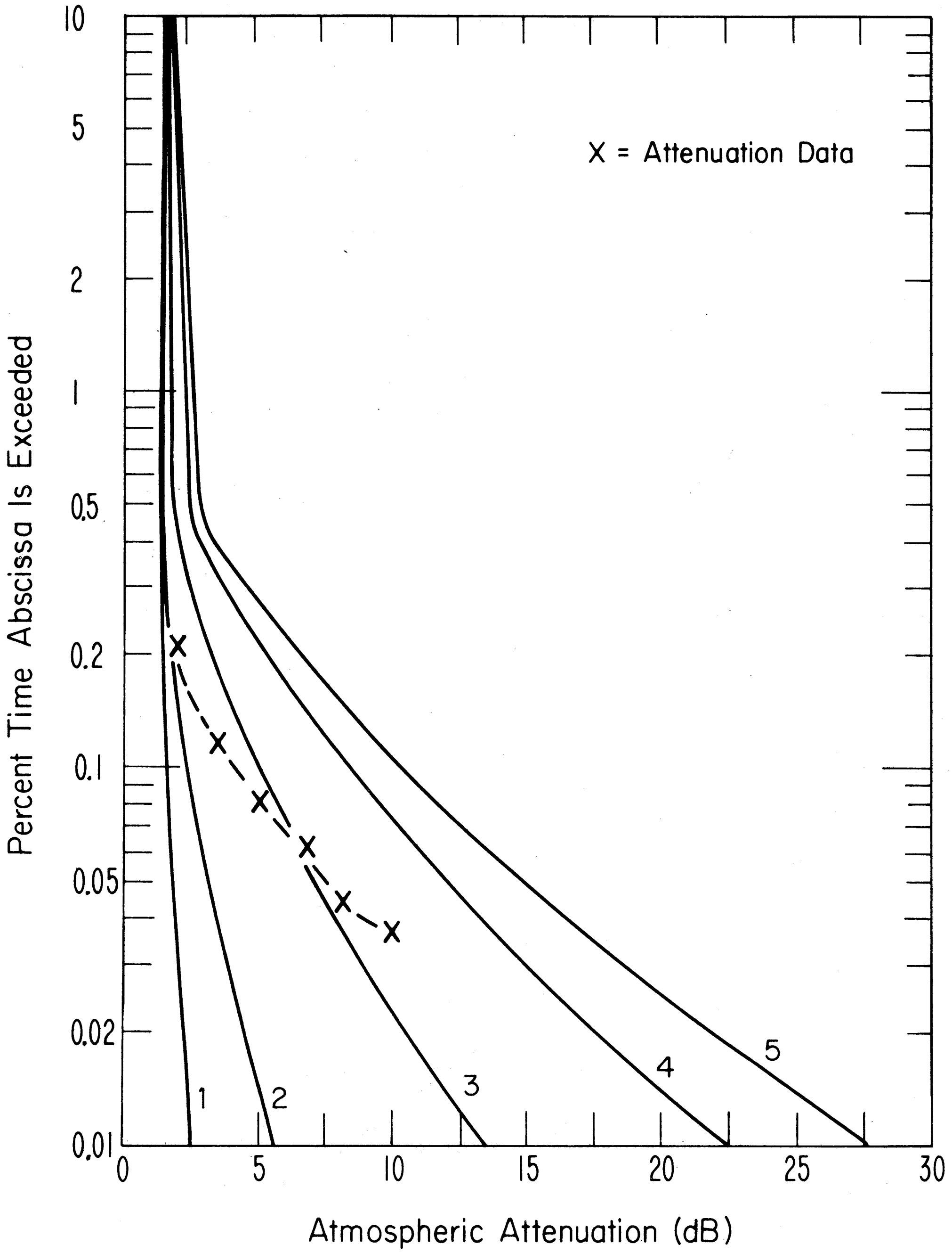

Figure 8. Comparison of radiometric data from Grant Park, IL, and predictions for Chicago, IL, for 13.6 GHz at an elevation angle of 27.3 degrees. Data period is July, 1976 to June 1977. See Figure 2 for definition of curves 1 to 5.

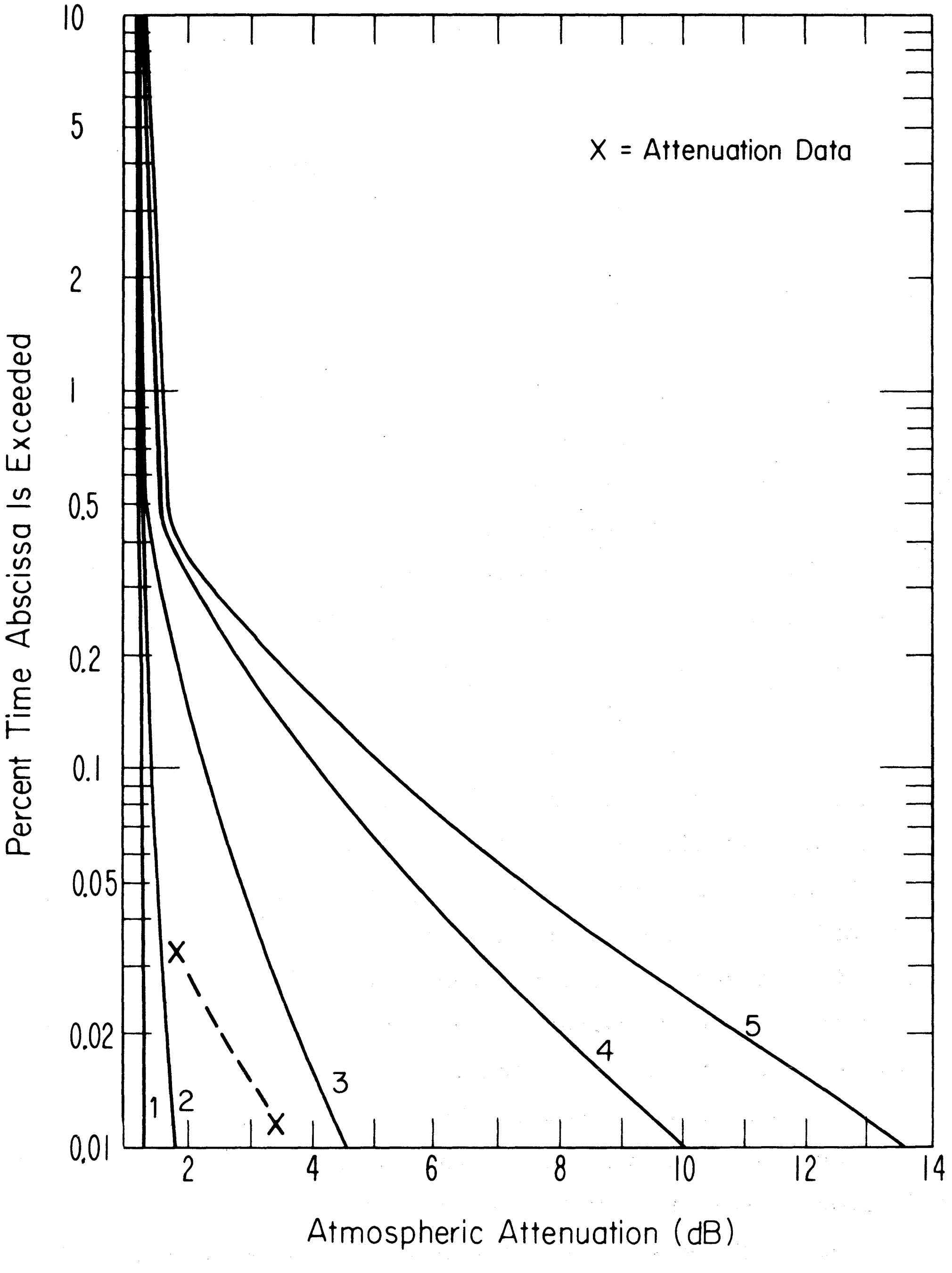

Figure 9. Comparison of radiometric data from Longmont, CO, and predictions for Denver, CO, for 13.6 GHz at an elevation angle of 42.6 degrees. Data period is June, 1973 to July, 1975. See Figure 2 for definition of curves 1 to 5.

3. PREDICTION RESULTS

Attenuation expected on earth-geostationary satellite links has been predicted for 75 geographically and climatically diverse locations throughout the U.S.A. These results are shown in Tables 1 through 4. Results are shown for four potential satellite suborbital longitudes, Λ_o, and are given for three percents of a year (.01%, .1%, and 1%) at each Λ_o. Table 1 shows the attenuation expected at 12.2 GHz during an average year, whereas Table 2 shows the predicted 99.5% confidence limit on that attenuation, using the truncated-normal distribution discussed in Appendix A. Table 3 shows the attenuation expected at 14.5 GHz during an average year, and Table 4 shows the predicted 99.5% confidence limit on that attenuation.

Results in these tables are fairly much as expected, with the largest values of attenuation on a given link occurring in the southeastern U.S.A and the smallest values occurring in the desert southwest, particularly for 0.01 and 0.1 percent of a year. Largest values at 1 percent of a year on a given link tend to occur in the northeast and the midwest, reflecting a greater tendency toward polar airmass type precipitation. Although the values in the 0.1 and 1 percent columns of tables 1 to 4 appear "small" compared to those in the 0.01 percent column, the user should keep in mind that these are values expected 10 and 100 times more often, respectively, than at 0.01 percent, and that an attenuation of 3 dB still represents 50 percent loss of signal power.

In Dutton (1977a), sample computations were made at some of the stations of Tables 1 to 4 for a satellite at 110°W longitude. Some of these computations were made at 12 and 14 GHz, so seemingly they should be comparable to the results in Tables 1 to 4, or just slightly less. However, one notes, especially for 0.01 percent of the time, that there are occasionally some apparent discrepencies between values at the same percent and same (nominal) frequency. Some of these values are larger at 12 GHz than at 12.2 GHz.

The reason for these differences is that the rain rate values, from which the attenuations are computed, were not obtained in exactly the same manner. As noted in Section 1, rain-rate values used in this report are obtained from the original RH model, whereas values in Dutton (1977a) were obtained from the modified RH model. As noted in Dutton (1977b), it is for rain rates that occur around 0.01% of the time in temperate climates that the greatest divergence

Table 1. Mean attenuation predictions for .01, .1, and 1 percent of a year at 12.2 GHz on earth-geostationary satellite links for satellites located at the indicated suborbital longitudes, Λ_o.

	Λ_o = 110°W			90°W			130°W			70°W		
Location	.01%	.1%	1%	.01	1	1	.01	1	1	.01	1	1
Worcester, MA	6.97	3.30	1.51	6.38	2.79	1.10	9.12	5.16	2.99	6.25	2.68	1.01
Boston, MA	8.44	3.63	1.50	7.91	3.12	1.08	10.4	5.50	3.04	7.79	3.01	.998
Providence, RI	6.10	3.05	1.48	5.48	2.54	1.07	8.34	4.92	2.96	5.34	2.43	.981
Concord, NH	5.14	2.78	1.54	4.53	2.27	1.13	7.41	4.64	3.03	4.39	2.16	1.04
Portland, ME	5.71	2.96	1.54	5.05	2.42	1.11	8.21	5.04	3.19	4.89	2.29	1.00
Burlington, VT	6.19	2.81	1.42	5.76	2.41	1.08	7.70	4.27	2.66	5.69	2.33	1.01
Newark, NJ	7.06	3.14	1.32	6.60	2.73	.990	8.66	4.56	2.46	6.51	2.65	.932
Hartford, CT	11.1	4.29	1.43	10.6	3.82	1.04	12.3	5.59	2.51	10.6	3.75	.981
Trenton, NJ	9.55	3.68	1.25	9.20	3.32	.946	10.8	4.93	2.28	9.14	3.26	.895
NY Central Park, NY	8.33	3.41	1.30	7.92	3.02	.970	9.76	4.80	2.43	7.84	2.94	.909
NY LaGuardia, NY	9.33	3.81	1.42	8.90	3.37	1.07	10.8	5.30	2.67	8.82	3.29	1.00
Rochester, NY	5.15	2.34	1.17	4.84	2.05	.934	6.17	3.29	1.98	4.82	2.03	.912
Buffalo, NY	4.95	2.31	1.17	4.65	2.04	.942	5.95	3.22	1.93	4.64	2.03	.932
Pittsburg, PA	4.97	1.61	.512	4.70	2.00	.834	5.87	3.04	1.67	4.70	2.00	.834
Philadelphia, PA	5.66	2.68	1.16	5.21	2.31	.879	7.17	3.92	2.13	5.14	2.26	.834
Wilmington, DE	7.78	3.22	1.17	7.39	2.86	.884	9.11	4.43	2.13	7.33	2.81	.842
Washington, DC	9.06	3.49	1.15	8.75	3.17	.888	10.1	4.54	2.00	8.71	3.14	.861
Albany, NY	4.91	2.44	1.28	4.46	2.06	.973	6.48	3.79	2.38	4.38	1.99	.916
Syracuse, NY	7.09	2.87	1.22	6.80	2.56	.952	8.11	3.93	2.12	6.76	2.52	.917
Harrisburg, PA	12.1	4.33	1.13	11.8	4.03	.884	13.1	5.33	1.93	11.8	3.99	.857
Baltimore, MD	11.1	4.06	1.17	10.7	3.74	.902	12.0	5.14	2.06	10.6	3.70	.871
Richmond, VA	12.7	4.54	1.05	12.4	4.24	.813	13.6	5.52	1.86	12.4	4.22	.790
Charleston, WV	9.95	3.50	.944	9.76	3.30	.780	10.6	4.17	1.49	9.77	3.31	.793
Greensboro, NC	10.1	3.55	.873	9.89	3.33	.696	10.8	4.28	1.46	9.89	3.33	.694
Charlotte, NC	9.23	3.36	.890	9.01	3.14	.712	9.96	4.08	1.47	9.02	3.15	.719
Columbia, SC	13.6	4.78	.879	13.4	4.55	.684	14.2	5.54	1.52	13.4	4.56	.693
Atlanta, GA	12.4	4.31	.815	12.2	4.13	.670	12.9	4.90	1.31	12.3	4.18	.707
Pensacola, FL	15.2	5.42	.742	15.0	5.25	.614	15.9	6.03	1.20	15.1	5.34	.683
Tampa, FL	18.1	6.90	.805	17.6	6.52	.579	20.0	8.15	1.55	17.7	6.57	.610
Miami, FL	19.6	7.71	.895	18.8	7.18	.597	22.2	9.39	1.86	18.8	7.19	.600
Birmingham, AL	14.7	5.23	.850	14.5	5.06	.707	15.3	5.86	1.36	14.6	5.15	.780
Montgomery, AL	17.0	6.32	.882	16.6	6.07	.708	18.1	7.24	1.50	16.8	6.18	.784
Memphis, TN	10.4	3.67	.768	10.3	3.56	.678	10.8	4.12	1.12	10.4	3.67	.768
Nashville, TN	11.7	4.04	.817	11.6	3.90	.700	12.2	4.55	1.24	11.6	3.97	.758
Jackson, MS	10.6	3.65	.705	10.5	3.55	.624	11.0	4.06	1.03	10.6	3.66	.708

Table 1 (Continued)

Mean attenuation predictions for .01, .1, and 1 percent of a year at 12.2 GHz on earth-geostationary satellite links for satellites located at the indicated suborbital longitudes, Λ_o.

	Λ_o = 110°W			90°W			130°W			70°W		
Location	.01%	.1%	1%	.01	1	1	.01	1	1	.01	1	1
Louisville, KY	11.4	3.98	.904	11.3	3.82	.773	11.9	4.54	1.36	11.3	3.88	.824
Columbus, OH	6.75	2.65	.970	6.55	2.46	.812	7.43	3.30	1.50	6.59	2.49	.838
Cleveland, OH	5.81	2.43	1.06	5.59	2.22	.878	6.56	3.15	1.66	5.61	2.23	.892
Cincinnati, OH	10.8	3.78	.934	10.7	3.60	.794	11.4	4.37	1.41	10.7	3.65	.832
Indianapolis, IN	9.56	3.39	.924	9.41	3.24	.799	10.1	3.93	1.37	9.47	3.30	.851
Detroit, MI	4.36	2.08	1.01	4.12	1.88	.852	5.17	2.76	1.56	4.16	1.91	.878
Des Moines, IA	10.5	3.55	.862	10.4	3.49	.812	10.8	3.90	1.13	10.6	3.64	.924
Milwaukee, WI	5.77	2.35	1.01	5.63	2.22	.897	6.29	2.85	1.43	5.72	2.30	.968
Minneapolis, MN	4.42	2.07	1.06	4.32	1.99	.993	4.89	2.48	1.40	4.51	2.16	1.13
Sioux Falls, SD	5.57	2.28	.969	5.53	2.24	.939	5.91	2.59	1.23	5.75	2.45	1.11
Fargo, ND	4.64	2.08	1.10	4.59	2.04	1.06	5.02	2.41	1.37	4.85	2.26	1.24
Billings, MT	3.19	1.82	1.21	3.32	1.93	1.30	3.37	1.98	1.34	3.92	2.43	1.72
Chicago, IL	9.94	3.51	.998	9.80	3.37	.885	10.4	4.03	1.42	9.88	3.45	.954
St. Louis, MO	6.31	2.52	.878	6.19	2.41	.792	6.80	2.96	1.23	6.31	2.52	.883
Kansas City, MO	9.23	3.24	.869	9.18	3.19	.821	9.56	3.58	1.15	9.34	3.35	.956
Wichita, KS	8.01	2.88	.808	7.99	2.85	.786	8.30	3.16	1.03	8.19	3.05	.946
Omaha, NE	9.97	3.35	.798	9.93	3.31	.768	10.3	3.64	1.02	10.1	3.48	.899
New Orleans, LA	16.2	5.88	.727	16.0	5.71	.614	17.0	6.52	1.18	16.2	5.88	.728
Shreveport, LA	10.3	3.54	.658	10.2	3.48	.608	10.6	3.87	.925	10.4	3.62	.724
Little Rock, AR	12.5	4.30	.752	12.4	4.21	.681	12.8	4.70	1.08	12.5	4.35	.797
Oklahoma City, OK	8.06	2.82	.696	8.03	2.80	.677	8.32	3.08	.897	8.23	2.98	.823
Tulsa, OK	14.6	5.08	.798	14.5	5.03	.756	14.9	5.45	1.10	14.7	5.25	.934
Dallas, TX	11.1	3.75	.709	11.1	3.72	.684	11.4	4.03	.932	11.3	3.90	.831
Ft. Worth, TX	9.27	3.13	.644	9.24	3.10	.621	9.53	3.38	.845	9.41	3.27	.753
Grand Rapids, MI	4.83	2.15	1.02	4.66	2.00	.895	5.43	2.70	1.48	4.74	2.07	.955
Amarillo, TX	6.99	2.48	.771	7.01	2.50	.785	7.18	2.67	.924	7.25	2.74	.979
Houston, TX	15.2	5.31	.646	15.1	5.25	.601	15.6	5.71	.942	15.4	5.47	.764
San Antonio, TX	10.1	3.18	.541	10.0	3.17	.533	10.2	3.37	.684	10.2	3.33	.650
Albuquerque, NM	1.83	1.35	1.05	1.92	1.42	1.11	2.02	1.49	1.17	2.36	1.77	1.41
Denver, CO	3.51	1.78	1.02	3.58	1.83	1.07	3.73	1.96	1.17	4.00	2.18	1.36
Cheyenne, WY	2.95	1.93	1.37	3.03	1.99	1.43	3.23	2.16	1.57	3.56	2.43	1.80
Boise, ID	1.75	1.28	.979	1.98	1.46	1.13	1.80	1.32	1.01	2.77	2.08	1.64
Salt Lake City, UT	2.44	1.47	.873	2.63	1.61	.972	2.57	1.56	.938	3.34	2.11	1.34
Phoenix, AZ	2.51	1.25	.495	2.70	1.36	.552	2.63	1.32	.531	3.41	1.77	.762
Reno, NV	1.91	1.22	.768	2.23	1.43	.915	1.92	1.22	.770	3.27	2.74	1.40
Las Vegas, NV	2.20	1.04	.331	2.44	1.17	.379	2.27	1.08	.345	3.27	1.59	.544
Los Angeles, CA	2.10	1.14	.575	2.33	1.30	.683	2.12	1.16	.584	3.06	1.80	1.04
San Francisco, CA	2.38	1.34	.709	2.72	1.58	.883	2.35	1.32	.694	3.81	2.37	1.46
Portland, OR	3.20	1.79	.932	3.62	2.11	1.19	3.16	1.75	.907	5.03	3.22	2.06
Seattle, WA	3.45	1.95	1.07	3.89	2.30	1.35	3.41	1.91	1.04	5.42	3.53	2.33

Table 2. 99.5 percent confidence limit attenuation predictions for .01, .1, and 1 percent of a year at 12.2 GHz on earth-geostationary satellite links for satellites located at the indicated suborbital longitudes, Λ_o.

	Λ_o = 110°W			90°W			130°W			70°W		
Location	.01%	.1%	1%	.01	1	1	.01	1	1	.01	1	1
Worcester, MA	13.3	5.64	1.79	12.6	4.99	1.28	15.9	8.02	3.66	12.4	4.84	1.17
Boston, MA	18.2	7.23	1.88	17.4	6.50	1.32	21.1	9.94	3.97	17.3	6.33	1.18
Providence, RI	11.6	5.10	1.75	10.8	4.46	1.24	14.3	7.46	3.60	10.7	4.31	1.12
Concord, NH	11.7	5.19	1.89	11.0	4.52	1.34	14.4	7.66	3.89	10.8	4.36	1.22
Portland, ME	11.5	5.13	1.87	10.7	4.43	1.30	14.4	7.81	4.01	10.5	4.26	1.17
Burlington, VT	15.5	6.06	1.85	15.0	5.47	1.34	17.3	8.18	3.69	14.9	5.36	1.24
Newark, NJ	12.5	5.16	1.56	12.0	4.64	1.14	14.5	6.97	3.00	11.9	4.54	1.07
Hartford, CT	22.6	8.62	1.86	21.9	7.88	1.29	24.8	10.7	3.43	21.8	7.78	1.21
Trenton, NJ	16.4	6.21	1.54	15.9	5.72	1.13	18.0	7.91	2.94	15.8	5.63	1.06
NY Central Park, NY	19.4	7.44	1.66	18.8	6.83	1.20	21.7	9.56	3.29	18.7	6.71	1.11
NY LaGuardia, NY	18.4	7.19	1.76	17.8	6.57	1.28	20.7	9.34	3.42	17.6	6.45	1.19
Rochester, NY	10.3	4.19	1.42	9.90	3.79	1.10	11.7	5.53	2.50	9.86	3.76	1.07
Buffalo, NY	10.9	4.36	1.40	10.5	3.99	1.10	12.2	5.60	2.40	10.5	3.98	1.08
Pittsburg, PA	10.4	4.12	1.22	10.0	3.80	.966	11.5	5.18	2.07	10.0	3.80	.966
Philadelphia, PA	10.7	4.53	1.38	10.1	4.60	1.02	12.5	6.11	2.61	10.1	3.99	.960
Wilmington, DE	14.8	5.71	1.40	14.3	5.24	1.03	16.5	7.31	2.65	14.3	5.17	.978
Washington, DC	16.1	6.08	1.41	15.7	5.63	1.06	17.6	7.55	2.57	15.6	5.59	1.02
Albany, NY	13.6	5.41	1.64	13.1	4.88	1.19	15.4	7.30	3.22	13.0	4.78	1.10
Syracuse, NY	17.5	6.57	1.62	17.1	6.08	1.21	19.0	8.23	3.02	17.0	6.01	1.16
Harrisburg, PA	21.8	7.96	1.56	21.4	7.47	1.15	23.2	9.58	2.93	21.4	7.42	1.11
Baltimore, MD	22.4	8.27	1.54	21.8	7.74	1.13	24.2	10.0	2.89	21.8	7.67	1.09
Richmond, VA	24.2	8.96	1.40	23.6	8.44	1.03	26.2	10.7	2.63	23.6	8.39	.997
Charleston, WV	20.3	7.13	1.23	20.0	6.82	.973	21.1	8.16	2.09	20.1	6.84	.994
Greensboro, NC	18.0	6.44	1.11	17.7	6.11	.853	19.1	7.53	1.97	17.7	6.11	.851
Charlotte, NC	16.1	5.83	1.07	15.8	5.52	.831	17.2	6.83	1.84	15.8	5.53	.840
Columbia, SC	27.5	10.2	1.12	26.9	9.72	.849	29.6	11.6	2.01	26.9	9.75	.862
Atlanta, GA	20.6	7.32	.971	20.3	7.06	.782	21.5	8.19	1.61	20.4	7.13	.831
Pensacola, FL	25.1	9.52	.876	24.7	9.26	.736	26.6	10.4	1.38	24.9	9.40	.811
Tampa, FL	28.5	11.1	1.03	27.5	10.5	.711	31.8	13.1	2.09	27.7	10.6	.755
Miami, FL	33.7	13.4	1.33	32.2	12.6	1.01	38.5	15.9	2.38	32.3	12.6	1.01
Birmingham, AL	22.5	8.19	.956	22.2	7.94	.790	23.6	9.09	1.55	22.3	8.07	.874
Montgomery, AL	24.8	9.34	1.04	24.2	8.97	.814	26.6	10.7	1.83	24.5	9.13	.913
Memphis, TN	19.6	6.95	.908	19.4	6.79	.793	20.3	7.60	1.37	19.6	6.95	.908
Nashville, TN	17.5	6.21	.974	17.3	6.01	.820	18.1	6.91	1.53	17.4	6.11	.897
Jackson, MS	20.9	7.34	.848	20.7	7.18	.739	21.6	7.96	1.29	20.9	7.34	.851

Table 2 (Continued)

99.5 percent confidence limit attenuation predictions for .01, .1, and 1 percent of a year at 12.2 GHz on earth-geostationary satellite links for satellites located at the indicated suborbital longitudes, Λ_o.

	Λ_o = 110°W			90°W			130°W			70°W		
Location	.01%	.1%	1%	.01	1	1	.01	1	1	.01	1	1
Louisville, KY	19.5	6.99	1.13	19.3	6.75	.944	20.3	7.83	1.79	19.4	6.84	1.02
Columbus, OH	12.0	4.44	1.14	11.7	4.19	.936	12.8	5.29	1.85	11.8	4.23	.970
Cleveland, OH	15.2	5.67	1.36	14.9	5.33	1.09	16.3	6.79	2.28	14.9	5.35	1.11
Cincinnati, OH	20.9	7.33	1.22	20.6	7.06	.995	21.6	8.24	1.98	20.7	7.13	1.05
Indianapolis, IN	17.1	6.04	1.15	16.9	5.82	.965	17.7	6.81	1.80	17.0	5.91	1.04
Detroit, MI	11.0	4.28	1.23	10.7	4.01	1.01	11.9	5.23	1.99	10.7	4.05	1.04
Des Moines, IA	21.4	7.46	1.21	21.3	7.34	1.11	21.9	8.07	1.72	21.5	7.60	1.33
Milwaukee, WI	12.0	4.48	1.23	11.8	4.29	1.07	12.7	5.20	1.84	11.9	4.41	1.18
Minneapolis, MN	13.7	5.12	1.33	13.6	5.01	1.23	14.3	5.73	1.84	13.8	5.25	1.44
Sioux Falls, SD	12.6	4.64	1.17	12.6	4.58	1.13	13.0	5.09	1.55	12.8	4.88	1.37
Fargo, ND	10.5	3.99	1.28	10.4	3.94	1.23	10.9	4.45	1.64	10.7	4.24	1.48
Billings, MT	12.5	4.77	1.41	12.6	4.92	1.54	12.7	4.98	1.59	13.3	5.63	2.13
Chicago, IL	20.8	7.34	1.34	20.6	7.11	1.15	21.5	8.19	2.06	20.7	7.25	1.27
St. Louis, MO	13.2	4.98	1.07	13.0	4.82	.952	13.9	5.62	1.56	13.2	4.99	1.08
Kansas City, MO	18.2	6.43	1.09	18.2	6.34	1.01	18.8	6.97	1.52	18.4	6.60	1.22
Wichita, KS	18.5	6.50	1.03	18.4	6.45	.991	19.0	6.98	1.40	18.8	6.79	1.26
Omaha, NE	20.3	7.02	1.10	20.3	6.95	1.04	20.8	7.52	1.51	20.5	7.25	1.29
New Orleans, LA	23.7	8.80	.794	23.3	8.58	.673	25.0	9.66	1.28	23.7	8.80	.795
Shreveport, LA	20.3	7.10	.790	20.2	7.00	.721	20.9	7.62	1.15	20.4	7.23	.880
Little Rock, AR	21.6	7.70	.889	21.5	7.57	.797	22.4	8.31	1.31	21.8	7.78	.947
Oklahoma City, OK	14.6	5.09	.841	14.6	5.05	.813	15.0	5.47	1.14	14.9	5.33	1.03
Tulsa, OK	30.9	11.4	1.12	30.7	11.3	1.04	32.1	12.3	1.67	31.4	11.8	1.37
Dallas, TX	24.1	8.43	.914	24.1	8.36	.869	24.8	8.98	1.31	24.5	8.73	1.13
Ft. Worth, TX	17.8	6.12	.797	17.8	6.07	.759	18.2	6.54	1.12	18.0	6.35	.974
Grand Rapids, MI	10.4	4.06	1.22	10.2	3.85	1.05	11.2	4.83	1.84	10.3	3.95	1.13
Amarillo, TX	12.6	4.43	.903	12.6	4.45	.924	12.8	4.71	1.13	12.9	4.81	1.21
Houston, TX	24.3	8.75	.773	24.1	8.65	.711	25.1	9.40	1.18	24.6	9.01	.937
San Antonio, TX	23.9	8.12	.734	23.9	8.09	.715	24.4	8.57	1.06	24.3	8.46	.980
Albuquerque, NM	3.98	2.16	1.08	4.09	2.25	1.15	4.22	2.34	1.22	4.69	2.70	1.49
Denver, CO	10.2	3.98	1.16	10.3	4.06	1.22	10.5	4.24	1.37	10.8	4.56	1.62
Cheyenne, WY	10.6	4.42	1.52	10.7	4.51	1.60	11.0	4.73	1.78	11.4	5.10	2.09
Boise, ID	4.37	2.20	.995	4.69	2.44	1.17	4.44	2.26	1.03	5.78	3.24	1.76
Salt Lake City, UT	7.87	3.29	.976	8.10	3.47	1.11	8.02	3.41	1.07	8.99	4.16	1.62
Phoenix, AZ	5.65	2.52	.709	5.88	2.68	.815	5.80	2.62	.777	6.75	3.27	1.21
Reno, NV	2.67	1.68	1.03	3.11	1.97	1.23	2.68	1.68	1.03	4.55	2.94	1.89
Las Vegas, NV	3.14	1.71	.829	3.44	1.90	.946	3.23	1.77	.864	4.45	2.54	1.35
Los Angeles, CA	4.54	2.02	.629	4.83	2.22	.769	4.57	2.03	.641	5.75	2.88	1.23
San Francisco, CA	6.35	2.76	.752	6.80	3.09	.989	6.31	2.72	.730	8.30	4.20	1.77
Portland, OR	11.2	4.55	1.16	11.7	5.02	1.53	11.1	4.50	1.13	13.6	6.62	2.77
Seattle, WA	8.70	3.89	1.29	9.28	4.37	1.66	8.65	3.84	1.25	11.3	6.04	2.96

Table 3. Mean attenuation predictions for .01, .1, and 1 percent of a year at 14.5 GHz on earth-geostationary satellite links for satellites located at the indicated suborbital longitudes, Λ_o.

	Λ_o = 110°W			90°W			130°W			70°W		
Location	.01%	.1%	1%	.01	1	1	.01	1	1	.01	1	1
Worcester, MA	10.4	4.75	2.06	9.55	4.04	1.50	13.3	7.32	4.11	9.38	3.88	1.37
Boston, MA	12.7	5.26	2.05	12.0	4.56	1.47	15.3	7.84	4.16	11.8	4.40	1.34
Providence, RI	9.00	4.37	2.01	8.15	3.66	1.46	12.1	6.96	4.05	7.96	3.50	1.33
Concord, NH	7.50	3.92	2.08	6.65	3.23	1.53	10.6	6.49	4.12	6.46	3.07	1.40
Portland, ME	8.36	4.20	2.09	7.46	3.45	1.50	11.8	7.06	4.34	7.24	3.27	1.35
Burlington, VT	9.17	4.00	1.92	8.61	3.45	1.45	11.2	5.98	3.59	8.49	3.34	1.36
Newark, NJ	10.6	4.54	2.46	9.93	3.97	1.35	12.7	6.50	3.37	9.81	3.86	1.27
Hartford, CT	16.8	6.30	1.94	16.3	5.67	1.40	18.4	8.08	3.43	16.2	5.57	1.33
Trenton, NJ	14.5	5.40	1.70	14.1	4.91	1.28	16.1	7.11	3.12	14.0	4.82	1.21
NY Central Park, NY	12.6	4.97	1.77	12.0	4.42	1.32	14.5	6.87	3.32	11.9	4.32	1.23
NY LaGuardia, NY	14.1	5.56	1.95	13.5	4.97	1.45	16.1	7.62	3.66	13.4	4.86	1.36
Rochester, NY	7.62	3.32	1.58	7.21	2.94	1.26	9.00	4.63	2.67	7.17	2.90	1.23
Buffalo, NY	7.30	3.28	1.58	6.90	2.91	1.27	8.67	4.53	2.61	6.88	2.89	1.25
Pittsburg, PA	7.37	3.20	1.39	7.00	2.87	1.13	8.60	4.29	2.27	7.00	2.87	1.13
Philadelphia, PA	8.39	3.85	1.58	7.78	3.34	1.19	10.5	5.57	2.90	7.68	3.26	1.13
Wilmington, DE	11.7	4.69	1.59	11.2	4.20	1.20	13.5	6.36	2.92	11.1	4.12	1.14
Washington, DC	13.8	5.12	1.56	13.3	4.69	1.21	15.2	6.56	2.74	13.3	4.64	1.17
Albany, NY	7.20	3.46	1.73	6.58	2.93	1.31	9.36	5.30	3.22	6.47	2.83	1.23
Syracuse, NY	10.6	4.14	1.64	10.3	3.72	1.28	12.0	5.58	2.87	10.2	3.67	1.23
Harrisburg, PA	18.6	6.43	1.52	18.2	6.03	1.20	19.8	7.79	2.63	18.2	5.98	1.16
Baltimore, MD	16.8	6.01	1.59	16.4	5.57	1.23	18.1	7.49	2.82	16.4	5.52	1.18
Richmond, VA	19.5	6.80	1.45	19.2	6.40	1.11	20.6	8.13	2.56	19.2	6.36	1.08
Charleston, WV	15.2	5.19	1.28	15.0	4.91	1.06	16.0	6.09	2.03	15.0	4.94	1.07
Greensboro, NC	15.5	5.29	1.19	15.2	4.99	.994	16.4	6.28	1.99	15.2	4.98	.942
Charlotte, NC	14.1	4.98	1.22	13.8	4.67	.970	15.1	5.98	2.02	13.8	4.69	.980
Columbia, SC	20.9	7.21	1.22	20.7	6.89	.940	21.7	8.25	2.12	20.7	6.91	.953
Atlanta, GA	19.2	6.49	1.12	19.0	6.25	.916	19.9	7.31	1.81	19.0	6.32	.969
Pensacola, FL	23.3	8.20	1.03	23.0	7.95	.846	24.2	9.08	1.69	23.2	8.08	.945
Tampa, FL	28.1	10.6	1.13	27.3	10.0	.805	30.8	12.4	2.20	27.4	10.1	.850
Miami, FL	30.5	11.8	1.27	29.3	11.1	.836	34.4	14.3	2.67	29.3	11.1	.840
Birmingham, AL	22.5	7.90	1.18	22.3	7.65	.974	23.4	8.79	1.91	22.4	7.78	1.08
Montgomery, AL	26.1	9.62	1.23	25.7	9.34	.976	27.8	10.9	2.10	25.9	9.41	1.09
Memphis, TN	16.0	5.50	1.05	15.8	5.35	.927	16.6	6.13	1.55	16.0	5.50	1.05
Nashville, TN	18.0	6.07	1.12	17.9	5.87	.953	18.6	6.78	1.70	18.0	5.97	1.03
Jackson, MS	16.3	5.49	.970	16.2	5.35	.856	16.9	6.06	1.43	16.4	5.50	.974

Table 3 (Continued)

Mean attenuation predictions for .01, .1, and 1 percent of a year at 14.5 GHz on earth-geostationary satellite links for satellites located at the indicated suborbital longitudes, Λ_o.

	Λ_o = 110°W			90°W			130°W			70°W		
Location	.01%	.1%	1%	.01	1	1	.01	1	1	.01	1	1
Louisville, KY	17.6	5.95	1.23	17.4	5.73	1.05	18.2	6.72	1.86	17.5	5.82	1.12
Columbus, OH	10.2	3.84	1.31	9.91	3.58	1.10	11.1	4.73	2.03	9.95	3.62	1.13
Cleveland, OH	8.68	3.49	1.43	8.38	3.20	1.18	9.69	4.48	2.25	8.40	3.22	1.20
Cincinnati, OH	16.6	5.63	1.27	16.4	5.39	1.08	17.3	6.43	1.92	16.5	5.45	1.13
Indianapolis, IN	14.6	5.02	1.25	14.4	4.81	1.08	15.3	5.75	1.86	14.5	4.90	1.15
Detroit, MI	6.42	2.95	1.36	6.09	2.67	1.15	7.53	3.88	2.10	6.15	2.72	1.18
Des Moines, IA	16.1	5.28	1.16	16.0	5.19	1.09	16.5	5.75	1.52	16.2	5.39	1.24
Milwaukee, WI	8.62	3.38	1.36	8.43	3.19	1.20	9.32	4.06	1.92	8.55	3.31	1.30
Minneapolis, MN	6.49	2.93	1.42	6.37	2.82	1.33	7.14	3.49	1.88	6.63	3.04	1.52
Sioux Falls, SD	8.31	3.27	1.30	8.25	3.22	1.26	8.77	3.70	1.65	8.55	3.50	1.49
Fargo, ND	6.82	2.93	1.47	6.76	2.88	1.43	7.34	3.38	1.84	7.10	3.18	1.67
Billings, MT	4.58	2.53	1.63	4.76	2.69	1.76	4.84	2.75	1.81	5.59	3.37	2.33
Chicago, IL	15.2	5.18	1.35	15.0	5.00	1.19	15.8	5.89	1.92	15.1	5.11	1.29
St. Louis, MO	9.50	3.66	1.19	9.33	3.51	1.07	10.2	4.27	1.68	9.51	3.67	1.20
Kansas City, MO	14.1	4.81	1.18	14.1	4.73	1.11	14.5	5.27	1.56	14.3	4.95	1.30
Wichita, KS	12.2	4.24	1.10	12.2	4.21	1.07	12.6	4.63	1.41	12.4	4.48	1.28
Omaha, NE	15.3	4.98	1.07	15.2	4.93	1.03	15.7	5.37	1.37	15.5	5.16	1.21
New Orleans, LA	24.9	8.93	1.01	24.7	8.70	.848	26.0	9.86	1.66	24.9	8.93	1.01
Shreveport, LA	15.9	5.32	.901	15.8	5.23	.830	16.3	5.78	1.27	16.0	5.43	.994
Little Rock, AR	19.3	6.50	1.03	19.2	5.38	.932	19.7	7.05	1.50	19.4	6.57	1.10
Oklahoma City, OK	12.3	4.18	.944	12.3	4.15	.918	12.7	4.53	1.22	12.5	4.40	1.12
Tulsa, OK	22.3	7.66	1.09	22.3	7.59	1.03	22.8	8.17	1.51	22.5	7.89	1.28
Dallas, TX	17.2	5.64	.969	17.2	5.60	.933	17.5	6.02	1.28	17.4	5.85	1.14
Ft. Worth, TX	14.2	4.68	.876	14.2	4.63	.844	14.6	5.03	1.15	14.4	4.87	1.03
Grand Rapids, MI	7.15	3.06	1.38	6.92	2.85	1.20	7.98	3.81	2.00	7.03	2.95	1.29
Amarillo, TX	10.6	3.64	1.05	10.6	3.67	1.07	10.9	3.90	1.26	11.0	3.99	1.33
Houston, TX	23.3	8.05	.893	23.2	7.96	.829	23.9	8.61	1.31	23.5	8.27	1.06
San Antonio, TX	15.5	4.80	.735	15.5	4.78	.724	15.8	5.05	.931	15.7	4.99	.885
Albuquerque, NM	2.57	1.86	1.43	2.69	1.96	1.51	2.83	2.06	1.60	3.31	2.45	1.91
Denver, CO	5.12	2.50	1.39	5.22	2.58	1.45	5.42	2.75	1.59	5.79	3.06	1.85
Cheyenne, WY	4.20	2.67	1.86	4.31	2.77	1.94	4.58	2.99	2.13	5.04	3.37	2.45
Boise, ID	2.45	1.75	1.32	2.76	2.00	1.52	2.51	1.81	1.36	3.68	2.85	2.21
Salt Lake City, UT	3.47	2.05	1.17	3.73	2.23	1.31	3.65	2.17	1.26	4.72	2.93	1.81
Phoenix, AZ	3.57	1.75	.656	3.84	1.90	.732	3.74	1.85	.705	4.82	2.46	1.01
Reno, NV	3.77	1.97	.875	4.19	2.25	1.06	3.77	1.98	.876	5.60	3.18	1.66
Las Vegas, NV	3.10	1.44	.423	3.44	1.61	.485	3.20	1.49	.441	4.58	2.18	.700
Los Angeles, CA	3.03	1.60	.764	3.34	1.81	.910	3.06	1.62	.776	4.36	2.51	1.39
San Francisco, CA	3.44	1.89	.945	3.91	2.22	1.18	3.40	1.86	.924	5.44	3.31	1.96
Portland, OR	4.65	2.51	1.26	5.23	2.96	1.60	4.59	2.47	1.22	7.20	4.50	2.79
Seattle, WA	5.01	2.74	1.44	5.63	3.23	1.83	4.95	2.70	1.41	7.75	4.92	3.16

Table 4. 99.5 percent confidence limit attenuation predictions for .01, .1 and 1 percent of a year at 14.5 GHz on earth-geostationary satellite links for satellites located at the indicated suborbital longitudes, Λ_o.

	Λ_o = 110°W			90°W			130°W			70°W		
Location	.01%	.1%	1%	.01	1	1	.01	1	1	.01	1	1
Worcester, MA	20.4	8.38	2.47	19.4	7.46	1.76	24.0	11.7	5.09	19.1	7.26	1.60
Boston, MA	27.9	10.8	2.60	26.8	9.79	1.81	31.9	14.7	5.54	26.5	9.55	1.63
Providence, RI	17.6	7.53	2.41	16.6	6.63	1.70	21.4	10.9	5.00	16.4	6.42	1.54
Concord, NH	17.8	7.65	2.60	16.8	6.70	1.84	21.5	11.1	5.40	16.5	6.49	1.67
Portland, ME	17.5	7.55	2.57	16.4	6.57	1.79	21.6	11.3	5.56	16.1	6.33	1.60
Burlington, VT	23.4	8.95	2.56	22.7	8.12	1.84	25.8	11.9	5.14	22.6	7.96	1.70
Newark, NJ	19.2	7.67	2.15	18.4	6.94	1.57	21.9	10.2	4.16	18.3	6.81	1.47
Hartford, CT	34.3	12.9	2.58	33.2	11.8	1.78	37.4	15.8	4.80	33.1	11.7	1.67
Trenton, NJ	25.0	9.29	2.13	24.4	8.59	1.55	27.2	11.7	4.10	24.2	8.47	1.46
NY Central Park, NY	30.0	11.2	2.31	29.1	10.4	1.65	33.1	14.3	4.60	28.9	10.2	1.53
NY LaGuardia, NY	28.3	10.8	2.43	27.4	9.92	1.76	31.5	13.9	4.77	27.2	9.76	1.63
Rochester, NY	15.7	6.16	1.95	15.1	5.61	1.50	17.5	8.02	3.46	15.1	5.56	1.46
Buffalo, NY	16.6	6.44	1.93	16.1	5.93	1.51	18.3	8.16	3.33	16.1	5.90	1.49
Pittsburg, PA	15.8	6.10	1.68	15.4	5.66	1.32	17.4	7.58	2.87	15.4	5.66	1.32
Philadelphia, PA	16.3	6.71	1.90	15.5	6.05	1.39	18.8	8.95	3.62	15.4	5.95	1.31
Wilmington, DE	22.4	8.48	1.94	21.7	7.81	1.42	24.8	10.8	3.70	21.6	7.71	1.34
Washington, DC	24.5	9.09	1.95	23.9	8.46	1.45	26.6	11.2	3.59	23.8	8.40	1.40
Albany, NY	20.7	8.02	2.26	20.0	7.27	1.63	23.1	10.7	4.48	19.9	7.13	1.51
Syracuse, NY	26.8	9.84	2.24	26.3	9.16	1.67	28.8	12.2	4.20	26.2	9.07	1.59
Harrisburg, PA	33.1	11.9	2.18	32.6	11.2	1.59	35.0	14.2	4.12	32.5	11.1	1.53
Baltimore, MD	34.0	12.4	2.14	33.2	11.6	1.57	36.6	15.0	4.07	33.1	11.5	1.50
Richmond, VA	37.1	13.6	1.96	36.2	12.8	1.43	39.9	16.0	3.71	36.1	12.7	1.38
Charleston, WV	30.9	10.7	1.71	30.5	10.2	1.34	32.0	12.1	2.93	30.5	10.3	1.37
Greensboro, NC	27.9	9.77	1.55	27.4	9.30	1.18	29.3	11.3	2.76	27.4	9.30	1.17
Charlotte, NC	24.7	8.78	1.48	24.3	8.34	1.14	26.2	10.2	2.58	24.3	8.36	1.16
Columbia, SC	42.3	15.5	1.57	41.4	14.9	1.18	45.4	17.7	2.84	41.4	14.9	1.20
Atlanta, GA	31.4	11.0	1.35	31.0	10.7	1.08	32.7	12.3	2.26	31.1	10.8	1.15
Pensacola, FL	38.8	14.6	1.21	38.2	14.2	1.01	41.0	15.9	1.91	38.5	14.4	1.12
Tampa, FL	44.1	17.1	1.49	42.6	16.2	1.01	49.1	20.2	3.08	42.8	16.3	1.08
Miami, FL	51.6	20.4	1.90	49.3	19.2	1.42	58.9	24.2	3.45	49.3	19.2	1.43
Birmingham, AL	34.5	12.4	1.33	34.0	12.1	1.09	36.2	13.8	2.18	34.3	12.3	1.21
Montgomery, AL	38.1	14.3	1.48	37.3	13.7	1.15	40.9	16.2	2.64	37.6	14.0	1.29
Memphis, TN	30.2	10.6	1.25	29.9	10.3	1.09	31.3	11.5	1.91	30.2	10.6	1.25
Nashville, TN	27.0	9.43	1.35	26.7	9.15	1.13	27.9	10.4	2.13	26.8	9.29	1.24
Jackson, MS	31.9	11.1	1.17	31.6	10.8	1.02	32.9	12.0	1.80	31.9	11.1	1.18

Table 4 (Continued)

99.5 percent confidence limit attenuation predictions for .01, .1 and 1 percent of a year at 14.5 GHz on earth-geostationary satellite links for satellites located at the indicated suborbital longitudes, Λ_o.

	Λ_o = 110°W			90°W			130°W			70°W		
Location	.01%	.1%	1%	.01	1	1	.01	1	1	.01	1	1
Louisville, KY	30.0	10.6	1.56	29.7	10.2	1.30	31.2	11.8	2.49	29.8	10.4	1.40
Columbus, OH	18.4	6.63	1.58	18.1	6.28	1.28	19.4	7.81	2.57	18.1	6.34	1.33
Cleveland, OH	23.0	8.43	1.88	22.6	7.95	1.50	24.5	10.0	3.17	22.6	7.99	1.53
Cincinnati, OH	31.6	11.0	1.69	31.3	10.6	1.37	32.7	12.3	2.77	31.4	10.7	1.46
Indianapolis, IN	26.3	9.11	1.59	26.1	8.81	1.33	27.2	10.2	2.51	26.2	8.94	1.44
Detroit, MI	16.8	6.36	1.70	16.4	5.97	1.39	18.0	7.67	2.77	16.4	6.03	1.44
Des Moines, IA	32.4	11.2	1.67	32.3	11.0	1.53	33.1	12.0	2.39	32.6	11.4	1.83
Milwaukee, WI	18.4	6.67	1.69	18.2	6.40	1.47	19.3	7.67	2.53	18.3	6.57	1.61
Minneapolis, MN	20.6	7.57	1.82	20.5	7.40	1.68	21.4	8.42	2.54	20.8	7.74	1.97
Sioux Falls, SD	19.4	6.93	1.61	19.4	6.86	1.55	20.0	7.55	2.14	19.7	7.26	1.89
Fargo, ND	15.9	5.88	1.74	15.9	5.81	1.68	16.6	6.50	2.24	16.3	6.22	2.01
Billings, MT	19.1	7.08	1.93	19.3	7.29	2.12	19.4	7.38	2.19	20.2	8.27	2.94
Chicago, IL	31.4	11.0	1.86	31.2	10.6	1.59	32.4	12.2	2.88	31.3	10.8	1.76
St. Louis, MO	20.4	7.49	1.48	20.2	7.27	1.31	21.4	8.39	2.16	20.4	7.50	1.48
Kansas City, MO	28.2	9.76	1.51	28.1	9.63	1.40	28.9	10.5	2.12	28.5	10.0	1.70
Wichita, KS	28.6	9.89	1.43	28.6	9.82	1.37	29.3	10.6	1.96	29.0	10.3	1.75
Omaha, NE	30.9	10.5	1.51	30.8	10.4	1.44	31.5	11.2	2.10	31.2	10.8	1.78
New Orleans, LA	36.5	13.5	1.11	36.0	13.1	.935	38.4	14.7	1.81	36.5	13.5	1.11
Shreveport, LA	31.0	10.7	1.09	30.9	10.6	.996	31.9	11.5	1.61	31.3	10.9	1.22
Little Rock, AR	33.1	11.6	1.23	32.9	11.5	1.10	34.2	12.5	1.83	33.2	11.8	1.31
Oklahoma City, OK	22.3	7.63	1.16	22.2	7.58	1.12	22.8	8.18	1.59	22.6	7.98	1.43
Tulsa, OK	47.4	17.5	1.59	47.2	17.4	1.48	49.3	18.9	2.40	48.3	18.2	1.96
Dallas, TX	36.9	12.8	1.28	36.7	12.7	1.21	37.8	13.6	1.86	37.4	13.2	1.59
Ft. Worth, TX	27.6	9.33	1.11	27.5	9.26	1.05	28.2	9.94	1.58	27.9	9.66	1.36
Grand Rapids, MI	15.8	6.01	1.68	15.5	5.72	1.44	16.9	7.08	2.54	15.7	5.86	1.55
Amarillo, TX	19.5	6.67	1.24	19.5	6.71	1.27	19.8	7.07	1.56	20.0	7.21	1.68
Houston, TX	37.3	13.4	1.09	37.1	13.2	.997	38.6	14.3	1.69	37.8	13.8	1.33
San Antonio, TX	36.5	12.3	1.02	36.5	12.3	.992	37.2	13.0	1.48	37.1	12.8	1.37
Albuquerque, NM	5.81	3.07	1.46	5.98	3.20	1.55	6.16	3.33	1.65	6.81	3.82	2.03
Denver, CO	15.6	5.90	1.59	15.7	6.01	1.68	16.0	6.26	1.88	16.5	6.70	2.24
Cheyenne, WY	16.2	6.51	2.09	16.3	6.63	2.20	16.6	6.94	2.45	17.1	7.45	2.88
Boise, ID	6.41	3.14	1.35	6.85	3.47	1.59	6.50	3.21	1.40	8.37	4.58	2.40
Salt Lake City, UT	11.9	4.82	1.34	12.2	5.08	1.52	12.1	4.99	1.46	13.4	6.04	2.23
Phoenix, AZ	8.38	3.64	.966	8.71	3.86	1.11	8.59	3.78	1.06	9.92	4.69	1.65
Reno, NV	5.47	2.80	1.17	6.06	3.19	1.42	5.47	2.80	1.18	8.02	4.47	2.25
Las Vegas, NV	4.50	2.40	1.12	4.91	2.66	1.28	4.62	2.48	1.16	6.33	3.55	1.82
Los Angeles, CA	6.77	2.92	.852	7.17	3.20	1.04	6.80	2.95	.868	8.47	4.12	1.68
San Francisco, CA	9.55	4.04	1.02	10.2	4.51	1.35	9.49	4.00	.993	12.3	6.06	2.45
Portland, OR	17.1	6.78	1.60	17.9	7.45	2.11	17.1	6.72	1.55	20.5	9.71	3.84
Seattle, WA	13.1	5.71	1.77	13.9	6.39	2.30	13.1	5.65	1.73	16.7	8.72	4.12

between the modified and original RH models is observed. Thus, Tables 1 through 4 should be interpreted as representing state-of-the-art earth-satellite attenuation values, at least insofar as modeling at the Institute for Telecommunication Sciences (ITS) is concerned.

4. CONCLUSION

In Dutton (1977a), it became evident, even in a small zone (subzone) of generally similar rainfall characteristics, that station-to-station meteorological data within that zone could still result in some substantial prediction differences for identical θ_o and $P(R_o)$. This conclusion is reinforced, particularly based on the results seen in Figures 5 and 6. As described in Section 2, here are two stations (Newark, NJ, and New York City, Central Park, NY) about 10 mi. apart and surrounded by essentially the same urban environment that result in completely different prediction-data comparisons using their respective meteorological data as prediction input. There may, of course, be a rational explanation (e.g., micro-climatological effects), but the fact remains that large predicted or observed differences in earth-space attenuation distributions are possible over relatively short distances. These differences are not resolvable with the current data base. Further these differences could well be important to a prospective user wishing to place an earth-station several miles from the exact location of the nearest first-order weather station from which data have been gleaned.

5. ACKNOWLEDGEMENTS

The author is particularly indebted to Dr. John Labrecque of the National Bureau of Standards Statistical Engineering Laboratory for his help in analyzing the rain rate variability problem. Other helpful advice and contributions to the report have come from Dr. P. M. McManamon, Dr. E. L. Crow, Dr. H. T. Dougherty of NTIA/ITS, Mr. E. C. Keppelmann of Potomac Research, Incorporated, and Messrs. C. B. Brooks and D. C. Howard of the University of Colorado.

6. REFERENCES

Bergmann, H. J. (1977), Satellite site diversity: results of a radiometer experiment at 13 and 18 GHz, IEEE Trans. Ant. Prop. AP-25, No. 4, July, pp. 483-489.

Bostian, C. W., S. B. Holt, Jr., S. R. Kauffman, E. A. Manus, R. E. Marshall, W. L. Stutzman, and P. H. Wiley (1977), A depolarization and attenuation experiment using the CTS satellite, Quarterly Technical Progress Report I (Second Year), Elec. Eng. Dept., Virginia Polytech. Inst. and State U., under Contract NAS5-22577, Blacksburg, VA 24061.

Bostian, C. W., W. L. Stutzman, E. A. Manus, P. H. Wiley, R. E. Marshall, S. R. Kauffman, W. P. Overstreet, and R. R. Persinger (1978), Current results of 11, 19, and 28 GHz satellite path attenuation measurements, presented at the National Radio Science Meeting, U. of Colorado, 9-13 Jan. 1978, Boulder, CO.

Dutton, E. J. (1977a), Earth-space attenuation prediction procedures at 4 to 16 GHz, Office of Telecomm. Report OTR 77-123, May (Access No. PB269228/AS, NTIS, Springfield, VA).

Dutton, E. J. (1977b), Precipitation variability in the U.S.A. for microwave terrestrial system design, OT Report OTR 77-134, November (Access No. A049041, NTIS, Springfield, VA).

Ippolito, L. J. (1978), Rain attenuation and communications link characterization measurements with HERMES (the Communications Technology Satellite), presented at a Symposium on HERMES (The Communications Technology Satellite), held by The Royal Society of Canada, 29-30 November 1977, Ottawa, Canada.

Rice, P. L., and N. R. Holmberg (1973), Cumulative time statistics of surface point-rainfall rates, IEEE Trans. Commun. COM-21, No. 10, October, pp. 1131-1136.

Rustako, A. J., Jr. (1978), An earth-space propagation measurement at Crawford Hill using the 12-GHz CTS satellite beacon, BSTJ 57, No. 5, May-June, pp. 1431-1448.

Ryde, J. W. (1946), The attenuation and radar echoes produced at centimetre wavelengths by various meteorological phenomena, in Meteorological Factors in Radio Wave Propagation (The Physical Society, London, U.K.), pp. 169-188.

Vogel, W. J., and A. W. Straiton (1977), CTS attenuation and cross-polarization measurements at 11.7 GHz, U. of Texas, Elec. Eng. Report under NASA Contract NAS5-22576, Austin, TX 78758, April.

APPENDIX A

IMPROVEMENTS IN RAIN RATE AND EARTH-SPACE ATTENUATION MODELLING

For all practical purposes, the parameters other than $\bar{R}_o$ in the expression (1) for $P(\bar{R}_o)$ can be simply expressed in terms* of M, D, and β. This is in contrast to the original R-H model expressions, particularly for $\bar{R}_{11}$ and T_{21}, as given in Appendix C of Dutton et al. (1974). The parameter $\bar{R}_{11}$ is very nearly a constant, with a U.S.A.-wide mean of

$$\langle \bar{R}_{11} \rangle = 33.6642 \quad , \tag{A1}$$

and the U.S.A.-wide standard deviation of

$$S_1 = 0.8017 \quad , \tag{A2}$$

based on the 305-station sample used in Dutton (1977b). The remaining parameters can be expressed as

$$T_{11} = \beta M/\bar{R}_{11} \quad , \tag{A3}$$

$$\bar{R}_{21} \cong 3.96D \quad , \tag{A4}$$

and

$$T_{21} = (1 - \beta)M/\bar{R}_{21} \quad . \tag{A5}$$

In Dutton (1977a), S_R^2 was obtained from the so called "modified" R-H model. This modeling allowed us to express S_R^2 algorithmically as

$$S_R^2 = F(M, \beta, D, S_M^2, S_\beta^2, S_D^2) \tag{A6}$$

where F denotes the function given in detail in Dutton (1977a), S_M^2, S_β^2 and S_D^2 are the variances of M, β and D at a particular location, respectively. The result (A6) was achieved by using the first term of a Taylor series expansion, and therefore requires that a criterion on the order of

$$3S_M < M \quad , \tag{A7}$$

and

$$3S_D < D \tag{A8}$$

---

*See section 1 for definitions of M, D, U, and β.

be imposed so that the higher order moments of M and D, and crossterms involving S_M^2 and S_D^2 will not influence (A6). A similar criterion applies to S_β^2, but since it can be expressed as a function of M, U, M_m, S_M^2, and S_U^2, by using (2) and the first term of a Taylor series, the result (A7) and the restriction

$$3S_U < U \tag{A9}$$

must also be imposed. In the above, S_U^2 is the variance of U. A further requirement for use of (A6) is that M, β, D, and U have low correlation between pairs. This is essentially no problem, except that, since β is partially a function of M, it would not be unreasonable to expect some correlation. Further, in Dutton (1977b), within the therein defined zones, M/β was a constant -- implying perfect within-zone correlation. The M/β characteristic was none too successful in defining these zones, however (Dutton, 1977b). Further, the contour maps in Dutton (1977b) give no indication of much correlation between M and β. Since the zonal concept is not used in this report, there is now no seeming contradiction in assuming M and β are not highly correlated.

In Dutton (1977, 1977b), the variances S_M^2, S_D^2, and S_U^2 were represented on a zone-wide basis by pooling all of the M', D' and U' data within a zone, where M' D' and U' represent annual values for a given year at a given location rather than average annual values as represented by M, D, and U, respectively, at a given location. The variances, S_M^2, S_D^2, and S_U^2, then, were those for the pooled data sample, and were assumed applicalbe at each location within that zone. As mentioned earlier, the conditions (A7) to (A9) should be met as frequently as possible to insure reasonable validity of the results obtained from (A6). Unfortunately, results obtained from the pooled-data variance approach for S_M^2, S_D^2, and S_U^2 gave values that for many zones -- particularly in the west and Alaska -- resulted in consistent violation of (A7) to (A9).

There is no a priori justification for the use of the pooled-data variances to represent the variances at a particular location in the zone. These zone-wide variances are heavily influenced by extreme values of M', D', and U'. If, for example, all the extreme values occur at one particular location in the zone, then the resultant variance would not be expected to be very representative of the other locations in that zone.

It was thought that some other more representative statistical descriptor of all variances within a zone could be found to replace the pooled-data variance. Indeed, another descriptor, called the "fixed effects model" variance (Brownlee, 1965) was examined in detail, but was found to be little better than the pooled-data variance, when applied on a per-station basis for stations within a zone.

Therefore, we are left with little choice but to use the station variances of M', D', and U', directly. It would have been expedient to use a single, zone-wide descriptor to represent variance for stations within a zone, but this descriptor must first and foremost have some meaning. Consequently, with reluctance, the author has tentatively abandoned the zone-wide approach to rainfall description, postulated in Dutton (1977b).

There are basically no major refinements to the SHF earth-space attenuation prediction technique, the Dutton-Dougherty (DD) model (Dutton, 1977a). However, as noted in that report, the use of the normal distribution to describe variability of R_o (in terms of $\overline{R}_o$ and S_R^2) is not completely compatible with the characteristic that R_o must be non-negative. The rain rate, R_o, is used to predict the rain attenuation, $\tau_f(\theta_o)$, on an earth-satellite link at frequency, f, and earth-station antenna elevation angle, θ_o. Further, $\tau_f(\theta_o)$ must also be non-negative. Therefore, the same problem with the normal distribution, as applied to R_o, also applies to $\tau_f(\theta_o)$. To maintain reasonable compatibility with the Dutton (1977a) procedure, the truncated normal distribution was used to assess the variability of the annual distribution of $\tau_f(\theta_o)$. The truncated-normal distribution was chosen because it a) is indistinguishable from the normal distribution for many situations in the U.S.A., especially when considering the upper confidence limit (i.e. 99.5%) of the distribution of $\tau_f(\theta_o)$, and b) it has a non-zero probability of $\tau_f(\theta_o) = 0$, a clearly feasible result that some other distributions (such as the gamma or Rayleigh) do not have.

Another new feature for the purposes of earth-space geostationary satellite attenuation modeling is the ability to produce a curve of attenuation versus satellite suborbital longitude, Λ_o, that is expected for a particular percent of a year. This methodology is applicable for $\theta_o > 5°$. This is because above $\theta_o = 5°$, ray bending due to atmospheric refraction (Bean and Dutton, 1968) is essentially negligible, and rays can be treated as straight lines over the earth's surface. This, in turn, means the value of θ_o can be determined from elementary spherical and plane trigonometry; thus, a straightforward relationship between θ_o, Λ_o, and the latitude, Φ, and longitude, Λ, of the earth station can be determined. Then, because at a specific frequency, $\tau_f(\theta_o)$ is an algorithmic function of Λ_o, it can be represented as a function of Λ_o graphically for any given earth-station location.

Consider the octant of a spherical earth shown in Figure A-1. Assume that on this model earth, an earth-station terminal of an earth-geostationary satellite link $\overline{ES}$ is located at point E. The point S represents the satellite terminal so that the path length is $\overline{ES}$, which we shall call R; i.e.

$$R = \overline{ES} \quad . \tag{A10}$$

Further, let C be the earth's center; Λ_o be the suborbital longitude of the satellite, measured at point B on the equator; Λ be the longitude of E, measured at point A on the equator; and Φ be the latitude of E, measured on the meridian intercepting the equator at A. If we are dealing with ray trajectories of earth-satellite paths in the conterminous U.S.A., then the ray path is essentially equal to the slant path R, and the elevation angle of the earth station antenna is equal to θ_o, the angle between the tangent plane to the earth at E and R. This is also shown in Figure A-2, which indicates the geometry in the plane ECS. In addition, let

$$r = \overline{CB} = \overline{CE}, \text{ the earth's radius,} \tag{A11}$$

$$x = \text{the great circle arc BE,} \tag{A12}$$

$$z = \overline{BS}. \tag{A13}$$

Since

$$\text{Angle BAE} = 90°, \tag{A14}$$

$$\text{Angle BCA} = \Lambda_o - \Lambda, \tag{A15}$$

$$\text{Arc BA} = r(\Lambda_o - \Lambda), \tag{A16}$$

$$\text{Angle ACE} = \Phi, \tag{A17}$$

$$\text{and Arc AE} = r\Phi, \tag{A18}$$

we can use the spherical trigonometric relation

$$\cos \frac{x}{r} = \cos \Phi \cos(\Lambda_o - \Lambda) \tag{A19}$$

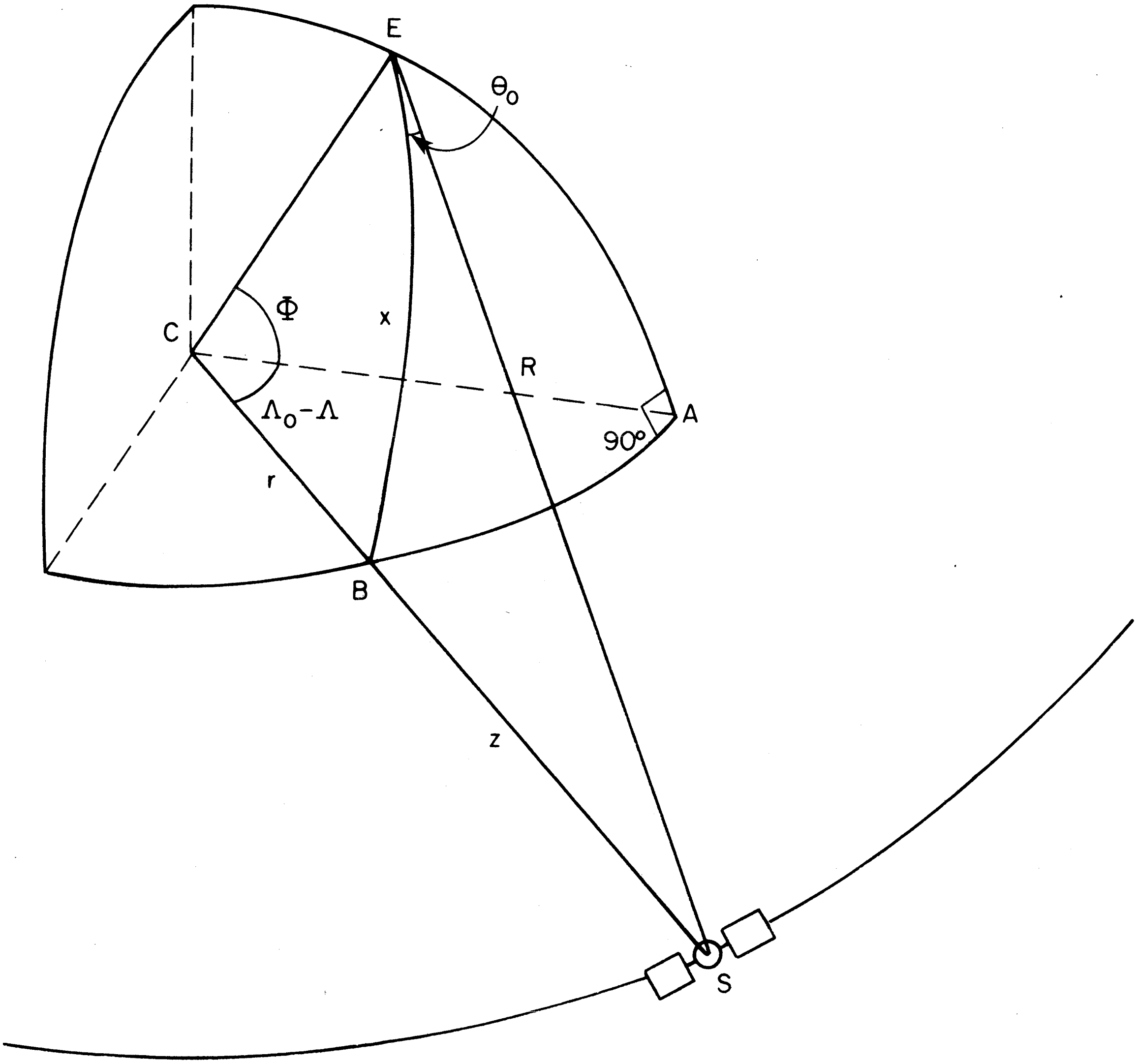

Figure A-1. Earth-satellite geometry over a spherical earth.

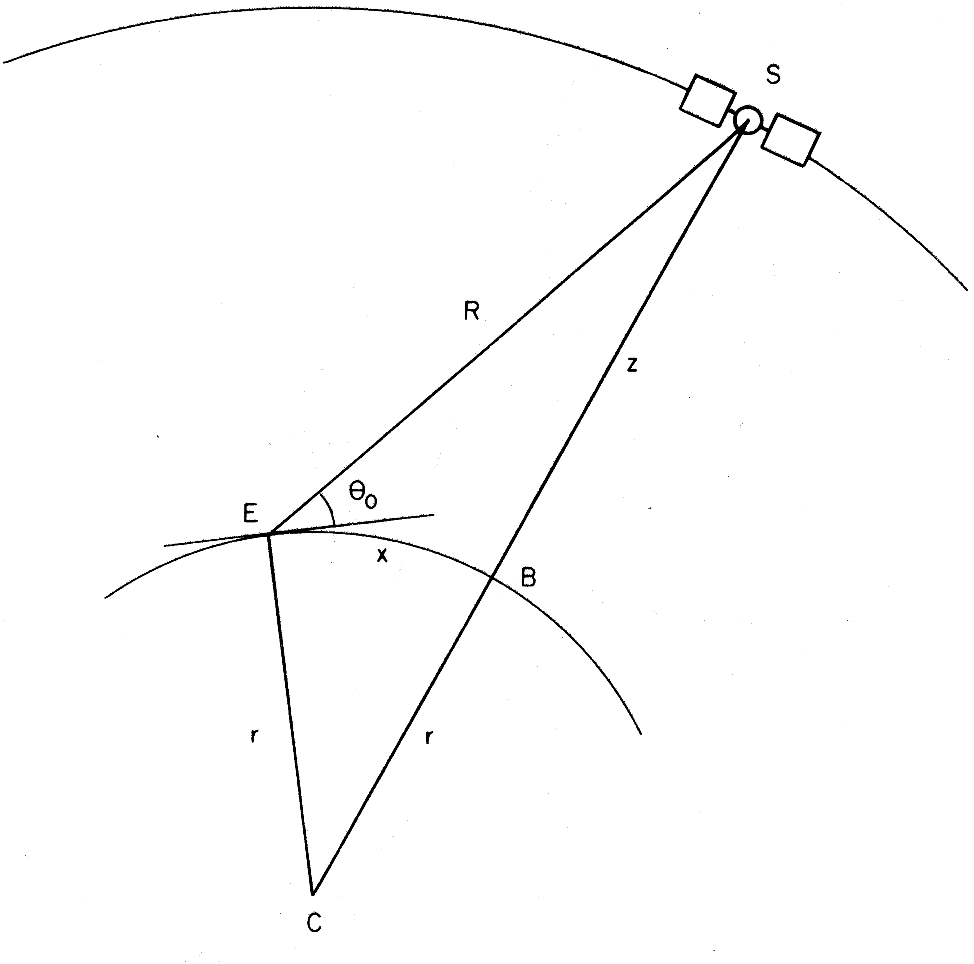

Figure A-2. Geometry in the plane of the earth-satellite link and the earth's center.

in the spherical triangle ABE to determine the angle ECB (=x/r) in Figure A-2. Then, in Figure A-2, we can use the law of cosines,

$$R^2 = r^2 + (r + z)^2 - 2r(r + z)\cos\left(\frac{x}{r}\right) \tag{A20}$$

to determine the slant path, R. Whence, using the law of sines in Figure A-2, we can determine the elevation angle, θ_o, as

$$\theta_o = \mathrm{Cos}^{-1}\left[(r + z)\ \frac{\sin\left(\frac{x}{r}\right)}{R}\right] . \tag{A21}$$

For geostationary satellites,

$$z \approx 5.619r, \tag{A22}$$

thus θ_o is readily determined for elevation angles, $\theta \geq 5°$.

For a given percentage of a year, P, the predicted attenuation results discussed in the main text are given by

$$\tau_f(\theta_o,P) = \tau_f(90°,P) + \frac{[\tau_f(5°,P) - \tau_f(90°,P)]\ (1 - \sin\theta_o)\ \sin 5°}{(1 - \sin 5°)\ \sin\theta_o}\ ; \tag{A23}$$

i.e., by a "cosecant law" (Dutton and Dougherty, 1973) applicable in the range

$$5° \leq \theta_o \leq 90° \quad . \tag{A24}$$

In (A23), τ is attenuation along the satellite-earth path at elevation angle θ_o, and f is frequency in GHz.

Thus we see that $\tau_f(\theta_o,P)$ can be determined from Λ_o, Λ, and Φ, or can be determined from Λ_o alone for any particular earth-station location with known co-ordinates Λ and Φ.

REFERENCES for Appendix A

Bean, B. R., and E. J. Dutton (1968), Radio Meteorology (Dover Publications Inc., New York, NY), p. 337.

Brownlee, K. A. (1965), Statistical Theory and Methodology in Science and Engineering, 2nd Ed. (John Wiley and Sons, Inc., New York, NY), pp. 310-330.

Dutton, E. J. (1977a), Earth-space attenuation prediction procedures at 4 to 16 GHz, Office of Telecomm. Report OTR 77-123, May (Access No. PB269228/AS, NTIS, Springfield, VA).

Dutton, E. J. (1977b), Precipitation variability in the U.S.A. for microwave terrestrial system design, OT Report OTR 77-134, November (Access No. A049041, NTIS, Springfield, VA).

Dutton, E. J., and H. T. Dougherty (1973), Modeling the effects of clouds and rain upon satellite-to-ground system performance, Office of Telecomm. Report OTR 73-5, March (Access No. COM 75-10950/AS, NTIS, Springfield, VA).

Dutton, E. J., H. T. Dougherty, and R. F. Martin, Jr. (1974), Prediction of European rainfall and link performance coefficients at 8 to 30 GHz, U.S.Army Communications Command Rept. No. ACC-ACO-16-74 (Access No. A000804, NTIS, Springfield, VA).

APPENDIX B

COMPARISON OF LESS THAN A YEAR'S ATTENUATION DATA WITH PREDICTIONS

Let $t_y(\tau)$ be the time during a year, y, that the attenuation τ will be observed, and let $t_x(\tau)$ be the time during a time interval, x, <u>less than</u> a year in duration, that the attenuation τ will be observed. Then clearly

$$t_y(\tau) = t_x(\tau) + t_{y-x}(\tau) \quad , \tag{B1}$$

where $t_{y-x}(\tau)$ is the time that the attenuation τ will be observed in the time interval y-x. Let the frequencies of occurrence of τ during y, x, and y-x be $p_y(\tau)$, $p_x(\tau)$, and $p_{y-x}(\tau)$, respectively. Clearly, then

$$p_y(\tau) = t_y(\tau)/y \quad , \tag{B2}$$

$$p_x(\tau) = t_x(\tau)/x \quad , \tag{B3}$$

and

$$p_{y-x}(\tau) = t_{y-x}(\tau)/(y-x) \quad , \tag{B4}$$

or, substituting in (B1),

$$yp_y(\tau) = xp_x(\tau) + (y-x)p_{y-x}(\tau) \quad . \tag{B5}$$

Upon integrating (B5) from τ to ∞, we obtain a relationship between the probabilities $P_y(A > \tau)$, $P_x(A > \tau)$, and $P_{y-x}(A > \tau)$ that a (random) attenuation, A, exceeds τ during the intervals y, x, and y-x, respectively; viz

$$P_y(A > \tau) = \frac{x}{y} P_x(A > \tau) + (1 - \frac{x}{y}) P_{y-x}(A > \tau) \quad . \tag{B6}$$

There are two possibilities in (B6) that are worthwhile considering. First, consider the situation when there is no attenuation τ observed in the interval y-x; i.e.,

$$t_{y-x}(\tau) = 0 \tag{B7}$$

for any value of τ. Then (B6) becomes

$$P_y(A > \tau) = \frac{x}{y} P_x(A > \tau) \quad . \tag{B8}$$

Second, consider the situation when the frequency of occurrence of τ in the interval y-x is identical with that in the interval x; i.e.,

$$p_x(\tau) = p_{y-x}(\tau) \; . \tag{B9}$$

This clearly leads to

$$P_y(A > \tau) = P_x(A > \tau) \; . \tag{B10}$$

When the data for what occurs in the interval y-x is unknown, as it is with much of the rain attenuation data alluded to in section 2 of this report, we can use the two hypothesized year-long data intevals, (B8) and (B10), to make comparisons with predictions. Note that while (B8) is certainly one extreme condition, (B10) is not the other. However, the other extreme is difficult to postulate. For example, no rain attenuation is one extreme that is realizable; i.e., dry and wet season climates. On the other hand, "infinite" rain attenuation in the interval y-x is simply unrealizable anywhere, and to postulate some other form than the straightforward linear extrapolation (B9) will involve additional and perhaps unwarranted assumptions, based strictly on conjecture. Furthermore, when (B10) is used to plot data as in Figures B-1 and B-3, it represents the actual distribution of the data during its observed interval x, as well as that hypothesized for an annual distribution. As a matter of fact, (B10) may well represent an extreme situation in Figures B-1 and B-3, because the data here is summertime data, and the frequency of occurrence of high rain attenuation during the off-summer period rarely exceeds the frequency of occurrence during the summer in practically all parts of the northern hemisphere.

As mentioned at the start of Section 2 and above, there are data of about a summer's length available from Blacksburg, VA (Bostian et al., 1978) and Austin, TX (Vogel and Straiton, 1977). Figure B-1 shows the comparison of the DD model annual distribution of earth-satellite attenuation with data for the (nominal) months of July, August, and September, 1977, at Blacksburg, VA, adjusted by (B8) ("Adjusted data" on graph) and by (B10) ("Attenuation data" on graph). The comparison is made at an earth-station elevation angle of θ_o = 33 degrees, the angle of data observation, and at the CTS frequency of

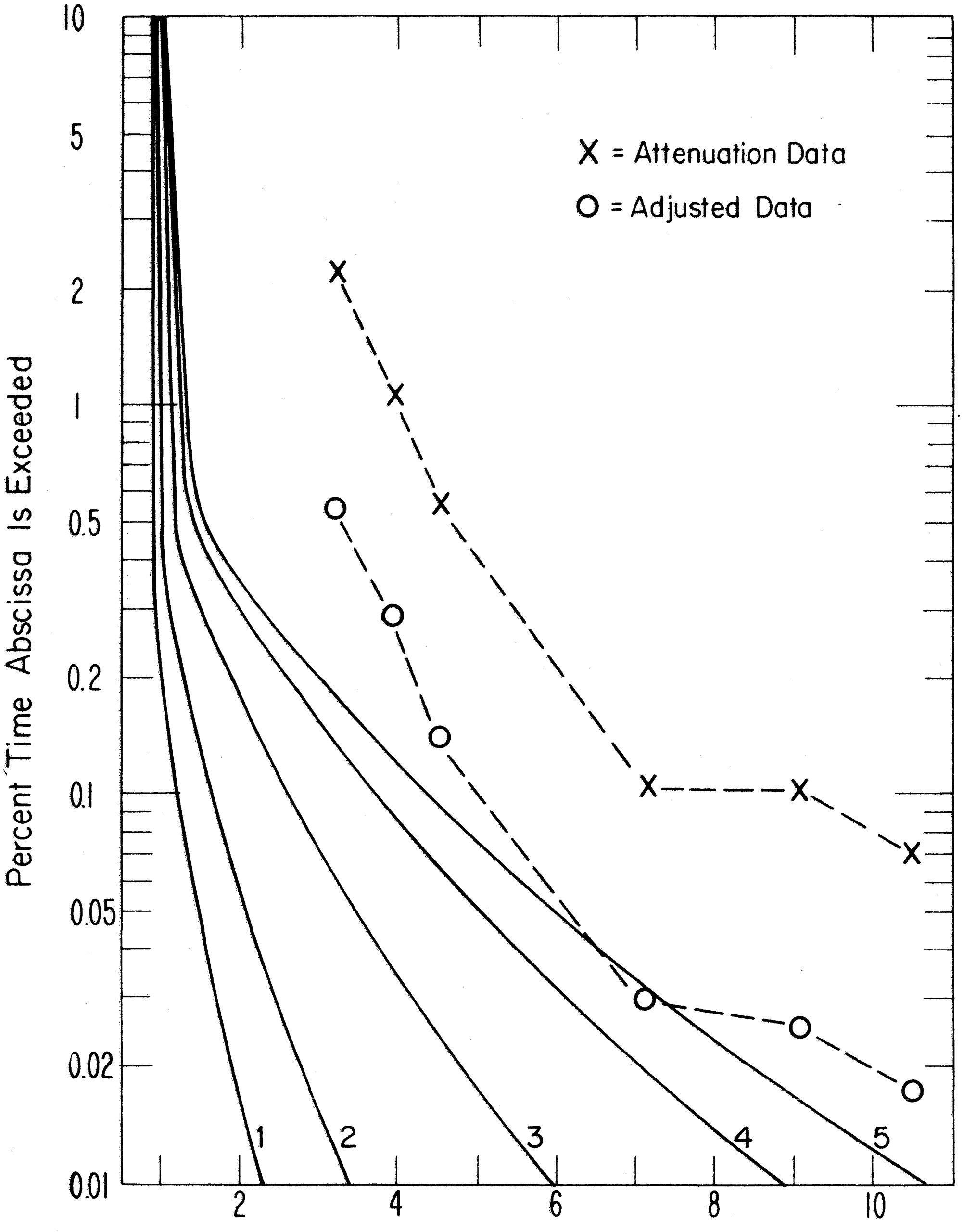

Figure B-1. Comparison of CTS data from Blacksburg, VA, and predictions for Roanoke, VA, for 11.7 GHz at an elevation angle of 33 degrees. Data period is July through September 1977. See Figure 2 for definition of curves 1 to 5.

11.7 GHz. In this case, the data are compared with predictions for Roanoke, VA, a location approximately 25 mi from Blacksburg, VA. Furthermore, in (B8) we have used x = 92 days and y = 365.25 days. The data were obtained from an experimental setup at the Virginia Polytechnic Institute and State University (VPI) at Blacksburg, VA.

It is readily apparent from figure B-1 that neither of the hypothesized data distributions compares very well with predictions. This is true of even the assumption (B8), which leads one to believe that even if a year's data were available, they would also not compare well with the Roanoke predictions. There is, however, a special extenuating circumstance with regard to these data that once again shows the profound influence of microclimatology. According to Bostian et al. (1978), the VPI path is located in a relatively mountainous region in the Allegheny Mountain chain. The CTS path looks almost directly down a valley along Stroubles Creek, which apparently is a location known for strong summertime convective activity. This fact would tend to bias any data results observed along the CTS path toward the high side (by the authors' own admission). By the same token, the experiment, which also observes 19 and 28 GHz results from the COMSTAR satellite, looks along the COMSTAR path over Price Mountain through a much drier microclimatological regime. Out of curiosity, this author made predictions at 19 GHz for the COMSTAR path (elevation angle = 44 degrees), and compared with the VPI 19 GHz COMSTAR data for the July-August-September 1977 period. These data were adjusted by (B8) ("Adjusted data" on graph) and (B10) ("Attenuation data" on graph), and the results are shown in Figure B-2.

The comparison of data and predictions in Figure B-2 are definitely closer than in Figure B-1, but the comparison of data adjusted by (B10) is still inadequate. This, however, only serves to reinforce the observation that less than a year's worth of data should be compared with annual predictions with considerable caution, especially in a mountainous area such as that between the prediction location, Roanoke, VA, and the data location, Blacksburg, VA.

Figure B-3 shows the comparison of CTS data adjusted by (B10) from the University of Texas at Austin, TX (Vogel and Straiton, 1977), with annual predictions for Austin, TX. Thus, at least here, data and prediction locations

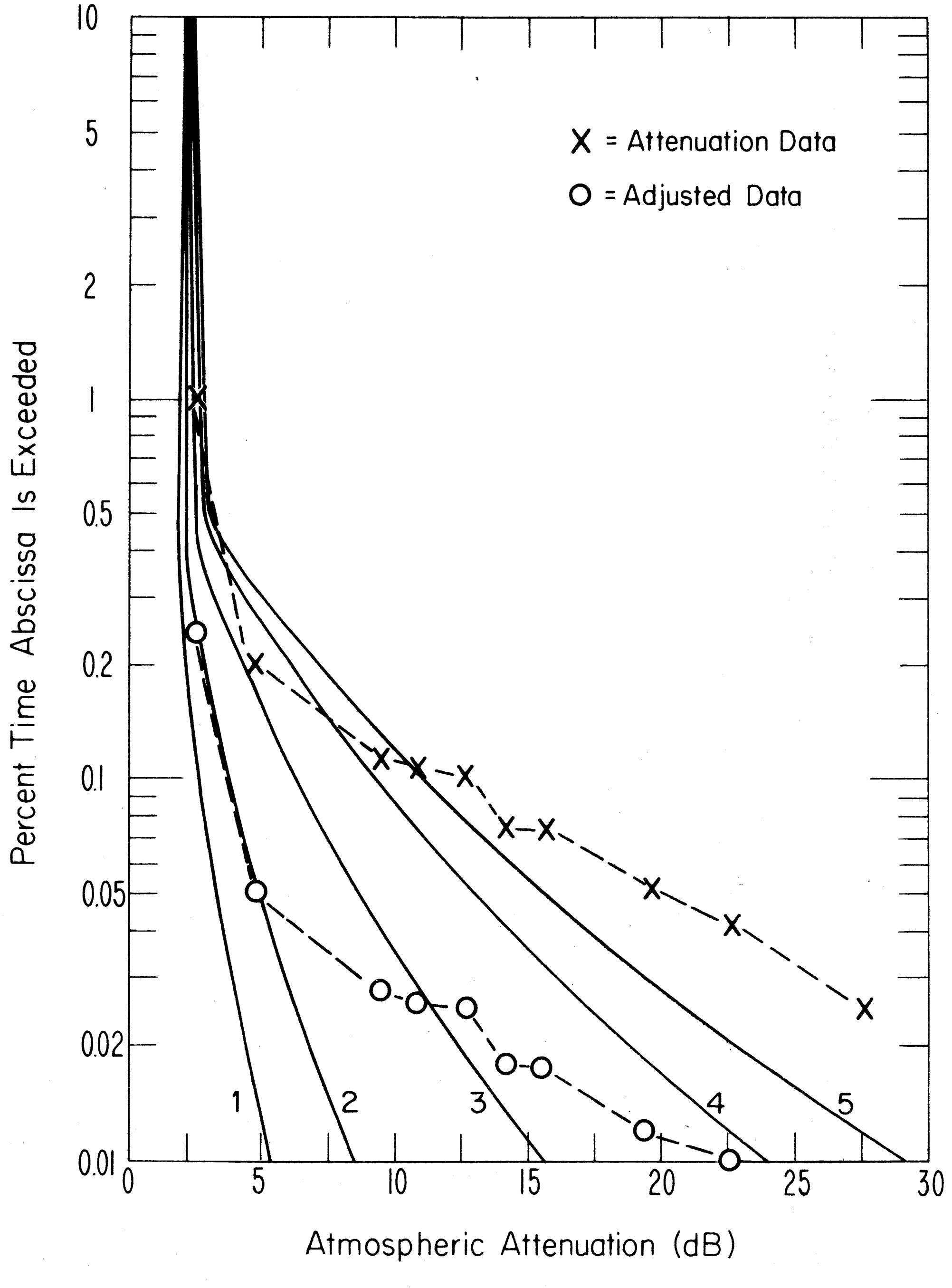

Figure B-2. Comparison of COMSTAR data from Blacksburg, VA, and predictions for Roanoke, VA, for 19.0 GHz at an elevation angle of 44 degrees. Data period is July through September, 1977. See Figure 2 for definition of curves 1 to 5.

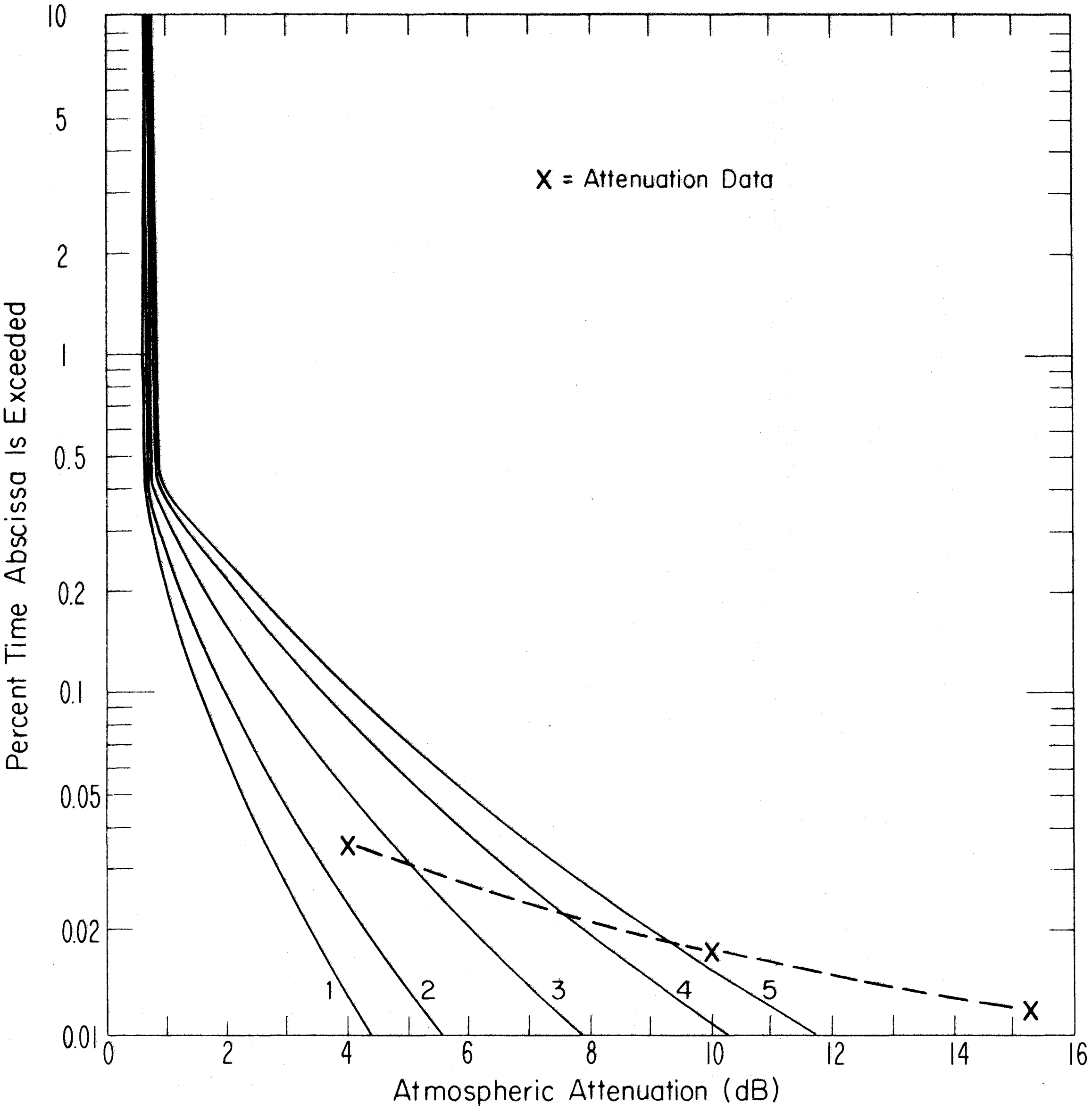

Figure B-3. Comparisons of CTS data from Austin, TX, and predictions for Austin, TX, for 11.7 GHz at an elevation angle of 49 degrees. Data period is June 12, 1976 to August 30, 1976. See Figure 2 for definition of curves 1 to 5.

are (nearly) coincident. These data were taken from the CTS satellite at a frequency of 11.7 GHz and an elevation angle of $\theta_o = 49$ degrees. Comparison of data adjusted by (B8) with predictions in figure B-3 was not possible, because data results were all below the 0.01 percent ordinate value. Comparison is "good" below the 0.01 percent ordinate between data and predictions, but since the model presupposes a lower limit of 0.01 percent of a year for prediction purposes (Dutton, 1977), such comparison is not meaningful in the current context. Comparison of data adjusted by (B8) with predictions in Figure B-3 is superior to the analogous situation in Figure B-1, but, of course, if such adjustment is meaningful, considering the proximity of data and prediction locations and the Texas terrain, one would expect a superior comparison in Figure B-3 to that in Figure B-1.

The methodology presented in this appendix should be used with considerable caution, and should be carefully interpreted. It is, however, recognized that occasions do arise when engineering estimates must be made based on less than a full year of data. In these cases, the meaningfulness of the estimates made must be properly assessed. It is still preferred that users have at least a year's data available before comparing with the prediction model results. As an example of concern in this regard, consider that one thunderstorm in an entire year's data is capable of so influencing the resultant distribution that the 0.01 percent of a year attenuation value can nearly double as a consequence of this one event. This implies that a distribution based on 3-months' data can be rather different than the distribution with 1 or 2 months' worth of additional data. A distribution based on a (continuous) year's worth of data, on the other hand, may not contain all the extreme events either, but the likelihood that the "peaks" and "valleys" of the climatological year are included is much greater.

REFERENCES for Appendix B

Bostian, C. W., W. L. Stutzman, E. A. Manus, P. H. Wiley, R. E. Marshall, S. R. Kauffman, W. P. Overstreet, and R. R. Persinger (1978), Current results of 11, 19, and 28 GHz satellite path attenuation measurements, presented at the National Radio Science Meeting, U. of Colorado, 9-13 Jan. 1978, Boulder, CO.

Dutton, E. J. (1977), Earth-space attenuation prediction procedures at 4 to 16 GHz, Office of Telecomm. Report OTR 77-123, May (Access No. PB269228/AS, NTIS, Springfield, VA).

Vogel, W. J., and A. W. Straiton (1977), CTS attenuation and cross-polarization measurements at 11.7 GHz, U. of Texas, Elec. Eng. Report under NASA contract NAS5-22576, Austin, TX 78758, April.

FORM **OT-29**
(3-73)

U.S. DEPARTMENT OF COMMERCE
OFFICE OF TELECOMMUNICATIONS

BIBLIOGRAPHIC DATA SHEET

	1. PUBLICATION OR REPORT NO. NTIA Report 78-10	2. Gov't Accession No.	3. Recipient's Accession No.

4. TITLE AND SUBTITLE
Earth-Space Attenuation Predictions for Geostationary Satellite Links in the U.S.A.

5. Publication Date
October 1978

6. Performing Organization Code

7. AUTHOR(S)
E. J. Dutton

8. PERFORMING ORGANIZATION NAME AND ADDRESS
U.S. Department of Commerce
NTIA/ITS-3
325 Broadway
Boulder, CO 80303

9. Project/Task/Work Unit No.

10. Contract/Grant No.

11. Sponsoring Organization Name and Address
U.S. Postal Service
Rockville, MD 20852

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.)*

The previously-developed Rice-Holmberg (RH) rain rate modeling and the Dutton-Dougherty (DD) attenuation modeling for earth-space links, and their subsequent modifications, are reviewed. Predictions are compared with data observed both from the Communications Technology Satellite (CTS) and from radiometric measurements. Then predictions are made at 12.2 and 14.5 GHz for 75 possible U.S.A.-based earth stations pointing to several potential geostationary satellite locations.

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

Attenuation distributions, earth-space attenuation, microwave frequencies, prediction confidence limits, rain rate distributions, satellite-earth communication links.

17. AVAILABILITY STATEMENT ☒ UNLIMITED. ☐ FOR OFFICIAL DISTRIBUTION.	18. Security Class *(This report)* Unclassified	20. Number of pages 48
	19. Security Class *(This page)* Unclassified	21. Price:

☆U.S. GOVERNMENT PRINTING OFFICE: 1978-0-677-448/226