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Microwave Radio Obstruction Fading

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The occurrence of obstruction fading on line-of-sight microwave radio paths can require tower heights that are substantially larger than those needed for transmission in a normal atmosphere. In this paper, we show that the occurrence probability of obstruction fading can be estimated from the probability distribution of positive vertical refractivity gradients. The occurrence of positive refractivity gradients is related to general meteorological variables in a companion paper. The work summarized is part of a recent effort that has resulted in a new tower-height design method where tower-height requirements are quantitatively determined from transmission performance requirements.

I. INTRODUCTION

The design and the transmission performance of terrestrial line-of-sight microwave radio paths is greatly influenced by two clear-air propagation phenomena, obstruction and multipath fading. Both types of fading are caused by anomalous stratification of the atmosphere. In the case of obstruction fading, atmospheric stratification temporarily changes the transmission path to such an extent that it becomes blocked by the terrain. In the case of multipath fading, a different type of atmospheric stratification temporarily creates multiple transmission paths that cause destructive interference of a number of waves at the receiving antenna.

Satisfactory transmission performance is attained when the height of microwave radio towers is sufficient to reduce the occurrence of obstruction fading to a tolerable value, and when diversity protection is used to eliminate transmission impairments caused by multipath fading. Methods for the estimation of multipath fading and the associated transmission performance have been developed, but a similar body of knowledge does not exist for obstruction fading.[1-6] One reason is that the variation of the occurrence of obstruction fading is much larger than that of multipath fading, which implies that the cost for establishing a data base for obstruction fading by direct measurement would be prohibitive.

However, obstruction fading can be related to meteorological variables for which a data base already exists. Recent work on this approach has resulted in a method that permits estimation of obstruction fading for any location in the United States. One part of this work, described in a companion paper, is the determination of probability distributions of positive vertical gradients of atmospheric microwave refractivity.[7] In this paper, we show that the probability of obstruction fading can be determined from probability distributions of the positive refractivity gradients. A mathematical model of obstruction fading is formulated to accomplish this. Obstruction-fading measurements are used to determine an obstruction loss expression for deep obstruction fading. A height interval for the definition of a positive refractivity gradient probability is also determined.

Tower-height requirements follow from transmission performance requirements when we use the mathematical model of obstruction fading. A new tower-height design method incorporating this approach supersedes the historical clearance rules (summarized in Ref. 2) previously used in the Bell System that did not relate performance to height in a quantitative manner. Additional advantages of the new method are geographic resolution and performance-based comparison of designs. We discuss transmission performance requirements applicable to tower-height determination in Section IX.

II. DAYTIME PROPAGATION

Microwave radio propagation on a line-of-sight path in a normal daytime atmosphere can be characterized by the trajectory of a ray that passes from the transmitting antenna to the receiving antenna. The trajectory is curved because the microwave index of refraction of the atmosphere decreases with height. The index of refraction (n) is usually described in terms of refractivity,[8]

$$N = (n - 1)10^6. \tag{1}$$

As an example, a refractivity of 320 N-units corresponds to a value of 1.000320 for the index of refraction. The vertical change of the refractivity can be considered to be a linear decrease with height in the first few hundred feet above ground.[9,10] A single parameter of the atmosphere, the refractivity gradient (N'), determines the trajectory of the ray under such conditions. An alternate parameter, denoted by K, is frequently used to describe the refractivity gradient.[11–13] The origin of K is a geometric transformation to an equivalent earth without atmosphere and a radius which is K times that of the actual earth. The conversion between the two parameters is

$$N' = -157(1 - K^{-1}), \tag{2}$$

where K is dimensionless, and N' is expressed in N-units per kilometer.[12,13] The daytime "standard" value of K is 4/3, which corresponds to a refractivity gradient of −39.25 N-units/km. Expressed as a function of K, the equation for the trajectory of the ray is

$$H_d = (D_1D_2/1.5)(1 - K^{-1}), \tag{3}$$

where H_d is the vertical deviation of the trajectory from a straight line between the antennas, and D_1 and D_2 are the distances from a point of interest to the ends of the path (Fig. 1). The units of H_d are feet when D_1 and D_2 are in miles.

The nearness of the trajectory of the ray to the terrain is usually described by a normalized vertical distance, which is the vertical distance between a terrain point of interest and the trajectory, divided by the radius of the first Fresnel zone,[11,12]

$$F_1 = 72.1(D_1D_2/fD)^{1/2}. \tag{4}$$

The units of F_1 are feet when the frequency f is in GHz and the path length D is in miles ($D = D_1 + D_2$). The normalization to F_1 introduces

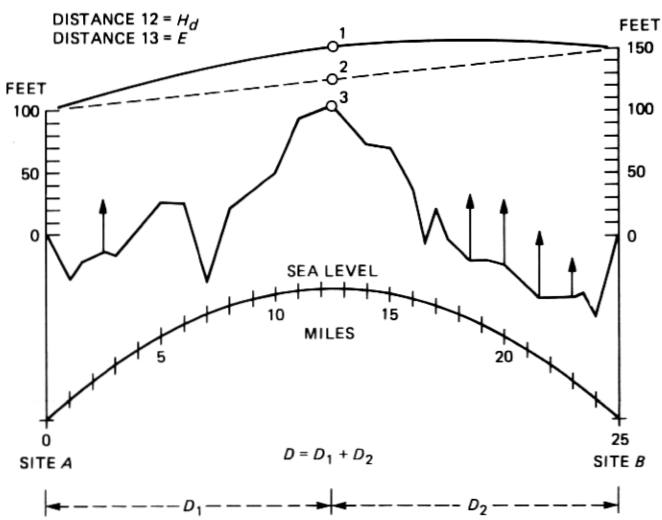

Fig. 1—Example of ray trajectory between antennas when $K = 4/3$ (solid line). In the absence of the atmosphere, or in the case of an atmosphere in which the vertical refractivity gradient is zero, the trajectory would be a straight line (dashed line). Arrows on the path profile denote tree cover.

scaling for frequency and distance that is convenient when signal attenuation due to the proximity of the terrain is considered. The attenuation is controlled by the terrain point with the smallest normalized vertical distance to the trajectory of the ray. This point on the terrain is referred to as the controlling obstruction. Tree cover and buildings must be included in the description of the terrain when the controlling obstruction is determined. The distance from the controlling obstruction to the trajectory of the ray is called clearance (distance E in Fig. 1).

Microwave radio paths are usually designed to avoid daytime attenuation caused by the proximity of the terrain to the trajectory of the ray. This is accomplished by using antenna heights such that the normalized clearance E/F_1 is unity or larger when K is 4/3.[2,12] Normalized clearances on many paths exceed unity at $K = 4/3$ because of antenna heights required to avoid excessive obstruction fading.

III. OBSTRUCTED PROPAGATION

Humid air can become positioned above drier surface-based air as a result of atmospheric stratification (layering).[7] Such stratification, when it occurs, develops gradually during the night and persists until broken up by air turbulence, caused either by a change in wind pattern or by a change in atmospheric conditions associated with sunrise. The resulting increase of refractivity with height causes the trajectory of the ray between the antennas to deviate downward from its normal daytime location. When the refractivity increase becomes sufficiently steep, the trajectory is blocked by the terrain, and the receiving antenna is placed in a shadow zone. The associated reduction in the received signal power is referred to as obstruction fading.

During obstruction fading, the lowest layer of the atmosphere controls propagation. The increases of refractivity with height in this layer are not necessarily linear, but it can be argued that the deviation of the trajectory is determined by a space-averaged gradient. Characterization of obstructed propagation by a single atmospheric parameter, a positive refractivity gradient, is therefore appropriate. This leads to the concept of a virtual trajectory (Fig. 2), which is a trajectory between the antennas that would exist for a particular positive refractivity gradient in the absence of the obstruction. The resulting geometrical description of blockage is similar to that of clearance, except that vertical distances from the terrain to the virtual trajectory are negative to signify blockage. The controlling obstruction in this case is that for which the normalized vertical distance has the largest negative value.

Quantitative description of obstruction fading in terms of the above geometry requires consideration of two topics. First, a relationship

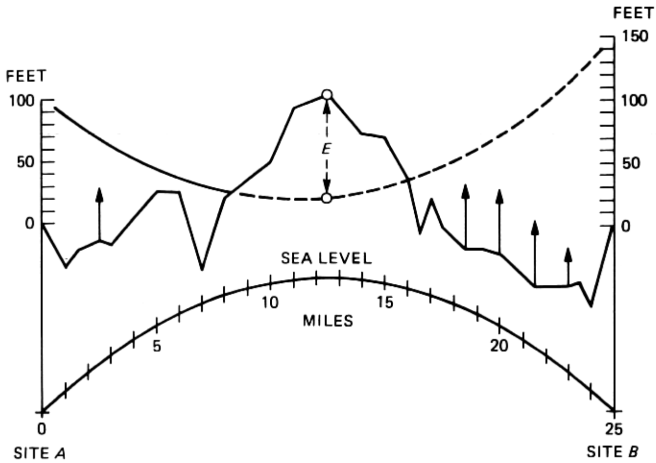

Fig. 2—Example of virtual trajectory between antennas when $K = 1/2$.

between obstruction loss and the normalized blockage E/F_1 at the controlling obstruction must be obtained. Second, probabilities of positive refractivity gradients must be translated into probabilities of blockage. We use the obstruction-fading measurements summarized in Section IV to accomplish this.

IV. MEASURED OBSTRUCTION FADING

We obtained quantitative information on obstruction fading from fading measurements carried out for one year (February 1974–January 1975) at 4.13 GHz on a 24.3-mi path in northeastern Florida where obstruction fading is prevalent. The measurement path was flat with substantial tree cover. At the transmitting site, referred to as station *T*, the ground elevation was 40 ft relative to the mean sea level. The centerline of the transmitting antenna (10-ft horn reflector) was 270 ft above ground. The controlling obstruction, located at 11.9 mi from the receiving site, consisted of 50-ft tree cover on ground that was 15 ft above the mean sea level. At the receiving site, referred to as station *R*, the ground elevation was 15 ft above the mean sea level. The centerline of the receiving antenna (10-ft horn reflector) was 220 ft above ground. Reception was also monitored on an antenna (10-ft dish) with a centerline at 185 ft above ground. We adjusted instrumentation gains to simulate operation with equal antenna gains and equal waveguide losses. A third receiving antenna (6-ft dish), added on November 1, 1974, had a centerline height of 73 ft above ground. During substantial fading experienced in November, the presence of the third receiving antenna permitted further verification of earlier conclusions that the amount of fading at station *R* was inversely related to antenna height in a manner that indicated the presence of obstruction fading.

We used Portable Propagation Recorders (PPRS) to record the experimental results. These devices sampled the received signals ten times per second and accumulated the time during which the strength of the signals was below a set of levels. The levels for the top antenna were, in dB relative to daytime normal, −10 and then −20 to −40 in 5-dB steps. Limitations of recording capacity forced us to assign a smaller set of levels to the two lower antennas. We transmitted the accumulated data to Bell Laboratories at Holmdel, New Jersey, once every working day. The accumulated data were also automatically punched out on paper tape at station R at noon every day. This permitted the signal statistics to be separated into noon-to-noon periods. The interpretation of the statistics was aided by strip charts (3 in/h) that accompanied each 24-h block.

Obstruction fading was present on four nights during 24-h periods that ended at noon on March 8, June 20, November 3, and November 17 in the 1-yr measurement period. We determined the presence of obstruction fading on the basis of three criteria: depressed levels of received signals on a time scale of tens of minutes, increase of fading with decrease of antenna height, and high degree of simultaneous fading on the two upper antennas. The last criterion separates nights with obstruction fading from those with heavy multipath fading.

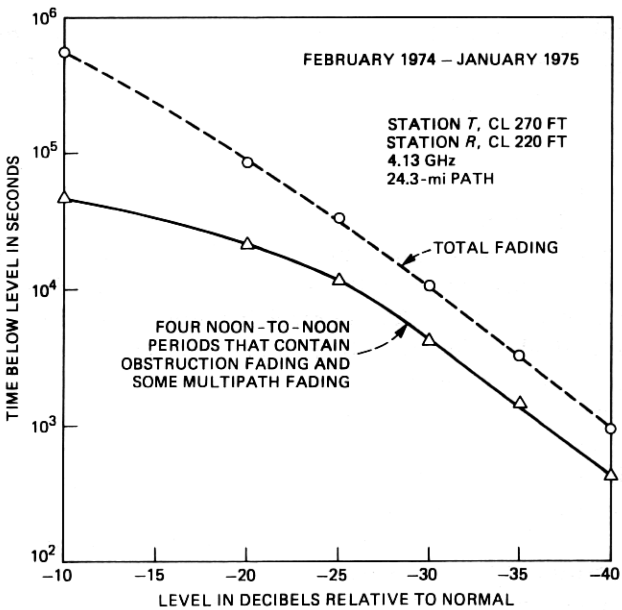

Fig. 3—Measured obstruction fading.

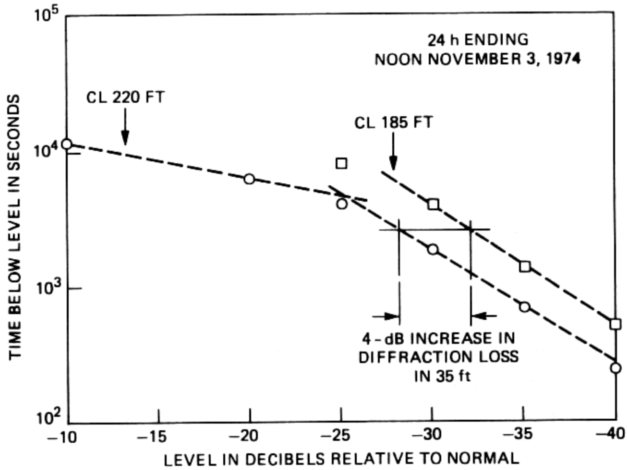

Fig. 4—Variation of obstruction fading with reception height at station *R*.

The measured time below −35 dB on the top antenna during nights with obstruction fading was 1425 s (solid curve in Fig. 3). The corresponding simultaneous time below −35 dB on the two upper antennas was 562 s. The space-diversity improvement is only 2.5 (1425/562), which demonstrates the incapacitation of diversity protection in the presence of obstruction fading.

The measured time below −35 dB on the top antenna caused by all fading was 3217 s (dashed curve in Fig. 3). Subtracting the obstruction-fading dominated time from this yields the amount of multipath fading (1792 s below −35 dB). The corresponding simultaneous time below −35 dB caused by multipath fading on the two upper antennas was 16 s. The space-diversity improvement of 112 (1792/16) is typical of multipath fading.

V. EMPIRICAL OBSTRUCTION LOSS EXPRESSION

We obtain a relationship between obstruction loss and blockage when measurements made at station *R* are related to diffraction theory. The measurements imply a linear relation between large obstruction loss in dB and normalized blockage, with a slope of 20 dB per unit of normalized blockage. This follows from the observation that (Fig. 4), for a given amount of loss larger than about 25 dB on the top antenna at station *R*, the loss on the antenna 35 feet below it is *4* dB larger. From the geometry of the path (specified in Section IV), the vertical offset corresponding to 35 ft at station *R* is 17.9 ft (35 × 12.4/24.3) at the controlling obstruction 11.9 mi from station *R* (12.4 mi from station *T*). The radius of the first Fresnel zone at this point on the path is 87.4 ft. Therefore, the vertical offset is 0.20 (17.9/87.4) in terms of a change of normalized blockage. This corresponds to a change of 20 dB per unit of normalized blockage (4/0.20).

Large values of the theoretical obstruction loss for extended obstructions, such as large spheres, vary approximately linearly with normalized blockage.[14] The theoretical results suggest that straight-line approximations for large losses intersect zero loss at 0.5 units of normalized clearance. Given this, and the experimentally inferred slope of 20 dB, the loss expression applicable to deep obstruction fading becomes

$$M = -10 + 20(E/F_1), \qquad M < -20, \tag{5}$$

where M is the fade level in dB relative to free space, and the value of the vertical distance E is negative to signify blockage. The term "free space" refers to a signal level that would be attained in the absence of atmospheric effects and without the proximity of the terrain.

The above empirical obstruction loss expression describes diffraction by "large" obstructions in the presence of atmospheric stratification. Paths with obstructions of "smaller" horizontal extent, such as a mountain ridge, may have obstruction losses smaller than those described by the empirical expression. This is suggested by a comparison with the theoretical limiting case of knife-edge diffraction (Fig. 5).[13,14] Such "smaller" obstructions usually occur in mountainous terrain where obstruction fading is not a problem. Based on general scaling

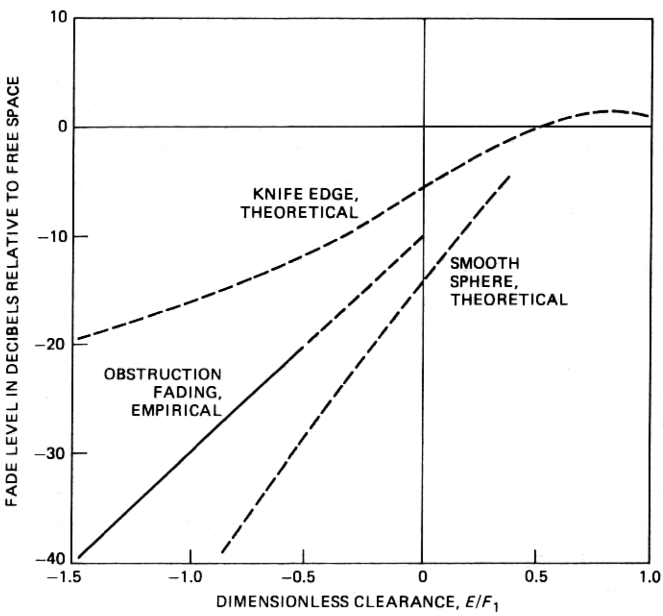

Fig. 5—Obstruction loss for deep obstruction fading on line-of-sight microwave radio paths.

experience in path engineering, the empirical loss expression can be applied at frequencies from 2 to 11 GHz on most practical paths between 20 and 30 mi in length.

VI. PROBABILITY OF OBSTRUCTION FADING

The practical problem in microwave radio path engineering is estimating the amount of time during which obstruction fading causes the received signal to be below a particular fade level. This time can be obtained from the probability of obstruction fading, which can be estimated from the probability distribution of refractivity gradients.

The steps in the procedure for making such an estimation are outlined in a simplified flow chart in Fig. 6. A fade level of interest corresponds to a normalized blockage E/F_1 as specified by the obstruction loss expression in eq. (5). The value of F_1 can be calculated when the radio frequency is specified and the location of the controlling obstruction is determined. This can be an iterative procedure, since the location of the controlling obstruction can change with antenna height and refractivity gradient. When F_1 has been calculated, the vertical distance E can be determined from a rearranged obstruction loss expression

$$E = (F_1/20)(M + 10). \tag{6}$$

Next, given the tentative heights of the transmitting and receiving antennas and the profile of the path, eq. (3) for the trajectory of the ray can be applied to determine a positive refractivity gradient (S) required to produce the value of E determined above.

The annual amount of time during which obstruction fading causes a received signal to be below a particular fade level can then be expressed, in seconds per year, as

$$T = T_0 P(N' > S), \tag{7}$$

where T_0 is the number of seconds in a year and $P(N' > S)$ is the annual probability that the refractivity gradient N' exceeds S.

The annual probability that the refractivity gradient exceeds a particular positive value S is composed of seasonal parts,[7]

$$P(N' > S) = (1/4) \sum_i P_i(N' > S), \tag{8}$$

where the summation extends over the four seasons of the year. Each seasonal probability consists of two components

$$P_i(N' > S) = 0.8P_{m,i} + 0.2P_{s,i}, \tag{9}$$

where the subscript m refers to the mixed (daytime) atmosphere, and the subscript s refers to a stratified (nighttime) atmosphere. Both

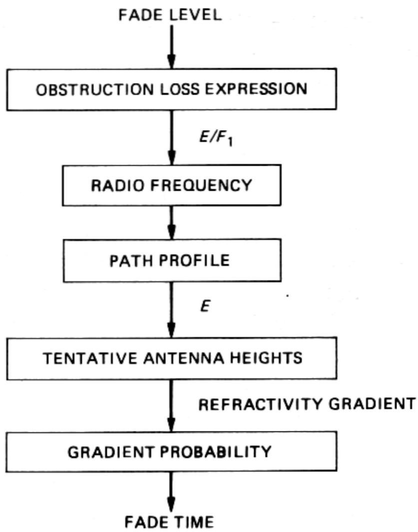

Fig. 6—Obstruction fading calculation.

components are Gaussian probability functions specified by appropriate values of their means and standard deviations.[7] The means vary with geographic locations, but in a given season they are the same for the mixed and stratified regimes in the above mathematical formulation. The standard deviation for the mixed regime is 15 N-units/km for all locations and all seasons of the year in the United States.[7] The amount of obstruction fading is governed largely by the standard deviations for the stratified regime, which exhibit considerable geographic and seasonal variation.[7]

VII. GRADIENT SCALE

Probability distributions of refractivity gradients usually describe the occurrence of increments of refractivity associated with an increment in height.[7,15] A frequently used height increment is 100 m. Analyzing data for other height increments shows that the standard deviation of positive refractivity increments in the stratified regime is inversely proportional to the fourth root of the height increment.[7] This arises because the absolute increase in refractivity that the atmosphere can support is limited. This behavior of the gradient statistics necessitates use of obstruction-fading measurements to determine the height increment (gradient scale) appropriate for microwave obstruction fading.

Simultaneous fading on the upper two receiving antennas at station R is the experimental measurement best suited for the determination of the gradient scale (centerlines of 220 and 185 ft above ground).

Simultaneous fading below the −35 dB fade level was measured on these antennas continuously throughout the experiment. The total simultaneous time below −35 dB was 562 s in the four 24-h periods when obstruction fading was present. This time represents "pure" obstruction fading below −35 dB at the 220-ft height, since the constraint of simultaneity removes multipath effects.

The calculated time below the −35 dB fade level can be expressed as a function of the height increment, or more specifically from eq. (9) in Ref. 7, as a function of the coefficient in the expression that relates the standard deviation of positive refractivity increments to meteorological parameters. This coefficient is inversely proportional to the fourth root of the height increment. The value of the coefficient is 440 when the height increment is 100 m.[7] The corresponding standard deviations for the area where the path is located are, in N-units/km, 71 for winter, 56 for spring, 58 for summer, and 96 for fall.[16] The coefficient that corresponds to the measured 562 s is 540 (Fig. 7). Therefore, the height interval (gradient scale) appropriate for calculation of obstruction fading becomes, as determined from Fig. 4 in Ref.

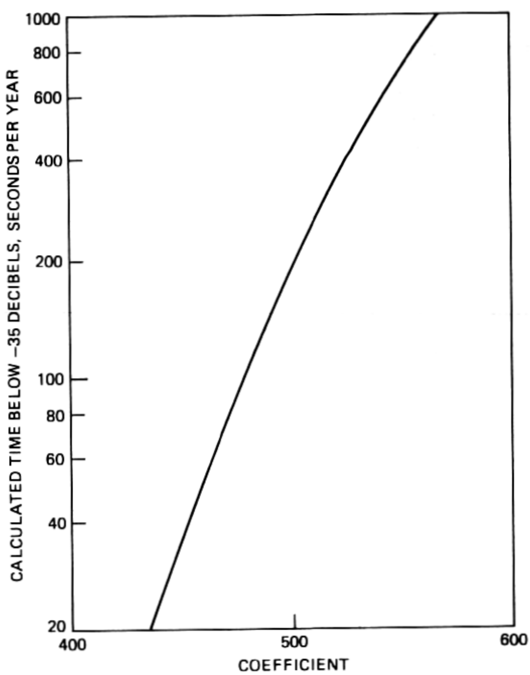

Fig. 7—Calculated obstruction fading as a function of the coefficient in the expression for the standard deviation of refractivity gradient.[7] Measured obstruction fading of 562 s and meteorological parameters for the propagation path between stations T and R determine 540 as the value of the coefficient.[16]

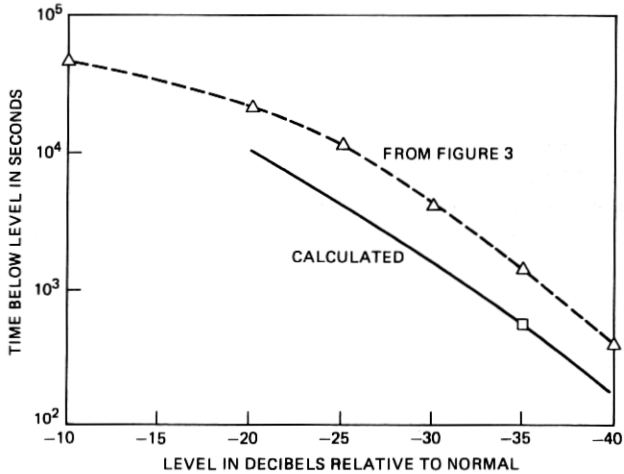

Fig. 8—Calculated obstruction fading at station *R*. Measured fading on nights when obstruction fading was dominant is shown by dashed curve (from Fig. 3), which contains some multipath fading.

7, $(1400/540)^4$ or 45 m. The corresponding standard deviations of the positive refractivity increments are, in *N*-units/km, 87 for winter, 69 for spring, 71 for summer, and 118 for fall.

The mean values of the refractivity gradients do not require scaling, since they describe the daytime reference condition of the atmosphere. The values of the means used in the above calculations are, in *N*-units/km, −46 for winter, −53 for spring, −58 for summer, and −53 for fall.[16]

VIII. CALCULATED OBSTRUCTION FADING

A comparison of calculated and measured obstruction fading at station *R* demonstrates the validity of the mathematical model. The slope of the calculated obstruction fading curve matches the measured results (Fig. 8). The slope is determined by the mathematical model, which has not been forced to conform in any way to slopes of measured fading curves. The calculated curve passes through the simultaneous fading point at −35 dB, which was used to determine the gradient scale and which describes "pure" obstruction fading. The dashed curve (from Fig. 3) describes measured obstruction fading accompanied by some multipath fading. Extension of the calculated curve to fade levels significantly shallower than −20 dB is not appropriate, since the obstruction loss curve incorporated in the mathematical model applies only to deep obstruction fades.

Additional calculated results for station *R* (Figs. 9 and 10) illustrate the variation of obstruction fading with antenna height and radio frequency. The time below −35 dB varies by more than two orders of magnitude as the receiving height at station R changes 200 ft. When the radio frequency is varied from 2 to 11 GHz, the fade level at 10 s/yr (Fig. 10) varies over a range of almost 20 dB. This variation is a consequence of the frequency dependence of the obstruction loss in eq. (5). The obstruction loss increases with frequency because, as illustrated in Fig. 11, the blockage of Fresnel zones increases with frequency.

IX. DESIGN SPECIFICATIONS

Tower-height design specifications can be derived from Bell System's annual all-cause two-way transmission unavailability design limit of 0.02 percent, which applies to a 4000-mi long-haul circuit or a 250-mi short-haul circuit.[1,2,6] For route engineering purposes, half of this is allocated to multipath fading in the 2-GHz, 4-GHz, and 6-GHz bands where clear-air propagation phenomena are the dominant causes of propagation impairments.[1,2] A new allocation to obstruction fading is 0.005 percent, which is both two-way and one-way, assuming that both directions of transmission use radio channels on the same terrestrial radio route. The other 0.005 percent is allocated to equipment impair-

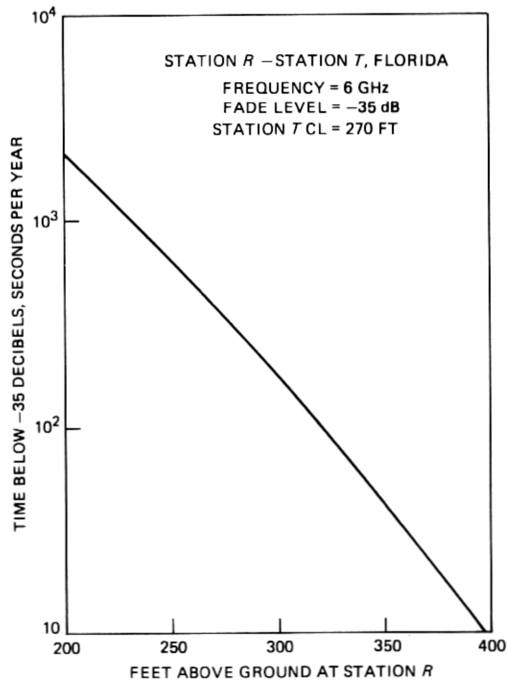

Fig. 9—Variation of obstruction fading with antenna height.

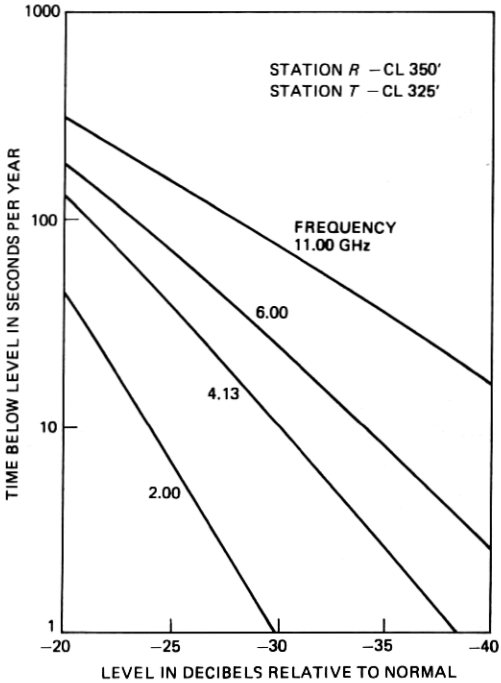

Fig. 10—Calculated obstruction fading for station R − station T.

ments and other causes. These design allocations emphasize that, in modern solid state radio systems, transmission performance is governed by propagation impairments. In the case of short-haul radio, tradeoffs between allocations are frequently invoked, particularly so in the 11-GHz band where transmission unavailability caused by rain can be dominant.

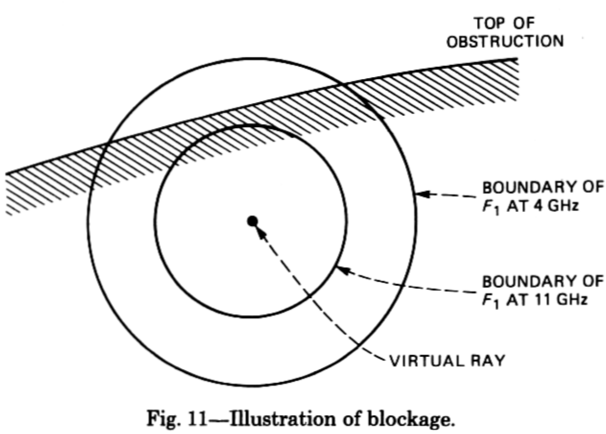

Fig. 11—Illustration of blockage.

The allocations are prorated to distance. For long-haul service, this implies that antenna centerline heights (tower heights) on a 25-mi path have to be such that the annual time below a specified fade level, caused by obstruction fading, is 10 s or less. A fade level of −35 dB is recommended as the obstruction fading outage threshold in tower-height design procedures. The choice of −35 dB as a design value is related to general characteristics of radio systems, interference considerations, and possible joint occurrence of obstruction fading and multipath fading. An advantage of an equipment-independent fade-level specification is design stability, since radio towers are "permanent" parts of the plant that can be expected to be used for a number of future varieties of radio equipment and service. Combined use of the allocation and the −35 dB value is necessary to achieve a balanced design where terrain clearance is adequate and where impairment of diversity protection is minimal when obstruction fading and multipath fading occur jointly.

When used as design criteria, the allocations are prorated to the length of a frequency-diversity switching section or to a route segment between terminals or drop and add points. For example, the allocation to a switching section containing three 25-mi paths (hops) is 30 s. The hops are permitted to contribute unequally to the 30-s total. A design where two hops contribute 5 s each and the third hop contributes 20 s is satisfactory. Design allocations such as these are related to measured performance in an average sense, since fading can vary from year to year, and because interactions of fading, actual fade margins, and protection system operation can be complicated.

Tower heights on radio hops in short-haul service frequently have been determined by clearance rules that are the same as those for hops in long-haul service. This permits flexibility in the routing of communications traffic with differing reliability requirements. Therefore, tower-height requirements for short-haul routes can be determined from the obstruction-fading allocation of 10 s/yr prorated to a 25-mi hop. An option for the determination of short-haul tower heights is an obstruction fading allocation of 160 s/yr prorated to a 25-mi hop. This retains the standard one-to-sixteen ratio of per-mile performance between long-haul and short-haul service. The 160-s option can be used only when reliability requirements are expected to remain constant over the life of the towers. When used as design criteria, these allocations are prorated to the length of a switching section or route segment.

In the case of paths equipped for space-diversity reception, the obstruction fading allocation for the lower antenna prorated to a 25-mi hop is 50 s/yr for long-haul service and for those hops in short-haul service where the height of the upper antenna is determined by the

10-s allocation. We apply the 50-s allocation on a per-hop basis to avoid impairment of space-diversity protection. A separate allocation for lower antennas is not made when we use the 160-s option to design short-haul paths, since this option represents a design limit.

The design criteria outlined above indicate that tower heights larger than previously required can be beneficial in regions where obstruction fading is severe. For example, a previous clearance rule has been grazing (zero) clearance at $K = 1/2$ in difficult propagation areas,[2] which requires approximately 180-ft towers on a 20-mi flat path covered by 50-ft trees. The new criteria indicate that towers on such a path may need to be as high as 250 ft for long-haul service in an area with a high occurrence probability of obstruction fading.

X. CONCLUSION

A new tower-height design method outlined in this paper permits more efficient use of construction funds, since tower heights are quantitatively related to transmission performance. High towers can be constructed where needed, whereas towers of minimal height, determined by daytime clearance requirements, can be used in the cooler regions of the United States.

XI. ACKNOWLEDGMENTS

The work on obstruction fading benefited considerably from interactions with W. T. Barnett. We had many helpful discussions with J. A. Schiavone about the meteorological aspects of radio propagation. Portable Propagation Recorders (PPRS) designed by G. A. Zimmerman made acquisition of the propagation data possible. A number of colleagues at Bell Laboratories, AT&T Long Lines, and Southern Bell provided assistance needed to carry out the propagation measurements.

REFERENCES

1. A. Vigants and M. V. Pursley, "Transmission Unavailability of Frequency-Diversity Protected Microwave FM Radio Systems Caused by Multipath Fading," B.S.T.J., *58,* No. 8 (October 1979), pp. 1779–96.
2. A. Vigants, "Space-Diversity Engineering," B.S.T.J., *54,* No. 1 (January 1975), pp. 103–42.
3. W. T. Barnett, "Microwave Line-of-Sight Propagation With and Without Frequency Diversity," B.S.T.J., *49,* No. 8 (October 1970), pp. 1827–71.
4. W. T. Barnett, "Multipath Propagation at 4, 6, and 11 GHz," B.S.T.J. *51,* No. 2 (February 1972), pp. 321–61.
5. S. H. Lin, "Statistical Behavior of Deep Fades of Diversity Signals," IEEE Trans. Commun., *COM-20,* No. 6 (December 1972), pp. 1100–7.
6. W. Y. S. Chen, "Estimated Outage in Long-Haul Radio Relay Systems with Protection Switching," B.S.T.J., *50,* No. 4 (April 1971), pp. 1455–85.
7. J. A. Schiavone, "Prediction of Positive Refractivity Gradients for Line-of-Sight Microwave Radio Paths," B.S.T.J., this issue.
8. B. R. Bean and E. J. Dutton, *Radio Meteorology*, National Bureau of Standards, U. S. Government Printing Office, 1966.

9. C. L. Pekeris, "Accuracy of the Earth-Flattening Approximation in the Theory of Microwave Propagation," Phys. Rev. *70,* Nos. 7 and 8 (October 1 and 15, 1946), pp. 518–22.
10. D. E. Kerr, *Propagation of Short Radio Waves*, New York: McGraw-Hill, 1951.
11. D. C. Livingston, *The Physics of Microwave Propagation*, Englewood Cliffs, New Jersey: Prentice-Hall, 1970.
12. R. F. White, *Engineering Considerations for Microwave Communications Systems*, San Carlos, California: Lenkurt Electric Co., 1970.
13. M. P. M. Hall, "Effects of the Troposphere on Radio Communications," London: Peter Peregrinus Ltd. on behalf of the Institution of Electrical Engineers, 1979.
14. K. Bullington, "Radio Propagation Fundamentals," B.S.T.J., *36* (May 1957), pp. 593–626.
15. C. A. Samson, "Refractivity Gradients in the Northern Hemisphere," OT Report 75-59, U. S. Department of Commerce, Office of Telecommunications, U. S. Government Printing Office, April 1975.
16. J. A. Schiavone, private communication, 1979.