RADIO PROPAGATION IN URBAN AREAS

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ABSTRACT

This paper reviews earlier work on radio propagation in urban areas, including data, studies of multipath fading, and empirical propagation models. A model is described, for use with a digital computer, which provides a rapid means of calculating both the median attenuation and the location, or path-to-path, variability.

INTRODUCTION

For many years land-mobile and broadcast services were concerned mainly with the lower part of the VHF band, but recently higher frequencies are allocated, so for both broadcast and mobile systems we must consider frequencies up to 1000 MHz.

The random selection of receiver locations for these systems results in greater median propagation loss than would occur with selected sites, and also in greater path-to-path variability. Some irregularity in terrain causes an increase in the median field strength by breaking up the destructive phasing between direct and reflected radio waves. However, as terrain irregularity increases, or as buildings and trees are added to the surface, the signal is reduced by shadowing, absorption, and scattering of the radio energy, and there is also an increased range of variation with location. These effects of terrain irregularity, and of surface clutter, increase with increasing frequency, so with the present trend toward the use of higher frequencies these effects become more and more important.

In land-mobile systems the antenna height on the mobile unit is low, usually not more than 3 m above ground. Between the base station and a mobile unit, and between the units themselves, an ever-changing and very large number of propagation paths are formed due to the motion from place to place. This multipath interference causes the signal to fade rapidly and deeply and can be a serious problem in highly built-up urban areas.

In addition to the rapid, multipath type of fading there is a variability in signal level from one location to another. This may be referred to as path-to-path or location variability. In urban areas the location variability is highly dependent on the type and density of surface features, as well as on terrain irregularity, and radio frequency.

The problems encountered in propagation in an urban environment contain too many unknown elements for complete theoretical modeling. For this reason data from measurements have been depended on in attempts to model radio propagation in urban conditions. Many such empirical models have been proposed. Of these several are presented in the form of curves of median field strength as a function of distance or range, with an allowance for path-to-path variability.

This paper reviews much of the available data, considers techniques to overcome or control the rapid, multipath type of fading, and describes early and existing models for predicting median propagation loss and location variability. A model is described which takes into account the dependence of transmission loss on radio frequency, antenna height, terrain irregularity and distance, with an additional allowance for attenuation in urban areas as a function of surface obstacles and radio frequency. This model is developed for use with a digital computer and has been tested against available data.

SURVEY OF PREVIOUS WORK

Many measurement programs have been carried out to ascertain the effects of shadowing by terrain and by natural and man-made objects. Most of the results have been considered in terms of urban, suburban, and rural areas.

In a mobile radio environment a multiplicity of signal paths is nearly always present. Spatial variations appear as changes in time and the signal fades rapidly and deeply, with depths of 30 dB being quite common. The fading rate is proportional to the speed of the mobile unit and to the radio frequency, with minima occurring about every half wavelength. Terrain features and natural and man-made obstacles cause great attenuation, and an infinitely large number of propagation paths are formed as a result of the multipath from place to place. In a highly built-up city, such as Manhattan, by far the most serious problem in urban propagation is the multipath degradation.

Results of Measurement Programs

Studies of the effects of shadowing and multipath in an urban area were begun more than 40 years ago. An early study[1] showed that the signal transmitted at a frequency of 34.6 MHz from a high building in Boston to a mobile receiver was quite variable, with an average value 12 dB less than the theoretical flat earth level, and a range of ±10 dB. Surveys in the Camden-Philadelphia area at 30 and 100 MHz[2] showed the shielding effect of the thickly built-up downtown area, especially at 100 MHz. Other early measurements[3] showed that channel 5 signals in the streets of New York City were far below theoretical values, and quite variable in level, even though the terrain is essentially flat. These effects were caused by the shadows and multiple reflections from the many high buildings. Similar measurements were made in New York City at frequencies of 67, 288, 510, and 910 MHz from a transmitter atop the Empire State Building.[4] A receiving van moved along two radials, one west over very hilly country through suburban areas with large houses and trees, and the other southwest over level terrain toward Princeton, New Jersey. Shadowing by hills, or other obstructions, had a steadily increasing effect as frequency increased, and in hilly or obstructed areas multipath effects became severe at 510 and 910 MHz. On the smooth southwest radial outside of Manhattan there was little evidence of multipath, while along the other radial, especially in shadowed areas, signals arriving by many paths were numerous. Measurements at 150 and 450 MHz from a transmitter on top of the telephone building in New York City to mobile receivers[5] gave values 20 to 40 dB below calculated smooth earth values. The mean excess loss was about 30 dB on cross-town streets and only about 15 dB on the north-south avenues. In suburban rolling country the excess loss was 5 to 40 dB, with a mean of 23 dB. On city streets the variation over a distance of 200 to 400 ft was roughly 20 to 25 dB, while in open country it was only about half as much. The results of other measurements in New York City have been reported[6,7] including those of a large program carried out by the Federal Communications Commission,[8,9] all of which show severe attenuation of the signal level, particularly at the higher frequencies tested.

Studies of transmission at 850 MHz in Jersey City[10] show the effects of different transmitting antenna heights. In a heavily congested area, with smooth terrain, the attenuation relative to free space was 26 and 15 dB with antenna heights of 200 and 740 ft, respectively. Similarly, in an area of open farmland the corresponding values were 16 and 0 dB. Mobile measurements in the 800 to 900 MHz range have also been made in Philadelphia and Washington DC,[11,12] and recently measurements at 450 and 850 MHz in the hilly terrain of Pittsburgh have been reported.[13]

Extensive studies of land-mobile services in Japan have been reported.[14,15] Measurements at frequencies from 200 to 2000 MHz were made in the heart of Tokyo and its environs. They show the effects of frequency, antenna height, terrain, and density of urban clutter.

Mobile measurements in cities in other parts of the world have also been reported by several investigators. In the streets of London[16] at 90.8 MHz buildings of normal height reduced the average field strength 10 to 12 dB, and local variations were much greater with vertical than with horizontal polarization. Similarly measurements have been reported from Russia, Poland, Italy and West Germany.

In heavily built-up city areas we have seen that the additional loss may range from zero to about 40 dB, depending on frequency, antenna height, angle of arrival of the signal, and the density and height of the buildings. At frequencies from 40 to 250 MHz there is no great difference in signal level between urban and rural areas as long as the receiving antenna is above local roof levels, but with the receiving antenna at 10 m the additional attenuation in urban areas is 6 to 16 dB depending on the character and height of the buildings. At higher frequencies, 450 to 1000 MHz, urban attenuation may be from about 6 to 28 dB depending on the density and heights of the buildings.

Some Height Gain and Polarization Effects

In a land-mobile service the receiving antenna is usually only about 3 m above ground, while for a broadcast service the height is about 10 m. The median gain when the receiving antenna is raised from 3 to 10 m depends on the frequency and surface features. In the range 40 to 100 MHz the height gain is 9 to 10 dB in both rural and urban areas. For frequencies of 150 to 250 MHz the height-gain is 10 to 11 dB in urban or hilly areas, and about 7 dB in flat terrain. At 450 to 1000 MHz the height gain is 14 dB in urban areas and 6 to 7 dB in the suburbs, while in irregular terrain it depends on terrain irregularity, going from 10 to 0 dB as the interdecile range of terrain elevations increases from 10 to 500 m. At any specific location the actual height gain on raising the receiving antenna from 3 to 10 m may be quite different from these median values. As the receiving antenna is raised above surface obstacles a further height gain is to be expected. In an urban area, with receiving antennas above local roof levels no increase in transmission loss above that in rural areas is expected at frequencies below 100 MHz. In the 150 to 250 MHz band there may be an additional attenuation of 5 to 15 dB in urban areas depending on the density and height of the buildings and the angle of arrival of the signal at the receiving antenna. In urban areas in England an additional 9 dB attenuation was observed in the range 450 to 1000 MHz. When the receiving antenna is lowered from 3 to 1.5 m the additional attenuation is approximately 3 dB.

In both urban and suburban situations, increasing the height of the transmitting antenna may have a marked effect. The increased field can be related to the increase in elevation angle. The amount of attenuation should depend on the angle of approach at the receiving antenna, and should be greater for low angles of approach because the path length through intervening obstacles is longer. Another effect of raising the transmitting antenna is that this may elevate it above nearby obstructions, such as tall buildings, which may practically block out a whole segment.

The directive gain patterns, polarization, and other characteristics of antennas are often greatly affected by the proximity of buildings and vegetation. In shadow regions at VHF the effect of reflections on vertically polarized signals is often sufficient to seriously distort FM reception, while they have little effect on horizontally polarized signals. It was noted[7] that at 100 MHz the average loss from nearby trees was 5 to 10 dB with vertical polarization and only 2 to 3 dB for horizontally polarized signals. Such polarization differences were not observed at frequencies from 300 to 500 MHz. But even at 900 MHz small sector signal variations are greater for vertical polarization than for either horizontal or circular polarization.

When a transmitter is located at a clear site some discrimination against unwanted signals may be achieved by the use of orthogonal polarization. In an urban setting, however, where multipath fading caused by scattering and reflection from buildings and trees is common, the resulting field is largely depolarized. Polarization discrimination exceeded at 90% of receiving sites is 20, 14, and 0 dB in flat, hilly, and mountainous terrain, respectively. With the transmitting antenna at a clear site the polarization discrimination at rooftop level in an urban area has a 90% value of about 9 dB. Some measurements at UHF indicate that there is slightly more depolarization for vertically than for horizontally polarized waves.

Attenuation by Trees

Many measurements have been made of the effects of forests and of individual trees on radio propagation. Typical dense, and rather extensive woods are practically opaque to radio signals at UHF and higher frequencies. The signal in the presence of woods near the receiving antenna appears to be principally that diffracted over the trees, but with less dense woods the signal transmitted through may be greater than that diffracted over them.

A small number of trees, or even a single tree, can cause considerable spatial variation in field strength at points within the shadow zone. When an antenna is placed in a grove of trees the signal is severely attenuated and the directive gain pattern, polarization, and other characteristics of the antenna may be strongly affected. Measurements made in jungles and rain forests show that jungle attenuation of radio signals at VHF is very great, and that vertically polarized signals are attenuated about 15 dB more than horizontally polarized fields.

Large measurement programs have been carried out in tropical jungles, and the vegetation has been modeled as an imperfect dielectric slab. This so-called "slab model" represents the inhomogeneous, anisotropic, real jungle as an homogeneous, isotropic, lossy dielectric. However, the scattering of VHF radio waves by trees is a significant factor, especially scattering by the tree trunks. As the frequency is increased, above 100 MHz, the trees tend to act more and more as individual scatterers. Multipath effects become increasingly significant, and there is much more radiowave attenuation than would be predicted by a slab model. At VHF and UHF the large attenuation is strongly frequency dependent, and is rather insensitive to tree density.

In urban areas we are concerned with the absorption, reflection, and scattering of radio energy by trees and other vegetation, and their effects on multipath near the receiving antenna. Several investigators have observed more attenuation through woods in summer than in winter. This foliage loss may be 3 to 4 dB at 500 MHz and 10 dB or more at 900 MHz. In a recent paper[17] measurements are reported over a grove of trees at frequencies from 80 to 3000 MHz, with transmitter antenna elevations from 200 to 400 m. The results suggest a better fit to propagation over an ideal knife-edge than over a smooth earth. At short receiver distances a significant amount of signal energy propagates through the trees, so their effective height is less than their true height. This agrees with earlier observations[18] of propagation to low antennas placed near, or within, heavy pine forests. Some propagation of radio energy through the trees above the critical angle of internal reflection was noted.

Multipath Fading

In a mobile radio environment the signal fades rapidly and deeply as a result of shadowing, reflections and scattering by terrain, buildings, and trees. Fading depths of 30 dB are common, with fading rates proportional to the radio frequency, and the speed at which the vehicle travels.

Many studies have been made of the interference caused by multipath which may seriously limit the performance of wide-band radio systems, and affect systems for the automatic location of mobile units. The characteristics of multipath fading have been carefully studied and described with a view to determining ways to offset destructive fading.

Several ways to reduce multipath fading have been tested. One of the most successful is space diversity. A recent paper[19] surveys various techniques, and concludes that diversity at the mobile receiver is preferable. With suitable diversity the fading depth is greatly reduced, from 30 dB to about 10 dB in many cases.

PROPAGATION MODELS FOR URBAN AREAS

Many investigators have tried to develop ways to predict median values of propagation loss in built-up areas, where buildings and trees may cause severe attenuation of the radio signals. Others have been concerned with describing path-to-path variability and multipath fading in statistical terms.

Existing Propagation Models

When we consider the median path loss in urban areas, we find that many investigators calculate first the propagation loss to be expected if the buildings and other surface features were not present. The additional observed loss is then assumed to be caused by the urban, or suburban, development. Over rather smooth terrain, such as we find in Manhattan, theoretical plane earth values have first been calculated. The differences between these and the measured values have then been variously referred to as the shadow loss, excess loss, urban factor, clutter factor, etc. In a similar manner some investigators have compared measured losses with calculated free space values.

An early model[20] describes a simplified method for calculating propagation over a smooth spherical earth, with empirical allowances for the effects of hills and buildings. Some 10 years later available data were used to develop a model based on the theoretical plane earth field[21] to which a terrain factor and estimate of location variability were added. Other investigators[10] calculate the free-space field reduced by knife-edge shadow loss in hilly areas, and certain "experience factors" and later a clutter loss as a function of angle of arrival of the signal.

Sets of propagation curves have been developed by the International Radio Consultative Committee (CCIR) and by the US Federal Communication Commission (FCC). These show field strength as a function of distance for various frequency ranges, with correction factors for terrain irregularity, and estimates of location variability.

A somewhat different approach is taken by a group of Japanese investigators.[14] They used an extended series of measurements in Tokyo and its environs to develop a series of curves of median attenuation relative to free space as a function of frequency at various distances. These curves, shown in figure 1, are for an urban area in almost smooth terrain with antenna heights of 200 and 3 m. This basic prediction can then be modified by a series of correction factors to obtain a prediction for the required situation. Another study[15] compared calculated theoretical values with observed field strengths to obtain a clutter factor, C, which describes the attenuation caused by buildings and trees. This factor is sensitive to differences in urban structure, frequency and elevation angle. A parameter Γ expresses the area occupied by buildings, etc., as a percentage of the total area in a unit of 2 sq km. Figure 2 shows median values of C as a function of elevation angle for frequencies of 150 and 750 MHz and values of Γ from 1 to 50%. Figure 3 shows median values of C as a function of frequency at a constant elevation angle of 0.005r for values of Γ from 1 to 50%.

Several investigators have shown that location variability increases with increasing frequency. This relationship has been expressed mathematically in terms that agree fairly well in the lower VHF range but give estimates of standard deviation that differ by more than 10 dB at 1000 MHz. A recent report[22] summarizes much of the earlier work, and describes location variability as a function of the parameter $\Delta h/\lambda$, where λ is the radio wavelength and Δh is a measure of terrain irregularity. This relationship was developed from data that was obtained largely in non-urban areas.

A Computer Prediction Model

Some of the parameters that have been shown to be important in urban propagation are: the radio frequency, the heights of buildings and trees relative to the height of the receiving antenna, the distance from the receiving antenna to the nearest obstacles, the uniformity and density of surface structures, and the possible absorption of radio energy by such obstacles.

Since the distribution and shape of clutter surroundings is quite irregular we must consider the problems on a statistical basis. The transmitting antennas for broadcast services, and the base station antennas for mobile systems, are usually well elevated above the buildings and trees, so we may consider the dominant factors influencing propagation to homes and mobile units to be (a) terrain irregularities along the transmission path, and (b) the urban or environmental clutter near the receiving site. If, however, the transmitting antenna is not elevated well above surrounding buildings, some attenuation results from interference to the direct transmission path, and nearby buildings could block out whole areas from adequate service.

We have developed a propagation model for computerized predictions of transmission loss over irregular terrain,[23] which is applicable to broadcast and mobile services. The prediction methods are based on propagation theory, and have been compared with measurements for a wide range of frequencies, antenna heights, terrain types, and distances. Most of the data previously considered were from open areas, towns, and small cities. This model calculates transmission loss, with allowances for radio frequency, terrain irregularity, path length, and antenna elevations. To this we can now add an allowance for the additional attenuation due to the urban clutter near the receiving antenna. This allowance is a function of radio frequency, distance from the transmitter, and probably the density of urban clutter. To estimate this allowance a comparison is made with curves through measured values.

Some of the most widely used prediction curves that were drawn through data are those of the CCIR, the FCC, and those shown in figure 1. These are all empirical curves, based on measurements, and are to a considerable extent interrelated. Because these prediction curves have been widely accepted we compared values of attenuation relative to free space calculated for non-urban areas using the Longley-Rice computer model, with those read from figure 1, for an urban area. For both models we assumed rather smooth terrain with effective antenna heights of 200 m and 3 m. Values were obtained for frequencies from 100 to 3000 MHz, and for distances up to 100 km. As expected the urban curves show greater attenuation. The differences between the two models may be considered as representing the additional power loss in an urban area, and referred to as an "urban factor". The values listed in Table 1 show this factor for each frequency and distance. The urban factor, UF, increases smoothly with increasing frequency, and decreases with increasing distance from the transmitter. This relationship can be expressed quantitatively as

$$UF = 16.5 + 15 \log(f/100) - 0.12d \text{ dB}, \qquad (1)$$

with an error of less than 1 dB at all frequencies, to a distance of 70 km. At frequencies greater than 500 MHz, and distances greater than 70 km, this relationship tends to over-estimate the loss, because the attenuation decreases somewhat more rapidly with distance in this range.

Comparisons were also made between the two models at frequencies of 150 and 450 MHz with transmitter effective heights of 30, 50, 100, 200, 600, and 1000 m. The differences between the two predictions show little change with height as ht_e is increased from 30 to 600 m.

This computer prediction model, with the urban factor added, should adequately predict the median attenuation for moderately large cities in rather smooth terrain. The median attenuation is calculated as a function of distance for a desired frequency, antenna heights, and degree of terrain irregularity in both urban and non-urban areas.

There is also a place-to-place or location variability to be considered. As described in an earlier report[22] the standard deviation, σ_L, of this location variability is a function of frequency and terrain irregularity. For data from non-urban areas, with randomly located receiving antennas, this relationship is expressed as

$$\sigma_L = 6 + 0.55(\Delta h/\lambda)^{1/2} - 0.004(\Delta h/\lambda) \text{ dB}, \qquad (2)$$

where Δh is the terrain irregularity parameter and λ is the radio wavelength. In smooth to slightly hilly terrain the frequency dependence is

$$\sigma_L \simeq 5 \log f - 1 \text{ dB} \qquad (3)$$

for frequencies $\geq$ 10 MHz. This is more variability than that observed in Japan but agrees with the relationship shown by Egli.[21]

To determine the service area of a transmitting station a simple area prediction of transmission loss as a function of distance may be used as described above. However, if the terrain in an area is not homogeneous, the computer model may be used to compute attenuation from point-to-point along a large number of radials from the transmitter. When digitized terrain elevations are available the profile along each radial is computed and the attenuation to a large number of points along each radial is calculated. With this information field strength contours can then be drawn to show in detail the predicted service area. The Longley-Rice computer model[23] has been used for this purpose in automated frequency assignment procedures for the land mobile radio services in the United Kingdom.[24]

SUMMARY AND CONCLUSIONS

This paper has reviewed some of the earlier work on urban propagation including the results of measurements by many investigators, and a number of models developed for predicting transmission loss in urban conditions. Some of the more important propagation parameters have been identified. A computerized model is described for predicting median attenuation as a function of distance and for determining the service area of a transmitting station, in an urban area. Equations are also given for calculating the location variability as a function of frequency and terrain irregularity, or for rather smooth terrain as a function of frequency alone. This computer model provides a ready means for determining the service area of a transmitter for broadcast and mobile services. However, a number of questions remain, and further analysis and development are desirable.

For example, most of the urban data are from areas where the terrain itself is rather smooth. What happens in a city where the terrain is hilly? Would this modify the "urban factor"? A limited amount of data indicates that this may indeed be the case. Measurements made in Pittsburgh[13] were compared with our area prediction. The measurements at 455 and 862 MHz were made over 2 paths to distances of 16 and 32 km. For the shorter path the terrain parameter $\Delta h = 185$ m and for the longer one $\Delta h = 116$ m. This represents quite hilly terrain. For these paths the computed attenuation agreed well with the measured values, with no addition of an urban factor. This would suggest that the urban factor is also a function of terrain irregularity and decreases

Table 1. Urban Factor: A(Okumura)-A(Longley-Rice) dB

	Frequency							
d km	100	150	200	300	500	1000	2000	3000 MHz
10	16.2	17.4	20.6	22.9	26.6			
20	13.4	15.9	18.2	20.6	24.1	29.4	36.3	
30	11.5	14.3	16.4	19.1	22.7	27.4	34.0	38.3
40	10.9	13.4	15.3	17.9	21.5	26.0	31.9	35.7
50	10.0	12.8	14.8	17.5	20.7	25.3	30.7	34.2
60	9.3	12.1	13.5	16.4	19.4	24.0	29.1	32.2
70	8.6	11.2	12.8	15.3	18.2	22.5	26.2	28.8
80	8.0	10.6	12.0	14.2	16.4	20.0	22.7	24.3
90	7.3	9.4	10.7	12.0	13.8	16.9	18.5	19.4
100	6.5	7.7	8.3	10.0	11.2	13.5	14.1	15.2

$h_1 = 200$ m, $h_2 = 3$ m

as the terrain becomes more irregular. Further study, including point-to-point predictions along the two profiles, would help to clarify this question.

It would be of considerable interest to pursue the question of the effects of elevation angle at the receiving antenna. This would require a knowledge of the heights of buildings and trees relative to the height of the receiving antenna, and the distance to the nearest obstacles. When the angle is low the ray path through the surface clutter is long, causing considerable attenuation, but as the elevation angle is increased the attenuation decreases rather sharply as the path of the radio ray rises above the clutter. This suggests a possible critical angle above which the radio energy is diffracted over and around the surface obstacles.

We have tended to emphasize the effects of buildings and trees near the lower, or mobile antenna. With very high transmitting antennas this is probably the most important effect, but with antennas only 50 to 80 m high the proximity of very tall buildings has a marked effect. Recent measurements show field strength values some 15 dB lower from a transmitter in an urban area than from one in a suburban or residential area to receivers in similar surroundings.

In a higly built-up area, such as parts of Manhattan, the general propagation model described in this report cannot allow for the differences observed along radial and cross streets, and for areas that are screened by very tall buildings. Such problems would require special treatment including consideration of the specific situations involved.

REFERENCES

1. C. R. Burrows, L. E. Hunt, and A. Decino, "Ultra-short-wave propagation: mobile urban transmission characteristics". BSTJ 14, pp. 253-272, 1935.

2. R. S. Holmes, and A. H. Turner, "An urban field strength survey at thirty and one hundred megacycles". Proc. IRE 24, pp. 755-770, 1936.

3. T. I. Goldsmith, R. P. Wakeman, and J. D. O'Neill, "A field survey of television channel 5 propagation of New York Metro Area". Proc. IRE 37, pp. 556-560, 1949.

4. G. H. Brown, J. Epstein, and D. W. Peterson, "Comparative propagation measurements: TV transmission at 67.25, 288, 510 and 910 megacycles. RCA Rev. 9, pp. 177-201, 1948.

5. A. J. Aikens, and L. Y. Lacy, "A test of 450 Mc urban area transmission to a mobile receiver". IRE Proc. 38, pp. 1317-1319, 1950.

6. W. R. Young, "Comparison of mobile radio transmission at 150, 450, 900, and 3700 Mc".. BSTJ 31, pp. 1068-1085, 1952.

7. K. Bullington, "Radio propagation fundamentals". BSTJ 36, pp. 593-626, 1957.

8. G. V. Waldo, "Report on the analysis of measurements and observations New York City UHF-TV Project". IEEE Trans. BC 9, No. 2, 7-36, 1963.

9. D. W. Peterson, "Comparative study of low VHF, high VHF, and UHF television broadcasting in the New York City area". RCA Rev. 24, pp. 57-93, 1963.

10. J. Epstein, D. W. Peterson, "An experimental study of wave propagation at 850 Mc". Proc. IRE 41, pp. 595-611, 1953, also

    "A method of predicting the coverage of a television station". RCA Rev 17, pp. 571-582, 1956.

11. D. M. Black, and D. O. Reudink, "Some characteristics of mobile radio propagation at 836 MHz in the Philadelphia area". IEEE Trans. VT-21, pp. 45-51, 1972.

12. J. Dietz, "Examination of the feasibility of conventional land-mobile operations at 950 MHz. Phase I, Base to Mobile". FCC Report No. R-7102, 1971.

13. F. A. Barton, and G. A. Wagner, "What happens when 900 MHz and 450 MHz take to the hills?" Communications Mar pp. 20-24, Apr pp. 22-25, 1974. (Also

IEEE VT Conf Record 1973).

14. Y. Okumura, E. Ohmori, T. Kawano, and K. Fukuda, "Field strength and its variability in VHF and UHF land-mobile radio service". (Tokyo), Rev. Elec. Com. Lab. 16, pp. 825-873, 1968.

15. A. Kinase, "Influence of terrain irregularities and environmental clutter surroundings on the propagation of broadcasting waves in the UHF and VHF bands." NHK (Japan Broadcasting Corp.), Tech. Memo 14, pp. 1-64, 1969.

16. H. L. Kirke, R. A. Rowden, and G. I. Ross, "A vhf field strength survey on 90 mc/s". Proc. IEE 98 Part 3, pp. 343-359, 1951.

17. A. H. La Grone, "Propagation of VHF and UHF electromagnetic waves over a grove of trees in full leaf". IEEE Trans. AP-25, pp. 866-869, 1977.

18. A. G. Longley, and G. A. Hufford, "Sensor path loss measurements, analysis and comparison with propagation models". OT Report 75-74 (NTIS, Springfield VA, Access No. PB 247 638/AS), 1975.

19. J. D. Parsons, M. Henze, P. A. Ratliffe, and M. J. Withers, "Diversity techniques for mobile radio reception". IEEE Trans. VT-25 No. 3, pp. 75-85, 1976.

20. K. Bullington, "Radio propagation at frequencies above 30 MHz". Proc. IRE 35, pp. 1122-1136, 1947.

21. J. J. Egli, "Radio propagation above 40 MHz over irregular terrain". Proc. IRE 45, pp. 1383-1391, 1957.

22. A. G. Longley, "Location variability of transmission loss--land mobile and broadcast systems." OT Report 76-87, 1976 (NTIS, Springfield VA, Access No. PB 254 472).

23. A. G. Longley, and P. L. Rice, "Prediction of tropospheric radio transmission loss over irregular terrain--A computer method--1968." Essa Tech Report ERL79-ITS67, 1968 (NTIS, Springfield VA, Access No. 676 874).

24. J. Durkin, "Computer prediction of service areas for VHF and UHF band mobile radio services". IEEE Trans. VT-26, No. 4, pp. 323-327, 1977.

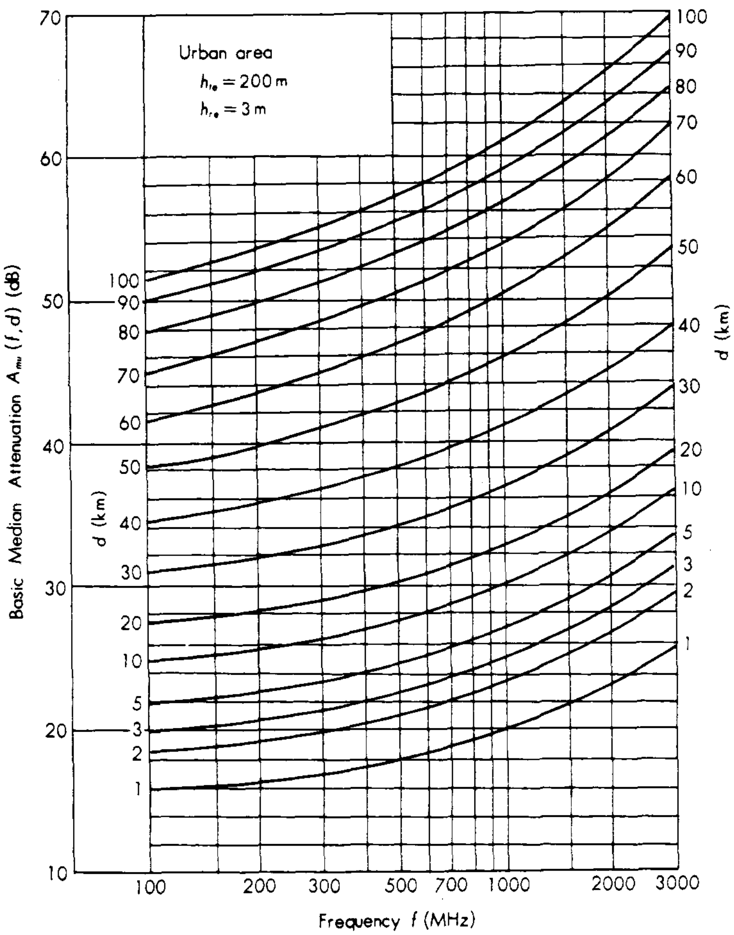

Figure 1. Prediction curve for basic median attenuation relative to free space in urban area over quasi-smooth terrain, referred to h_{te} = 200 m, h_{re} = 3m. From Okumura et al. (1968).

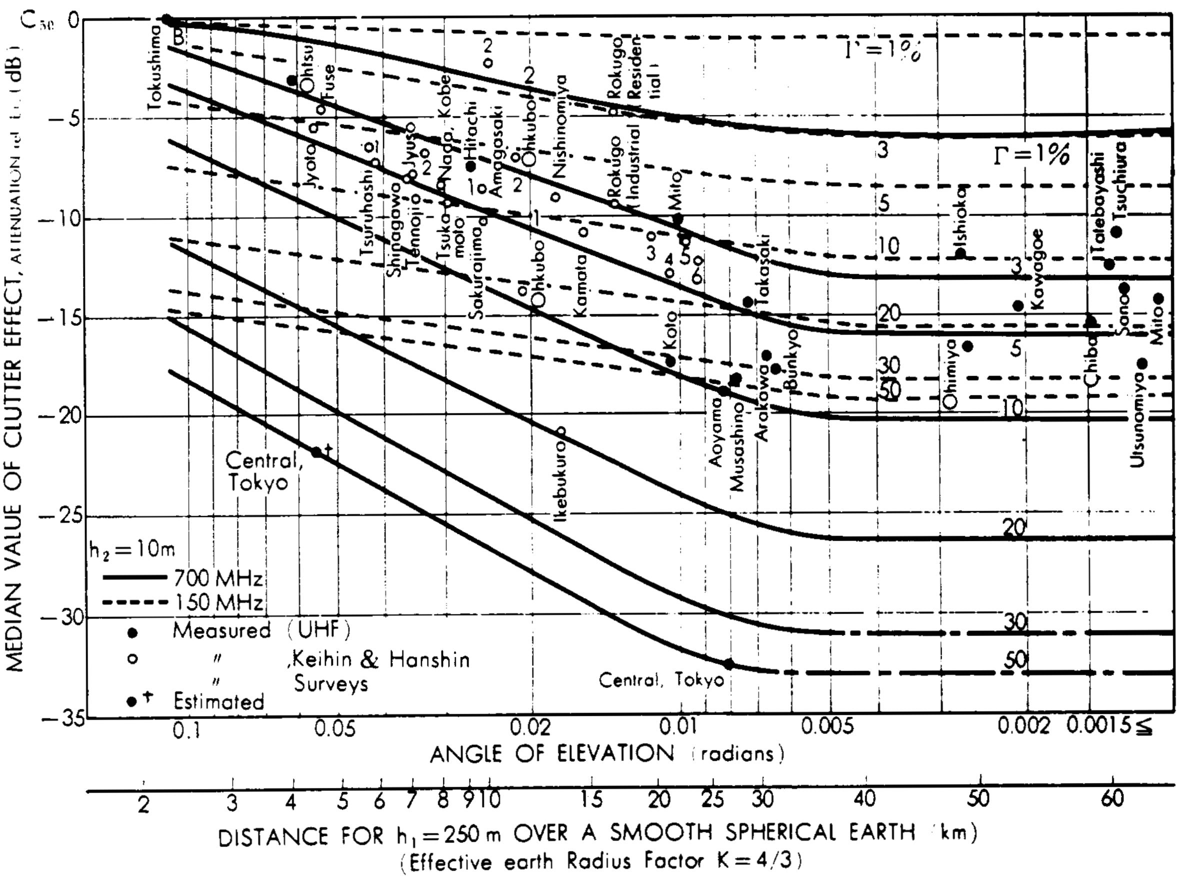

Figure 2. Median value of environmental clutter effect as a function of angle of elevation. From Kinase (1969).

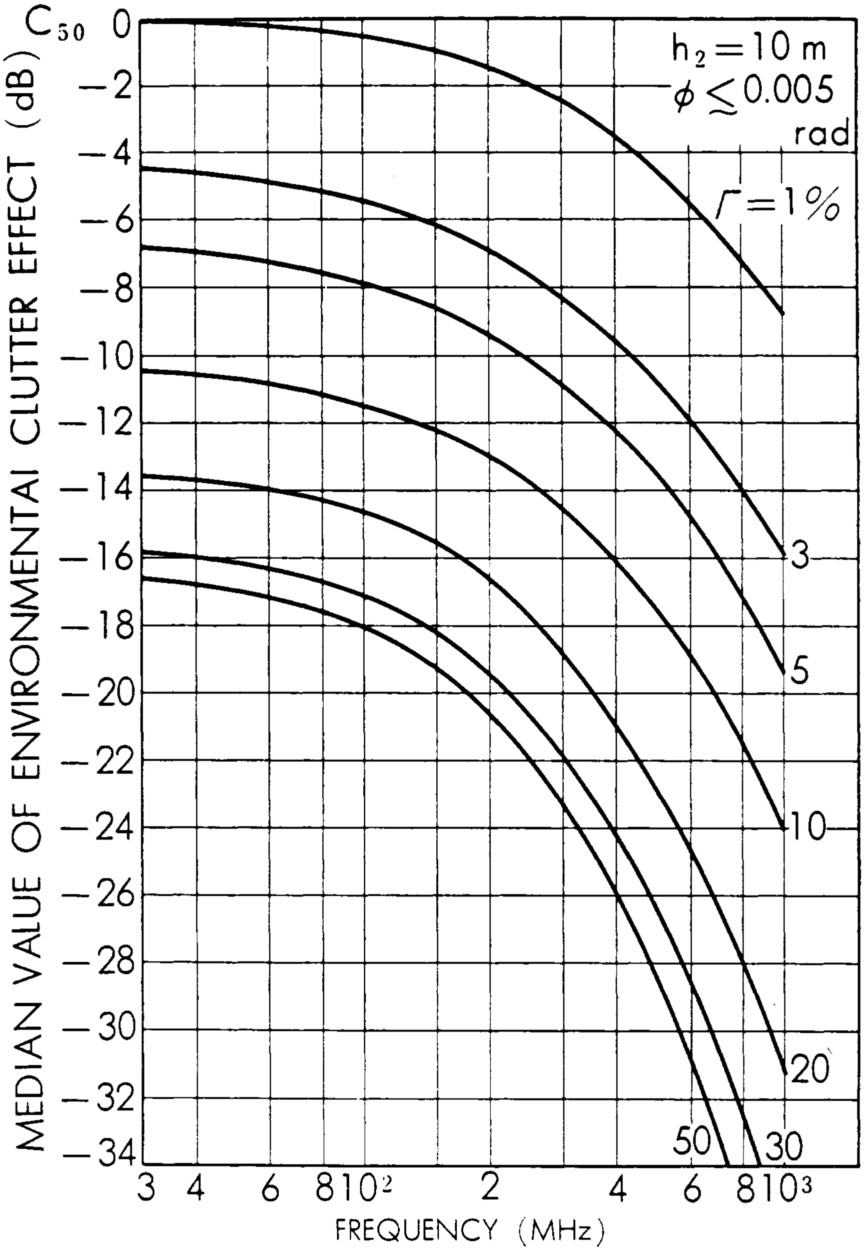

Figure 3. Median value of clutter effect as a function of frequency. From Kinase (1969).