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RADIO PROPAGATION IN URBAN AREAS

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RADIO PROPAGATION IN URBAN AREAS

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This report reviews much of the earlier work on radio propagation in urban areas, including a good deal of data from measurement programs, careful studies of multipath propagation, and techniques to reduce multipath fading. A number of investigators have also developed propagation models for use in urban areas. Most of these are largely empirical, and are presented as curves with various correction factors for antenna height, frequency and terrain irregularity.

The present report describes a model, intended for use with a digital computer, which provides a rapid means for calculating both the median attenuation and the location variability expected in urban areas. The model has been tested against measured values and is applicable for a wide variety of conditions.

Key words: Broadcast systems; irregular terrain; land-mobile systems; location variability; radio propagation; urban communications.

1. INTRODUCTION

For many years land-mobile and broadcast services were concerned mainly with the lower part of the VHF band, but higher frequencies are now 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 field strength by breaking up the destructive phasing between direct and reflected radio waves that occurs over smooth terrain. 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.

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These effects of terrain irregularity, and of surface clutter, increase with increasing frequency. 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 where a large number of propagation paths may be formed.

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 as indicated in section 3.1. 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 report 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 heights, 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.

2. 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. Such shadowing may cause great attenuation of the radio signal and wide variation from one receiver location to another. The results of a number of such programs are described. Some studies of antenna height gain, the effects of differences in polarization, and the attenuation caused by trees are also discussed.

A serious problem in urban propagation is the multipath interference, which causes the radio signal to fade rapidly and deeply, depths of 30 dB being quite common. Many investigators have studied multipath fading, describing and analyzing its characteristics, and small scale statistics, with a view to developing techniques to limit or control this fading. Several approaches have been tried, including the use of directional antennas to reduce the number of reflected signals received, but probably a more useful technique is some form of space diversity. Much of this work on multipath interference and its control is referenced and discussed below.

2.1. Results of Measurement Programs

A great many measurement programs have been carried out to determine the effects of urban conditions on radio propagation. A number of these programs are discussed in this section, with significant numerical values listed in Table 1.

The effects of shadowing and multipath in an urban area were studied more than 40 years ago by Burrows et al. (1935). They measured the signal transmitted at a frequency of 34.6 MHz from the top of a high building, in the downtown area of Boston, to a mobile receiver. The received signal was quite variable, with an average value 12 dB less than that for a flat earth and a range of ±10 dB. They concluded that transmission under urban conditions may be considered in terms of transmission over level ground plus the wave interference patterns caused by reflections from the buildings, and an additional urban attenuation that is independent of path length. At about the same time measurements were made in Ann Arbor, Michigan by Muyskens and Kraus (1933). They obtained good coverage of Ann Arbor and environs with a signal at 58.8 MHz transmitted from a tower on the university campus. They obtained better results with vertical than with horizontal polarization. Jones (1933) reported observations at 44 and 61 MHz from the Empire State

Building in New York. He reported the absorption through and around buildings as about 50% per 500 ft at 44 MHz and per 200 ft at 61 MHz. He also discussed reflection phenomena and interference patterns. During the same period Holmes and Turner (1936) made field strength surveys in the Camden-Philadelphia area at 30 and 100 MHz. They noted that the shielding effect of the thickly built-up downtown area of Philadelphia was very apparent, especially at 100 MHz, and that local conditions sometimes completely mask the relationship between terrain elevation and field strength.

Other early measurements reported by Goldsmith et al. (1949) showed that channel 5 signals in the streets of New York City were far below theoretical values and showed great variability in level, even though the terrain is essentially flat. They concluded that these effects were caused by the shadows and multipath reflections from the many high buildings. Brown et al. (1948) reported on measurements made in New York City at frequencies of 67, 288, 510, and 910 MHz from a transmitter atop the Empire State Building. 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. They noted that shadowing by hills or other obstructions has a steadily increasing effect as frequency increases, and in hilly or obstructed areas multipath effects become 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. As directional receiving antenna arrays were rotated, several positions were noted where strong signals were received, some as strong as the main signal. At the higher frequencies, multipath signals are profuse and the field may be badly distorted. In suburban areas over smooth terrain with many houses and trees, the median losses observed were 15 and 20 dB greater than calculated smooth earth values at 510 and 910 MHz, respectively. In these measurements, transmission from directional antennas at 510 and 910 MHz prevented multipath signals that would be caused by reflections from the buildings on Manhattan Island. High-gain directive receiving antennas failed to function properly in shadowed areas where the field is distorted.

Kirke et al. (1951) conducted a mobile survey of field strength in the streets of London, with the transmitter at Wrotham, Kent. Transmission at

90.8 MHz from an antenna 220 ft above ground was received on mobile units with 20 ft antennas. They found that buildings of normal height in London reduced the average field strength by 10 to 12 dB, and also that the average for one street represented the average ±4 dB for the district. In a hilly and highly populated district the contours covered a range of some 34 dB. Local variations were much greater with vertical than with horizontal polarization, especially in the vicinity of trees. With vertically polarized radiation, the trees seemed to act as screening or absorbing agents rather than as reflectors, as the field strength tends to drop near trees.

In a series of mobile measurements in the Washington, D. C. and Baltimore areas, at frequencies of 71.75 and 94 MHz, Kirby and Capps (1956) compared the the path-to-path variability in various surroundings. They noted consistently more variability at the higher frequency, with 10 to 90% ranges of 7, 13, 14, and 15 dB in overwater, wooded, urban, and farm areas, respectively, for distances up to 50 mi. These ranges correspond to standard deviations of about 3, 5.2, 5.6, and 6 dB. Glentzer (1956) performed tests at 450 MHz from four possible coverage stations in Chicago, Illinois. He observed the best coverage over a 30 mi radius from the top of the Field building, about 575 ft above ground. He also noted that coverage is affected by the shadows of tall buildings, trees, and hills. Head and Prestholdt (1960) on analyzing a large number of measurements at VHF and UHF found much more variability of field strength values in rugged than in smooth terrain, and a much wider range of values in the higher frequency band. From a study of the variation of field intensity over irregular terrain, within line of sight, Fine (1952) reported that, for a distance of 5 to 30 mi, the median measured field strength at 400 to 600 MHz is 22 dB below that for a plane earth, with a standard deviation of about 12 dB. He also observed somewhat more variability at 910 MHz than at the lower frequencies.

Measurements were made by Aikens and Lacy (1950) at 150 and 450 MHz from a transmitter on top of the telephone building in New York City to mobile receivers. In Manhattan, city of skyscrapers, all measured values were 20 to 40 dB below calculated smooth-earth values. The mean excess loss was about 30 dB on cross-town streets but 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. In Manhattan and the Bronx, Young (1952) compared mobile radio performance at 150, 450, 900, and 3700 MHz. He concluded that for mobile radio telephone both 450 and 900 MHz are somewhat preferable to 150 MHz. At frequencies above 1000 MHz performance falls off because fluctuations in received signal level occur at an audible rate when the unit moves at normal speeds. For all frequencies the losses are about 30 and 20 dB greater than smooth-earth values for urban and suburban areas, respectively, with a 10 to 90% range of values of 25 dB in urban areas.

Studies by Epstein and Peterson (1953) and (1956) of transmission at 850 MHz in an urban area show the effects of different transmitting antenna heights. The radio signal was broadcast from station WOR in Jersey City and received at points along radials to the west and southwest through a heavily congested area, and through open country. At each receiving site the maximum field between 10 and 30 ft above ground was recorded. In the congested area over quite smooth terrain, within 13 mi of the transmitter, the attenuation relative to free space was about 26 dB from a transmitting antenna height of 200 ft, and only 15 dB when the height was increased to 740 ft. Similarly, about 14 to 20 mi from the transmitter, in an area of open farm land with occasional woods and some buildings, the corresponding attenuations are 16 and 0 dB, respectively. They conclude that useful estimates of propagation loss can be made by calculating the free-space loss, the terrain shadow loss using knife-edge diffraction theory, and an additional factor which depends on the elevation of the transmitting antenna above suburban and rural areas. This attenuation factor depends on the angle of approach at the receiving antenna. This is the angle between an incoming ray from the transmitter and a tangent to the earth at the receiver. Attenuation is greater for low angles of approach since the path through intervening obstacles is longer. Based on an analysis of data at 67 and 850 MHz they define a "clutter loss" as a function of frequency and the angle of arrival of the signal. (In this study the receiving antennas were 5 to 10 ft above housetops so the clutter loss does not include a dependence on the height of the receiving antenna.) For angles of arrival greater than 2° the clutter loss is quite small but for smaller angles it becomes appreciable, more than 20 dB estimated at 900 MHz.

Bullington (1957) reported that in New York City the median field for random locations at street level is about 25 dB below the corresponding plane earth value at 150 and 450 MHz, with a 10 to 90% range of 20 dB. Similarly, Nylund (1968) reported on mobile tests at 152.6 MHz in New York City and suburban areas. In the suburbs, the base station antenna was 80 ft high while in the city transmission was from a 205 ft antenna which was partially blocked by nearby buildings. The losses in excess of calculated smooth-earth values averaged about 11 and 36 dB in the suburban and urban areas, respectively. The statistical distributions of the depth and width of fades in rural, suburban, and urban areas are similar. The average fading depth was about 10 dB with 10% of fades reaching a depth of 25 dB, and a maximum of 35 dB.

The Federal Communication Commission (FCC) carried out a large measurement program to determine the usefulness of a UHF broadcasting station in the canyon-like city of Manhattan. The plan for this program was reported by Skrivseth (1961), data from mobile measurements along radials were listed by Hutton (1963), and the results of the program were described by Waldo (1963). Transmission from the top of the Empire State Building on channels 2, 7, and 31 (about 58, 178, and 576 MHz) was measured out to a range of 25 mi, with mobile surveys along radials to the limit of measurement. Tests were also made at nearly 4000 fixed locations, half of them in Manhattan within 5 mi of the transmitter. The average attenuation relative to free space on unobstructed roofs within a range of 15 mi was about 10 dB at all three frequencies. Comparison between reception at rooftop sites and with indoor antennas showed additional loss inside buildings in Manhattan of about 30 dB at the two lower frequencies, and 26 dB at the higher one. Outside of Manhattan the building penetration losses were about 5 dB less at all three frequencies.

Peterson (1963) discussed the results of the FCC measurement program with particular attention to the mobile surveys along radials. Along a radial over smooth terrain through a residential area, the average losses at all tested frequencies were 20 dB more than calculated smooth-earth values. A second radial over highly irregular terrain showed heavy shadowing by mountains but little "clutter" loss. He stated that the use of high-gain transmitting antennas has objectionable consequences in hilly terrain, and in a heavily built-up city area the receiving antennas are immersed in a sea of clutter, with no possible use of antenna directivity or gain.

Measurements at 836 MHz in Philadelphia, reported by Black and Reudink (1972), were from a 500 ft base station antenna to a van moving at 15 mi per hr along streets in a small area in the central part of the city, and a larger area farther out. In the smaller area, variations of 20 dB or more were observed in the shadows of tall buildings, with a median path loss about 27 dB in excess of the calculated line-of-sight loss. In the larger area, where the buildings are more uniform in size, the median attenuation was about 17 dB, with an interdecile range of 13 dB. Changes in signal level with distance from 2 to 5 mi show local mean values about 24 dB below free space, with a spread of some 30 dB. Near the transmitter, the variability is greater than it is farther away. Changes in local mean level depend on the terrain, the width of the street, sizes of buildings, and whether or not the transmitter is shadowed by tall buildings. They noted that the signal along radial streets is about 10 dB higher than on cross streets, even at a distance of 3 mi from the transmitter. Measurements at 956 MHz from a base station 80 ft above ground in Washington, D. C., are reported by Deitz (1971). Signals received by a mobile unit fluctuate at a rapid rate, with fading amplitudes up to 40 dB. Along a narrow valley, Rock Creek Park, he observed about 5 dB more attenuation when the trees were in full leaf than during winter months.

Recently Barton and Wagner (1974), have reported mobile radio performance in urban, hilly terrain. They measured transmission loss at 455 and 862 MHz from a base station transmitter located on a bluff some 125 m high, in the central part of Pittsburgh. Measurements were made at Meadow Lands and at Harmarville, at distances of 32 and 16 km, respectively, over terrain with deep valleys and thick tree cover, the terrain having a peak-to-peak variation of 156 m. The average measured power received at 862 MHz was -107 and -97.5 dBm for the longer and shorter paths, respectively. This corresponds to an attenuation relative to free space of about 40 dB. Similar values were obtained at 455 MHz. They concluded that city-wide dispatch systems at 900 MHz will be practical not only in level areas but in hilly terrain as well. They also made measurements in long tunnels and under elevated roads which showed a remarkable improvement at 862 MHz over those at 450 MHz. They attributed this to more scattered signal illumination at tunnel entrances and multipath reflections along the tunnel walls at the higher frequency.

Extensive studies of land-mobile radio services in Japan have been reported by Okumura et al. (1968), and by Kinase (1969). Measurements at 200, 453, 922, 1310, 1430, and 1920 MHz, were made in the heart of Tokyo and its environs. Okumura et al. show the effects of "environmental clutter" in urban, suburban, and open areas for various frequencies, antenna heights, distances, and terrain types. They define an open area as clear for 300 to 400 m from the receiving antenna, a suburban area includes villages with scattered trees, and an urban area is a built-up city crowded with large buildings, two-story houses, and tall trees. (Until recently, the maximum building height in Japan has been 31 m.) Measured values of field strength in urban areas, over smooth terrain, are plotted versus path length for each frequency at several transmitting antenna heights with a 3 m receiving antenna. From these measurements they derived a set of curves of median attenuation relative to free space as a function of frequency for various distances in an urban area over practically smooth terrain. For a frequency range of 100 to 1000 MHz, the attenuation is 6 to 10 dB less in suburban areas, while in open areas it is 23 to 29 dB less than in an urban area. They note that the variability of the signal increases with frequency, and that there is less loss on radial than on cross streets.

Kinase (1969), reporting on measurements at 670 MHz in Tokyo and suburban areas, stated that in the heavily built-up central area of Tokyo the attenuation relative to free space is about 15 dB greater than in any other area. He reported median values of attenuation of 40, 30, and 25 dB in central urban, urban, and suburban areas. He calculated the effects of terrain irregularity to obtain a basic or theoretical field strength, and defined a clutter factor C as the ratio of observed to calculated field strength. This factor increases progressively with lower antenna heights, and with lower elevation angles, and is independent of terrain type. He noted that in suburban areas with large trees, C is comparable to that in built-up areas. Kinase defined a single parameter Γ as the area occupied by buildings, vegetation, etc., expressed as a percentage of the total area, in a unit area of 2 km^2. The clutter factor is then expressed as a function of elevation angle and radio frequency for each value of Γ. For example, in central

Tokyo, Γ = 50%, and the median clutter factors for a frequency of 700 MHz are about 22 and 32 dB at elevation angles of 0.055 and 0.008 radians, respectively. This parameter Γ can be used to describe clutter independent of such classifications as rural, small city, urban, etc.

Mobile measurements in other large cities have been reported by several investigators. In a large Russian city such measurements are reported by Trifonov et al. (1964) at frequencies of 50, 150, and 300 MHz. They observed deep fading with minima every half wavelength in the center of the city, about every wavelength at open sites within the city, and practically no interference fading at open sites outside of the city. The distribution of samples taken every half wavelength along city streets was log-normal in multilevel streets in the center of the city and Rayleigh in suburban areas, with intermediate Nakagami-Rice (Rayleigh plus a constant) distributions. They also observed less fading on wide streets and along radials than in cross streets.

Mobile measurements in Poland* at 158 and 306 MHz are reported from Warsaw, and from a town with a population of about 30,000. At 158 MHz in the heart of Warsaw attenuation due to urban clutter is 9 to 18 dB. At 306 MHz in suburban areas, 9 to 14km from the transmitter, the attenuation is 12 to 21 dB, while in a small town it is about 10 dB. In another series of tests, signals received on a 30 m antenna in suburban and denser areas from a base station 1 to 6 km away, show clutter attenuations of approximately 5, 7, 10, and 13 dB at frequencies at 34, 46, 171, and 306 MHz, respectively.

Measurements on city streets in Italy* at 146 and 475 MHz from a mobile transmitter show that the additional loss in an urban environment depends on the density and heights of the buildings and on the vertical angle of arrival of the signal. These results are quite similar to those reported by Okumura from measurements in Japan, where the attenuation increases about 30 dB as the elevation angle is reduced from 4° to nearly zero.

Measurements in West Berlin at 12 GHz are reported by Sakowski (1971). Transmission was with vertical polarization from three transmitting antennas at heights of 200, 95, and 56 m above average ground. He did not obtain adequate reception on 10 m receiving antennas but with 25 m receiving antennas the attenuation relative to free space for distances of 10 to 25 km was zero for 200 m height, 2 to 14 dB for 95 m height, and 10 to 25 dB for the 56 m

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* Private communication

antenna height.

Some of the results of these measurement programs are listed in table 1. Values shown in the table were for the most part recorded over smooth terrain and represent the attenuation caused by built-up urban and suburban developments at several frequencies. Some of the effects of irregular terrain will be considered in the section on propagation models.

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.

2.2. 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 height gain when the receiving antenna is raised from 3 to 10 m depends on the frequency. The CCIR (1974d) reported that 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 Δh increases from 10 to 500 m. (The parameter, Δh, is the difference in heights exceeded by 10% and 90% of the terrain in the range 10 km to 50 km from the transmitter.) 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

Table 1. Summary of Measured Values

Reference	ht ft	d mi	f MHz	Median A in dB	10-90% Range in dB	Description of Area
Burrows et al. (1935)		4-10	35	12*	20	Boston
Fine (1952)		5-30	400-600	22*	28	Summary of a number of US measurements
Brown et al. (1948)	1300		288	(little attenuation)		NY suburban, with many
			510	15*	20	houses and trees over
			910	20*	30	smooth terrain
Aikens and Lacy (1950)	460	3-11	150 & 450	30*	20	Manhattan, crosstown
				15*		Manhattan radial
		13-26		23*	35	hilly, suburban
Bullington (1950)			150 & 450	25*	20	Manhattan
Waldo (1963)	1300	15	58	10		New York City, at rooftop
			178	10		levels
			576	10		
Young (1952)	460	<10	150	24*	25	Manhattan and the Bronx
			450	30*		
			900	25-40*		
		>10	150	12*	25	Suburban NYC
			450	20*		
			900	24*		
Epstein and Peterson	740	0-13	850	15		Urban, Jersey City
(1953)	560			16		heavily congested
	380			18		area over smooth
	200			26		terrain
	740	14-20		0		Farmlands with trees
	560			4		and buildings
	380			11		
	200			16		
Peterson (1963)	1280	5-25	55	20*		Suburban over smooth
	1430		70	20*		terrain NYC
	1370		175	20*		
	1280		575	20*		
Nylund (1968)	80	3	153	11*	10	Suburban NJ
	205	1		36*	25	Manhattan NY
Black and Reudink (1972)	500	1-2	836	27	20	Urban Philadelphia
		2-5		24	30	Suburban Philadelphia
Barton and Wagner (1974)			455	39		Pittsburgh, rolling
	375	20	862	43		hills with deep valleys
			455	41		and thick tree cover
		10	862	40		
Okumura et al. (1968)	220 m	5 km	453	24	15	Urban Tokyo
			922	27	17	
			1317	28	18	
			1430	29	19	
Kinase (1969)	220 m		670	40		Central Urban Tokyo
				30		Urban
				25		Suburban
Kirke et al. (1951)	220		91	10-12		London, England
Private Communication	25 m					
			158	9-18		Urban Warsaw
		9-14 km	306	12-21		Suburban Warsaw
			306	10		Small town in Poland
		1-6 km	34	5		Suburban and denser
			46	7		areas in Poland
			171	10		
			306	13		
Private Communication			450-1000	9		Urban areas in SE England

*Attenuation relative to calculated smooth earth value. The others are relative to free space.

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, as noted by Kinase (1969) and Epstein and Peterson (1953). 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, as noted by Black and Reudink (1972).

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. Bullington (1957) noted 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.

Measurements in a hilly, wooded region near Detmold, Germany* at 97 MHz show the advantage of horizontal polarization in both field strength and quality of reception. The field strength was 5 dB higher and practically no reflections were observed with horizontal polarization.

Even at higher frequencies, Cunningham (1973) noted that small sector signal variations at 900 MHz are greater for vertical polarization than for either horizontal or circular polarization. The received signal typically exhibits a variation of t6 dB with vertical as compared with ±2 to 3 dB with 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 polarizations. In an urban setting, however, where multipath fading caused by scattering and

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*Private communication

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 (CCIR, 1974c). Some measurements at UHF indicate that there is slightly more depolarization for vertically than for horizontally polarized waves.

2.3. 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 by Herbstreit and Crichlow (1964) 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 at a distance of one mile. Bergman and Vivian (1970) report measurements in jungles in the mountainous terrain of Panama. At about 50 MHz, for distances of 10 to 40 km, the average jungle loss was about 18 to 20 dB below free space, with a standard deviation of about 12 dB.

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. (See reports by Pounds and La Grone, 1963; Hagn and Barker, 1970; Sturgill et al., 1967; Tamir, 1967; and others.) However, Vincent (1969) noted that scattering of VHF radio waves by trees is a significant factor, especially scattering by the tree trunks. He also measured values of the relative dielectric constant, ε, and conductivity, σ, for various frequencies. As the frequency is increased from 7 to 100 MHz ε decreases from 15 to 10 and σ increases from 3 to 20 mS/m. As frequency is further 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 large attenuations are observed between antennas separated by a few hundred meters of trees. This 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.

Trevor (1940) measured attenuation through a patch of woods 500 ft thick at 500 and 250 MHz in summer and in winter. He observed strong standing wave patterns, with 3 to 4 dB more loss with vertical than with horizontal polarization. At 500 MHz the attenuations were 19 and 15 dB in the summer and winter, respectively, with vertical polarization. At 250 MHz the corresponding winter loss was 14 dB. The loss over 5 to 6 ft scrub pines was about 8 dB more than over a smooth earth. Sofaer and Bell (1966) also reported a foliage loss of about 4 dB at frequencies of 200 and 750 MHz in dense woods, with somewhat less loss through a single line of trees. Recently, Reudink and Wazowicz (1973) reported foliage attenuations of 10 and 20 dB behind a tree-covered obstacle at 836 MHz and 11.2 GHz, respectively.

La Grone and Chapman (1961) reported the effect of a single large oak tree on propagation at 2880 MHz. At distances of 300 and 900 ft from the tree the measured attenuations were 28 and 25 dB, respectively. These results agree with those of McPetrie and Ford (1946) which show a loss of 24 dB at a distance of 7 m behind the trunk of a large tree, at a frequency of 3260 MHz. They note that, at this frequency, trees in full leaf are practically as opaque everywhere as the tree trunk itself. Megaw (1948) reported measurements at 3260 MHz over a 37 mi line-of-sight path, where a row of trees and houses near the receiver caused 25 dB attenuation below free space.

Saxton and Lane (1955) summarized the results of several sets of measurements in terms of rate of attenuation in dB per m of trees as a function of frequency. For trees in full leaf the attenuation rates range from about 0.05 to 0.5 dB/m as frequency is increased from 100 to 3000 MHz. The authors warn that this serves only as a guide to the order of magnitude, and that the rate of attenuation depends on many factors, such as the density of the woods. It should also be noted that these rates apply to situations where both antennas are in the woods.

Head (1960) considered the effects of thickets of trees between the path terminals, but with the receiver in the clear. Measurements at 485 MHz show that the signal is much attenuated near the woods, and that considerable clearing distance is required for recovery. He defined a clearing depth as the distance from the woods to the receiver. The signal then increases in proportion to the logarithm of the clearing depth, expressed in miles. At clearing depths of 0.01 and 1 mi the corresponding attenuations are 35 and 12 dB.

A paper by P. L. Rice (1971) summarizes much of the previous work on the effects of vegetation. He notes that wetting the foliage increases its conductivity sharply, which tends to produce a depolarization of the overall field; and that the motion of trees causes depolarization fading of several decibels amplitude even with quite moderate winds.

In a recent paper La Grone (1977) reports measurements over a grove of trees at frequencies of 82, 210, 633, 1280, and 2950 MHz. The transmitter antenna elevations were 424, 148, 170, 225, and 225 m for each frequency, respectively, with path lengths of about 40 to 67 km. The grove of trees was about 9 m tall. The receiver was placed successively 4.5, 19.8, 35.1, 65.6, and 111.3 m behind the trees and the receiving antennas lowered from 18.3 to 1.5 m. The measured data show a better fit to propagation over an ideal knife-edge than that over a smooth spherical earth. At short receiver distances a significant amount of the signal energy propagates through the trees so that their effective height is less than their true height. This agrees with observations by Longley and Hufford (1975) of propagation to low antennas placed near, or within, heavy pine forests. They allowed for some transmission through the trees above the critical angle of internal reflection. Assuming an effective dielectric constant ε for the woods, the critical angle θ_c, defined as

$$\sin\theta_c \equiv \varepsilon^{-\frac{1}{2}},$$

was about 110 mr or 6°. This was then taken as the maximum allowable elevation angle at the receiver. The predicted values agreed well with measurements.

2.4. Multipath Fading

In a mobile radio environment the signal fades rapidly and deeply as a result of shadowing, multipath reflections, and scattering caused by terrain, buildings and trees. Fading depths of 30 dB are quite common. The fading rate is proportional to the radio frequency and the speed at which the vehicle travels. Increasing terrain irregularity and clutter cause increasing scatter and divergence or defocusing of the radio waves. Convergence or focusing and specular reflection also playa part in multipath phenomena.

Many studies have been made of the interference caused by multipath. Brooks (1965) analyzed the multipath interference to FM transmission of television between vehicles moving over a flat earth. Young and Lacy (1950), using short pulses at 450 MHz studied the echoes resulting from transmission from a land station to a moving car in lower Manhattan. Their results show delays ranging from -3 to +12 μs, with the greatest number from 1 to 3 μs. In the interval 2 to 3 μs delay there is a 45% chance of a path within 12 dB of the main one, and an 18% chance of one within 6 dB. Such echoes may seriously limit the performance of wide-band radio systems.

Engel (1969) described the effects of multipath transmission on the propagation delay of a signal. Measurements of differences in propagation delay are used in automatic location of mobile units. If the signal is a pulse the receiver can detect the leading edge of the pulse and multipath does not impair the measurement. Engel described a procedure to determine the distribution of errors in measured values of propagation delay. Similarly, Figel et al. (1969) describe a method of vehicle location based on measurement of signal attenuation from a mobile transmitter. They developed an automatic sampler and totalizer for this purpose.

In measurements at 836 MHz in New Providence, N. J., Lee (1966) and Stidham (1966) observed a marked reduction in fading rate using a directional antenna on the mobile unit. Increasing the antenna directivity further reduced the fading rate, at a distance of about 2 mi with an average attenuation of about 33 dB below free space. Antenna orientation had little effect on the average signal level, but minimum fading occurred along and at right angles to the direction of motion and in the direction of the base station.

Many studies have been made of the characteristics of multipath. Some of these deal with the statistics of time-domain representations of multipath propagation in a mobile radio environment. For some applications such descriptions are convenient, but in other cases frequency-domain descriptions such as frequency correlation functions and correlation bandwidths are more useful. In the time domain we consider Doppler shifts, time delays, and crossing rates. Reudink (1972) noted that fading rate is proportional to vehicle speed and frequency with minima occurring at about half wavelength spacing. The rate of fading and crossing rate are the same for urban and suburban streets, and for those parallel to and perpendicular to the transmitter in New York City. In a later report, Reudink (1974) describes the amplitude variation of the signal envelope as Rayleigh distributed when measured over distances of a few 10's of wavelengths, with statistically independent phases from zero to 2π. The vehicle motion introduces a Doppler shift in every wave and the received frequency differs from that transmitted by an amount

$$w_n = kv \cos \alpha_n ,$$

where $k=2\pi/\lambda$, λ is the radio wavelength, v is the velocity of the mobile unit and α_n is the angle between the incoming wave and the direction of motion. The Doppler shift is bounded by ± kv which is much less than the carrier frequency. For example, at 1000 MHz, with a vehicle traveling 96 km/hr the Doppler shift w_n is 560 Hz. At much higher frequencies the Doppler shifts may lie well within the audio band. Signals arriving by various paths may be shifted by different amounts producing a beat between them.

Cox (1972a,b) described small-scale statistics of time delays and Doppler shifts associated with multipath propagation in a vehicle traveling along suburban streets. He notes that while the distribution of signal amplitudes at fixed delays is usually Rayleigh this is not always the case. For Doppler shifts associated with scattered fields arriving from different angles, multipath characteristics can be obtained by measuring the complex bandpass impulse response as a function of distance along the direction of travel. These measurements yield delay Doppler power profiles (scattering functions), average power delay profiles (power impulse responses), and correlation of transfer function fluctuations as a function of frequency separation. These parameters set bounds on system performance parameters such as FM-distortion, adjacent channel interference levels, error rates in digital systems, the effectiveness of some diversity systems and the accuracy of vehicle locating systems. His measurements in Middletown, New Jersey, at 910 MHz showed excess power delays of 6 or 7 μs and delay spread of about 2 μs. In suburban residential and commercial areas in relatively flat terrain the delay spread is usually less than 0.25 μs. Cox (1973) reported that measurements in New York City at the same frequency showed excess time delays of 9 to 10 μs with delay spreads of 2 μs. He describes an urban mobile radio channel as a Gaussian quasi-wide-sense stationary uncorrelated scattering channel within a 10 MHz bandwidth and for intervals along the street of up to 30 m. Usually for intervals of more than 50 to 100 m along a street the multipath scattering process becomes grossly non-stationary.

Bello (1963) has shown that since time and frequency-domain descriptions are related through Fourier transforms, frequency-domain descriptions can be obtained directly from time-domain measurements. He suggests that time-varying linear channels may be characterized in a symmetrical manner by arranging system functions in time and frequency pairs. For example, he considers a wide-sense stationary channel in terms of channel correlation functions. Jakes and Reudink (1967), considering the envelope of the received signal as a bandlimited time-varying function, obtained power spectra by taking the Fourier Transform of the autocorrelation function. The spectrum cutoff occurs at the expected value of $2v/\lambda$ Hz. Below this frequency the energy is approximately uniformly distributed.

Bello (1971) relates multipath and frequency-selective fading caused by scatter phenomena to the statistical spatial characteristics of the refractive index. When multipath causes distortion he suggests that the scatter portion of the channel be modeled as a continuum of uncorrelated scatterers.

Schmid (1970) described a model to predict the probability distribution of direct path and multipath received signal power. He calculated the probability of occurrence of distinct multipath propagation of pulse signals over irregular terrain, and with an irregular distribution of obstacles such as buildings. Pulse communication systems are generally tolerant of multipath propagation that produces a reflected pulse whose delay is small compared to the pulse width. If delays are sufficient to pose a potential problem, their amplitudes will generally have to fall within a certain range of the amplitude of the direct path signal before system degradation results.

Turin et al. (1972) performed measurements in the San Francisco Bay area with the simultaneous transmission of 100 ns pulses at 488, 1280, and 2920 MHz received at a mobile van. They state that most data are by CW techniques and show fading distributions useful for narrow band systems but are of little use for analysis and design of wide-band systems, which use as much as 10 MHz bandwidth for some radiolocation systems. They consider that the propagation medium acts as a linear filter and consider the impulse response to this filter. The procedure requires absolute timing for radio-location techniques, and they used stable, synchronized, and calibrated atomic clocks at both transmitting and receiving terminals to obtain the statistics of excess delays. The model assumes that the carrier phases of the various paths are mutually independent and uniformly distributed over the range zero to 2π. The statistics of path delays and strengths are then needed to describe the propagation medium. They assume that path strengths over local areas have a Rayleigh or Rice distribution, while over larger areas they are log-normal, and that path delays form a Poisson sequence.

Ossanna (1964) described a model for mobile radio fading based on the geometry of reflections from randomly placed vertical plane reflectors. He noted that the detailed shape and especially the sharp cutoff frequency of spectra depend critically on the angle between the direction of vehicle motion and the direction to the fixed station. As the angle increases from 0° to 90° the cutoff frequency falls from about 37 to 20 Hz. Clarke (1968) developed a scatter model in contrast to Ossanna's reflection model. This scatter model assumes that the incident field is composed of randomly phased azimuthal plane waves of arbitrary azimuthal angles. Amplitude and phase distributions, spatial correlations, amplitude spectra, and frequency correlations of the received signal are deduced. In urban areas the amplitude for a short run is Rayleigh distributed which implies that there is no significant direct component and the fields are entirely scattered. In towns and woodlands the distribution may be Rice or non-zero-mean Gaussian.

indicating a significant direct component wave. The spatial correlation of the field components is derived from the probability density function $p(\alpha)$ where α is the angle between an input component wave and the vehicle. The spectrum is derived from $p(\alpha)$ and $g(\alpha)$, the azimuthal gain of the antenna, and the coherence of two radio frequencies is derived from $p(\Delta t)$ the probability of time delays. The model then describes mobile radio fields in terms of $p(\alpha,\Delta t)$.

A knowledge of the fine structure of the radio field can be useful in determining ways to offset destructive fading. For instance, Gilbert (1965) derived statistical properties from mathematical models of multipath fading, which include energy density distribution functions. He points out the advantages of receivinq from a vertically polarized transmitting antenna on three antennas, a vertical dipole and a pair of loop antennas whose axes are perpendicular to each other and to the dipole. These receive the three field components E_z, H_x, and H_y, which are added to obtain the total energy density. Lee (1967) noted that using an energy density antenna the signal fades only about half as often as the electric field and the fades do not last as long. (The antenna receives the three field components simultaneously, and summing the squares of these signals gives an output proportional to the energy density.) Several other ways to reduce fading effects are discussed below.

2.5. Diversity Techniques

The depth of fading can be reduced by spatial diversity and predetection combining. Rustako (1967) noted that multipath fading is greatly reduced using a predetection combining receiver in four branches. Tests were made at 836 MHz in a mobile van moving at 15 mi per hr in New Providence, using a single channel and two, three, and four-channel diversity. The receiving antennas were one-fourth wavelength vertical whips with antenna spacings of 1/4, 3/4, and 5/4 λ. In all tests there was increasing improvement with increasing diversity. With four-channel diversity the fading was reduced from 30 dB to 10 dB fades for 0.1% of the distribution. Rustako et al. (1973) compared two types of predetection switching space diversity systems at 840 MHz with vehicle speeds at 80 mi per hr. The first type was conventional receiving antenna switching with a single transmitting antenna. The second type was a feedback diversity system with a single receiving antenna and two transmitting antennas which were switched by remote control from the receiver. The differences in performance were due primarily to the time delay inherent in the remote antenna switching. Parsons et al. (1973) suggest the use of a single receiver diversity system, with a predetection combiner incorporated into the receiver design, using a 3-element self-phasing antenna array. A later paper, Parsons et al. (1976), discusses the nature of the electromagnetic field in urban environments and surveys a number of diversity techniques as applied to mobile systems. The authors conclude that diversity at the mobile receiver appears to be preferable to diversity at the base station.

Bitler et al. (1973) describe a system to provide two-way diversity with diversity combining done at the base station. The mobile transceiver is very simple, while at the base station we have a multiple branch diversity receiver and diversity transmitter. Jakes (1971) noted that relatively modest use of diversity can afford savings in transmitter power of 10 to 20 dB. Such savings may be achieved using receiver diversity with either selective or maximum ratio combining of two to four branches, with selection giving somewhat better performance. The advantages of transmitter diversity are for larger bandwidths and generally are not as great as for receiver diversity.

Lee (1973) studied the correlation between signals received on two base station antennas to determine the spacing required for diversity. He noted that propagation in the direction of a line connecting the two antennas is the critical case, and requires a large separation of about 70 λ. When the incoming wave is as much as 150 away from the in-line axis the required spacing drops to 30 λ. Local scatterers near the base station tend to decrease the correlation between signals at the two antennas, and when the correlation is less than 0.7 most of the advantages of dual diversity are obtained. In a built-up urban area, where the base station is surrounded by tall buildings, the correlation is expected to be low.

Arredondo and Smith (1977) discussed diversity and vehicle speed as they affect fade durations on voice transmission, and bit-error probability for data systems.

Different base stations in a mobile radio system transmit different signals simultaneously, at the same frequency, to mobile vehicles in their respective areas or "cells". As a vehicle moves, both desired and interfering signals show local deep fading so that at times the undesired signal may be the stronger. Schiff (1972) described the use of additional antennas to provide independently fading signals. He considered three different switch diversity techniques to avoid interference.

3. 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.

3.1. 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 by Bullington (1947) describes a simplified method for calculating propagation over a smooth spherical earth, with empirical allowances for the effects of hills and buildings. In a later report, Bullington (1950) described a "shadow loss" as a function of frequency and terrain irregularity, which is added to theoretical "plane earth" values. This shadow loss increases from 0 to 35 dB as a parameter $\sqrt{H/\lambda}$ increases from 0 to 26. Here λ is the wavelength, and H is the difference in elevation between the lowest point on a path and the elevation required to provide line-of-sight conditions. In discussing the effects of buildings and trees he noted that in the range 40 to 450 MHz in Manhattan the median loss at street level is 25 dB greater than the plane earth value, with a 50 to 90% range of 10 dB. For trees and other objects he found the shadow loss to be small, but it increases with increasing frequency.

Egli (1957) used available data to develop empirical formulas, which he presented in the form of nomograms and correction curves. The basic model is the theoretical plane earth field to which he added a "terrain factor" that depends on frequency but not distance, and an estimate of location variability that is frequency dependent.

Sets of propagation curves have been developed by the International Radio Consultative Committee (CCIR) and by the US Federal Communication Commission (FCC). The CCIR (1974a) Curves for broadcasting services are presented in Recommendation 370-2. These show field strength as a function of distance for various frequency ranges, with correction factors for terrain irregularity, and estimates of location variability. The FCC curves, reported by Carey (1964), were derived from certain of the CCIR curves, with adjustments for antenna heights. These curves of field strength versus distance were adjusted downward by 9 dB to allow for the low receiving antenna heights. The curves for various transmitting antenna heights assumed a linear height gain within line of sight and are blended into the transhorizon values. Damelin and Daniels (1965) reported some modification in the FCC curves.

Burroughs (1966) compared measurements in urban areas with those in jungles. He concluded that the additional attenuation observed in both cities and jungles is frequency sensitive, but its average value is independent of both antenna height and path length. When the terrain is irregular additional problems are encountered as some allowance must be made for terrain effects. Epstein and Peterson (1953) suggest that useful predictions of propagation can be made using the calculated free-space field reduced by knife-edge shadow loss in hilly areas, and certain "experience factors" which are functions of transmitting antenna heights in congested suburban and rural areas. Later the same authors, Epstein and Peterson (1956), noted that received field strength is a function of surface clutter around the receiving site, unless the receiving antenna is above the clutter. They therefore defined a "clutter loss" as a function of angle of arrival of the radiation at the receiving site, and the frequency, assuming a linear frequency dependence. Based on the analysis of data at 67 and 850 MHz they define this clutter loss for antennas 5 to 10 ft above housetop levels. La Grone and Chapman (1961) also noted that the elevation angle toward the transmitter has a marked effect on the attenuation caused by a solid grove of pine trees. Reudink and Wazowicz (1973) calculated knife-edge diffraction to predict the loss over a tree-covered hill. The measured loss was about 10 and 20 dB greater at 836 MHz and 11.2 GHz, respectively. They suggest predicting coverage from a base station using knife-edge diffraction plus a factor for foliage. Deygout (1966) suggested calculations of multiple knife-edge diffraction to estimate the effects of a series of hills or ridges.

Gilbert (1975) describes a simple model for line-of-sight paths over random terrain. He considers all terrain irregularities as composed of conical hills, all the same height, distributed randomly over a spherical earth. He then assumed that a base station is located at the peak of a hill and calculated horizon distances, coverage area, and the probability that a random point at ground level is within line of sight of a peak at a specified distance. Neham (1974) compared several propagation models and finally chose a coverage prediction model based on the plane earth formulation described by Egli (1957) but his modification allows for irregular terrain in terms of a factor for location variability.

A somewhat different approach is taken by a group of Japanese investigators. Okumura et al. (1968) 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 h_{te} = 200 and h_{re} = 3 m. This basic prediction can then be modified by a series of correction factors to obtain a prediction for the required situation. Correction factors relating to suburban and open areas, different antenna heights, vertical angle of arrival of the signal, orientation of the street, and terrain irregularity, are given.

Kinase (1969) introduced a parameter Γ to represent the effects of environmental clutter in the vicinity of a receiving site. He calculates a reference value using theoretical values for a smooth spherical earth, single and multiple mountain ridges, cliffs, and rounded and rectangular objects. This calculated theoretical value is then compared with the observed field to

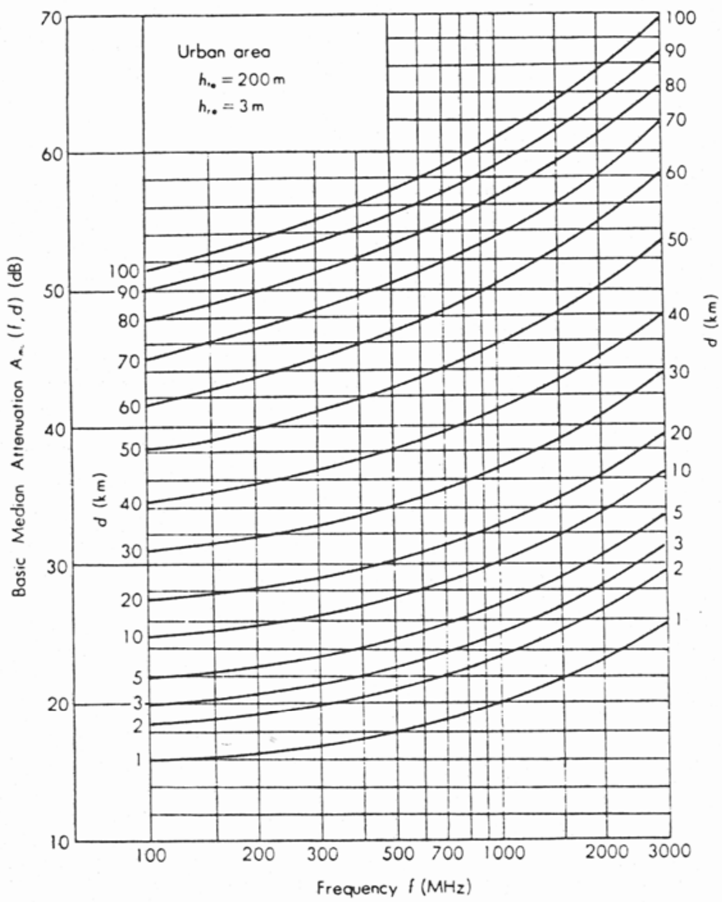

Figure 1. Prediction curve for basic median attenuation relative to free space in urban area over quasi-smooth terrain, referred to h_{te} = 200 m, h_{re} = 3 m. From Okumura et al. (1968).

obtain a clutter factor C which is independent of terrain, and describes the additional attenuation caused by buildings and trees. The clutter factor is sensitive to differences in urban structure, in frequency, and in angle of elevation. The parameter Γ expresses the area occupied by buildings, vegetation, 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 0.005 rad for values of Γ from 1 to 50%.

While Kinase (1969) observed that lowering the receiving antenna from

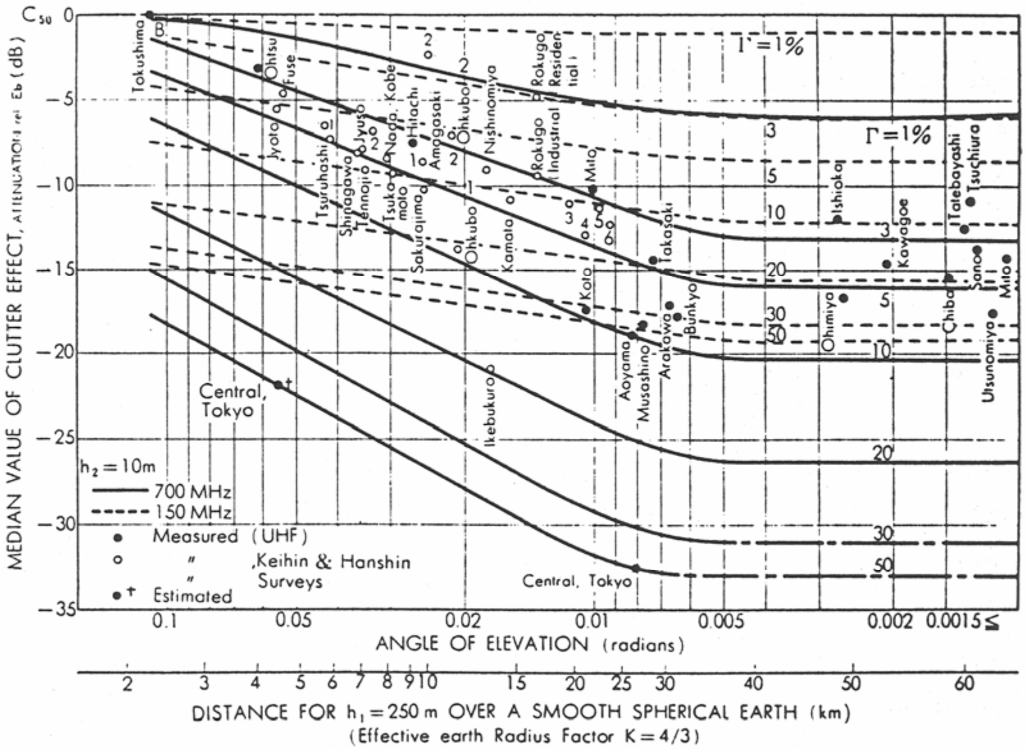

Figure 2. Median value of environmental clutter effect as a function of angle of elevation. From Kinase (1969).

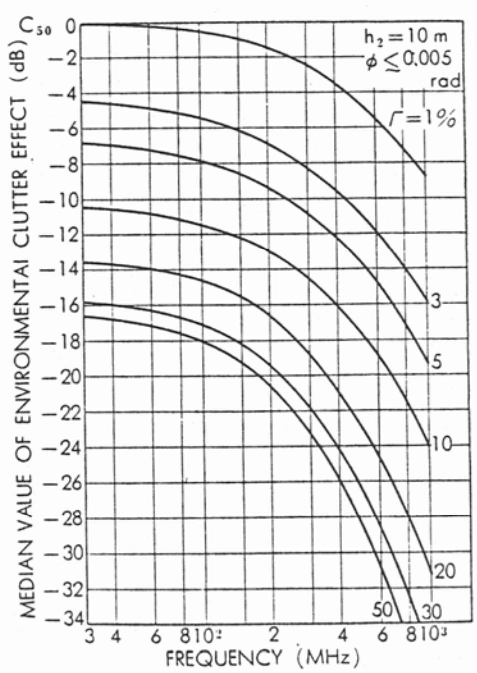

Figure 3. Median value of clutter effect as a function of frequency. From Kinase (1969).

10 m to 4 m had little effect on location variability in rural and suburban areas, one would expect greater variability at street level than on rooftops in an urban area.

A study by Dymovich (1959), which reviewed the results of early measurement programs and prediction models, suggested that field strength in towns be predicted as a function of the radiated power, the product of the antenna heights, and the reciprocal path length, with two coefficients to be determined by data. He noted that measured values of field strength are log-normally distributed, and that measurements in Leningrad at 45 MHz, with receiving antenna heights of 5.2 and 8.2 m show the same location distribution, with a 10 to 90% range of 6 dB.

Palmer (1976) reviewed much of the work on propagation in land mobile systems in the 470 to 890 MHz frequency range. He considered a number of propagation models that are currently in use. These have all been developed to fit measured data, and are expressed as functions of frequency, antenna heights, and distance, with allowances for path-to-path variability. Neham (1974) in a similar comparison of existing models noted that the various models give similar results in predicting coverage ranges for 90% of the receiver locations. For this 90% comparison he used location variability factors of 11, 14, and 17 dB in the frequency bands 25 to 50 MHz, 150 to 170 MHz and 450 to 470 MHz, respectively.

Allsebrook and Parsons (1977) report the results of measurements in three British cities, Birmingham, Bath, and Bradford. The median attenuation relative to plane earth values was 16, 18, and 35 dB at frequencies of 86, 167, and 441 MHz respectively. This urban attenuation was not dependent on distance for a range of 1 to 10 mi, but was strongly frequency dependent. They suggest a model for predicting propagation loss to mobile receivers as the sum of plane earth loss plus diffraction loss over obstacles plus a correction factor for UHF. For a hilly city, such as Bradford, they use an additional term to allow for the effects of hills.

In a recent paper Bullington (1977) presented a series of nomograms for the ready calculation of free space, plane earth, and diffraction losses. He commented that buildings are more transparent to radio waves than the earth is, so they should not cause as much attenuation as hills. On the other hand the artificial canyons caused by buildings in cities are much narrower than naturally occurring ones, which would increase the attenuation. At higher frequencies, about 1000 MHz, if trees block one's vision they are equivalent to solid obstacles.

Durkin (1977) reports a prediction model used for frequency assignment procedures for the land-mobile services in the United Kingdom. This model combines values from the CCIR (1974a) curves within line-of-sight with values calculated using the Longley and Rice (1968) model for transhorizon paths. The latter is used, with digitized terrain elevations, to calculate the attenuation to a large number of points along 72 equally spaced radials from the transmitter. Field strength contours are then drawn to show the predicted service area. He gives a comparison with measurements made at 85 MHz along one of these contours from a transmitter base in Barkway, Hertfordshire.

The various models described above have been used to estimate median attenuation in urban areas. There is also considerable variation from path-to-path about this median value. Estimates of path-to-path or location variability are based on the results of measurements, which show that the variability is log-normally distributed with a standard deviation that ranges from about 5 to 20 dB depending on the radio frequency, type of terrain, and whether the lower terminal is in open or cluttered surroundings.

Saxton and Harden (1954) reported measurements at 593.6 MHz which showed 10 to 90% ranges of 19 to 34 dB. Location variations over short distances showed smaller ranges of 2 to 4 dB at open sites, 8 to 10 dB with isolated trees and buildings, and 15 to 20 dB in a built-up area with trees and large buildings.

Report number 228, CCIR (1974b) describes a variation factor, V (50 to 90% of locations) for towns in the United Kingdom. In 121 towns at frequencies from 700 to 1000 MHz the median location variability V was 9.8 dB, while in 40 towns at 250 MHz the observed median V was 7.7 dB. These correspond to standard deviations of approximately 7.8 and 6.2 dB for the higher and lower frequency bands, respectively.

Okumura et al. (1968) observed a gradual increase in location variability with increasing frequency, the standard deviation increasing from 5 to 8 dB, and from 6.5 to 10 dB as frequency increased from 100 to 3000 MHz in the smooth urban area of Tokyo, and in the hilly suburbs, respectively. However, in highly built-up urban areas the variability may be much greater. Waldo (1963) reported standard deviations of 16, 17, and 18 dB at frequencies of 57, 177, and 576 MHz at rooftop receiving antennas in Manhattan.

Reudink and Wazowicz (1973) observed that location variability in Holmdel, New Jersey, increased with increasing distance from a base station to standard deviations of 15, and 18 to 20 dB at 836, and 11,200 MHz, respectively, at a distance of 12,000 to 18,000 ft. Neham (1974) suggests that in an urban area location variability factors of 11, 14, and 17 dB be used for frequency ranges of 25 to 50, 150 to 170, and 450 to 470 MHz to estimate 90% values. These would correspond to standard deviations of about 9, 11 and 14 dB for these three frequency ranges. The CCIR (1974c) recommends that location variability at frequencies from 450 to 1000 MHz should include an allowance for terrain irregularity. They show standard deviations of 10, 15, and 18 dB for rolling, hilly and mountainous terrain, respectively, in this frequency range.

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, Longley (1976), 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 were obtained largely in non-urban areas.

3.2. 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.

A propagation model for computerized predictions of transmission loss over irregular terrain, developed by Longley and Rice (1968), is applicable to broadcast and mobile services. This model is based on propagation theory, and has been compared with measurements for a wide range of frequencies, antenna heights, terrain types and distances. Several small modifications have been made since the development of the original prediction model. Some of these have simplified certain computations, or increased the efficiency of computer programming. But, recently, changes have been made in the original formulation of the model in the line-of-sight region. These changes are described in the appendix to this report. They provide better agreement with both theoretical and measured values, especially at UHF with one antenna elevated, than was obtained with the original method. The propagation model calculates transmission loss, with allowances for radio frequency, terrain irregularity, path length, and antenna elevations.

Most of the data previously considered were from open areas, towns and small cities. To this model we can now add an allowance for the additional attenuation due to 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 measured values are those of the International Radio Consultative Committee (CCIR), the U. S. Federal Communication Commission (FCC), and those derived by Okumura et al. (1968) and shown in figure 1. These are all empirical curves, based on measurements, and are to a considerable extent interrelated. The curves shown in CCIR Report number 567 (1974d), and intended for the land-mobile services at 150 MHz, are obtained from the curves in CCIR Recommendation 370 by adjusting the receiving antenna height from 10 m down to 3 m, an increase in attenuation of about 10 dB. The CCIR 150 MHz curve, with h_1 = 200 m and h_2 = 3 m, for rural conditions, shows about 3 dB less attenuation than the corresponding Okumura curve, for urban conditions. The CCIR curves at frequencies of 450 and 900 MHz for an urban area are taken directly from the basic Okumura curves, with 3 dB additional attenuation for a receiving antenna height of 1.5 m instead of 3 m. The FCC curves, in turn, were derived in part from the CCIR curves shown in Recommendation No 370 (1974a) assuming a linear height gain within line of sight and blending into the transhorizon region.

Because these prediction curves have been widely accepted, and are interrelated as shown, we compared values of attenuation relative to free space calculated for non-urban areas using the modified Longley-Rice computer model, with those read from Okumura's curves, 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 Okumura 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 2 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. With frequency in MHz and distance in km this relationship can be expressed quantitatively as

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

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 Okumura and Longley-Rice predictions show little change with height as the height 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

Table 2. Urban Factor: A(Okumura)-A(Longley-Rice) dB

d km	Frequency 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

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, Longley (1976), 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

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

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

$$\sigma_L \cong 5 \log f-1 \text{ dB} \tag{3}$$

for frequencies $\geq$ 10 MHz. This is more variability than that observed by Okumura in Japan but agrees with the relationship shown by Egli (1957).

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. Durkin (1977) describes using the Longley-Rice (1968) model for this purpose in automated frequency assignment procedures for the land mobile radio services in the United Kingdom.

4. SUMMARY AND CONCLUSIONS

This paper has reviewed much 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 in section 3.2 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 by Barton and Wagner (1974) were compared with the Longley-Rice (1968) area prediction. The measurements at 455 and 862 MHz were made over 2 paths at distances of 16 and 32 km. For the shorter path the terrain parameter Δh=185 m and for the longer one Δh=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 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 (Kozono and Watanabe, 1977).

In a highly built-up area, such as parts of Manhattan, a general propagation model, such as that described in section 3.2 of 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.

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APPENDIX

1977 MODIFICATION OF THE LONGLEY-RICE COMPUTER MODEL

The Longley-Rice model was originally developed for use with rather low antennas in irregular terrain, and was tested against data from measurements made with low antennas at frequencies from 20 to 100 MHz. Very few of these original test paths had terminals within radio line-of-sight. Later tests against data obtained with higher antennas and at higher frequencies showed rather poor agreement with the line-of-sight area predictions.

The present study was undertaken to improve the formulation in the area prediction model for possible line-of-sight paths. As a first step computations made using the original propagation model for smooth earth conditions were compared with values obtained from smooth earth theory. Then comparisons were made between calculated values and data obtained from measurements over irregular terrain. These studies indicate the need for several changes in the line-of-sight model for area predictions.

In considering propagation over a smooth earth, the model makes no attempt to predict the "lobing" that occurs with high antennas at UHF as a result of alternate enhancement and cancellation of the direct ray by one reflected from the surface of the ground. This "lobing" is illustrated in figure A-1, which shows field strength as a function of distance over a smooth homogeneous earth at a frequency of 100 MHz, for several antenna heights. The horizon distance is marked by a dot on each curve, while the dashed line represents the free space field. Our "area" prediction model calculates attenuation relative to free space for distances beyond that at which the field is _last_ equal to the free space field. For shorter distances we assume that the field is equal to the free space field, disregarding both the enhancement and cancellation that may occur. We made this decision because the model is intended for use over irregular terrain, where changes in the surface features break up the regular reflection pattern that occurs over smooth terrain.

In the propagation model, two distances, d_0, d_1, smaller than the smooth-earth horizon distance, d_{LS}, are chosen, and the attenuation relative to free space is calculated for each of these three distances. A smooth curve is then fitted through these three points to provide an estimate of attenuation as a function of distance within line of sight. As both frequency and antenna heights are increased the line-of-sight attenuation tends to become simply an extrapolation of the line which represents diffraction attenuation as a function of distance. The prediction model includes a weighting factor, w_0, that chooses smoothly between the calculated line-of-sight and extrapolated diffraction values of attenuation at d_0 and d_1.

Comparison of theoretical smooth-earth values with those calculated using the Longley-Rice model showed very good agreement at all tested frequencies with low antenna heights, but poor estimates for higher antennas even at a frequency of 100 MHz. Comparisons with data from measurements over irregular terrain showed that the original propagation model tended to overestimate attenuation for paths whose terminals were within radio line-of-sight.

To overcome these observed deficiencies in the original Longley-Rice, model the following changes in formulation were made:

(1) Change equation (3.16) page 3-6 as follows:

For $A_{ed} \geq 0$, define

$d_0 = 4 \times 10^{-5}\ h_{e1}\ h_{e2}\ f$ km, or $0.5\ d_L$, whichever is smaller.

$d_1 = d_0 + 0.25\ (d_L - d_0)$

For $A_{ed} < 0$, define

$d_1 = -A_{ed}/m_d$ or $0.25\ d_L$, whichever is larger.

$d_0 = 4 \times 10^{-5}\ h_{e1}\ h_{e2}\ f$ or d_1, whichever is smaller.

If $k_2 = 0$, define $k_1 = (A_{LS} - A_1)/(d_{LS} - d_1)$.

(2) Change equation (3.18) page 3-7 as follows:

In (3.18a) delete "or A_{od}, whichever is smaller".

In (3.18b) delete "or A_{1d}, whichever is smaller".

Replace (3.18c) with

$w_0 = [1 + (f\ \Delta h\ 10^{-4})/0.1\ d_{LS}]^{-1}$ for $d_{LS} \geq 10$ km

If $d_{LS} < 10$ km, set $d_{LS} = 10$ km.

Some comparisons of calculated theoretical smooth-earth values of attenuation relative to free-space loss with those calculated by the original Longley-Rice model, and as modified above, are shown in figures A-2, A-3, and A-4. These three figures show attenuation below free space as a function of distance over a smooth earth. In all three figures one antenna is at a fixed elevation, with the other at the elevations shown which range from 5 to 2000 m. The solid dots are at the horizon distance on each curve. The solid lines were drawn using the proposed modifications, and the dashed lines were calculated using the original Longley-Rice 1968 Model. The open circles are calculated points based on smooth earth theory, which are connected by smooth curves. These figures clearly show good agreement of the model with theoretical values with low antennas, and the improvement using the modified prediction with higher antennas.

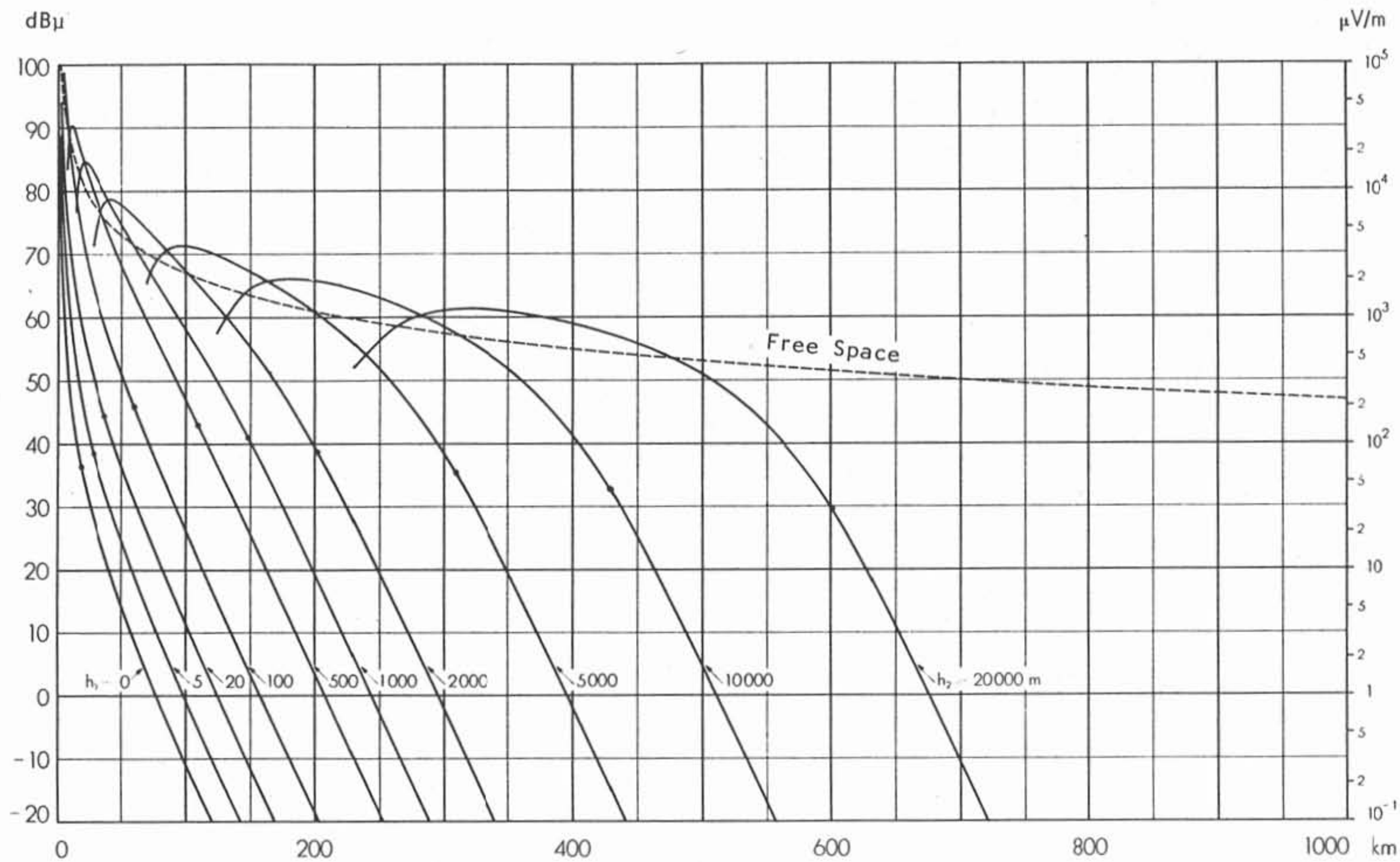

Figure A-1. Field strength (for 1 kW ERP) as a function of distance over a smooth homogeneous earth. Frequency 100 MHz, $\varepsilon = 10$, $\sigma = 10$ mS/m, $h_1 = 20$ m, $h_2 = 0$ to 20,000 m.

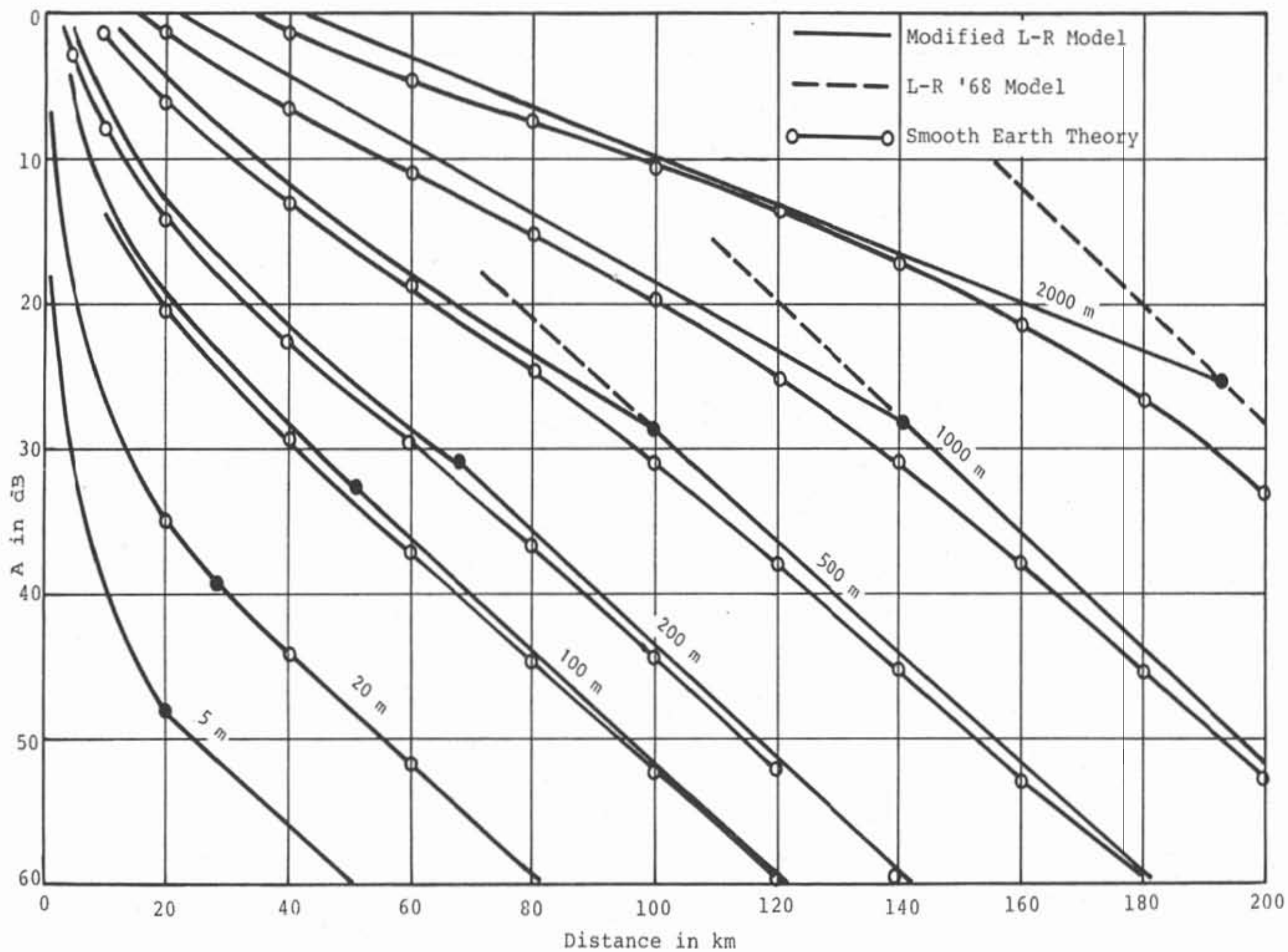

Figure A-2. Attenuation relative to free space as a function of distance over a smooth homogeneous earth. Frequency 100 MHz, $\varepsilon = 15$, $\sigma = 5$ mS/m, $h_1 = 5$ m, $h_2 = 5$ to 2000 m

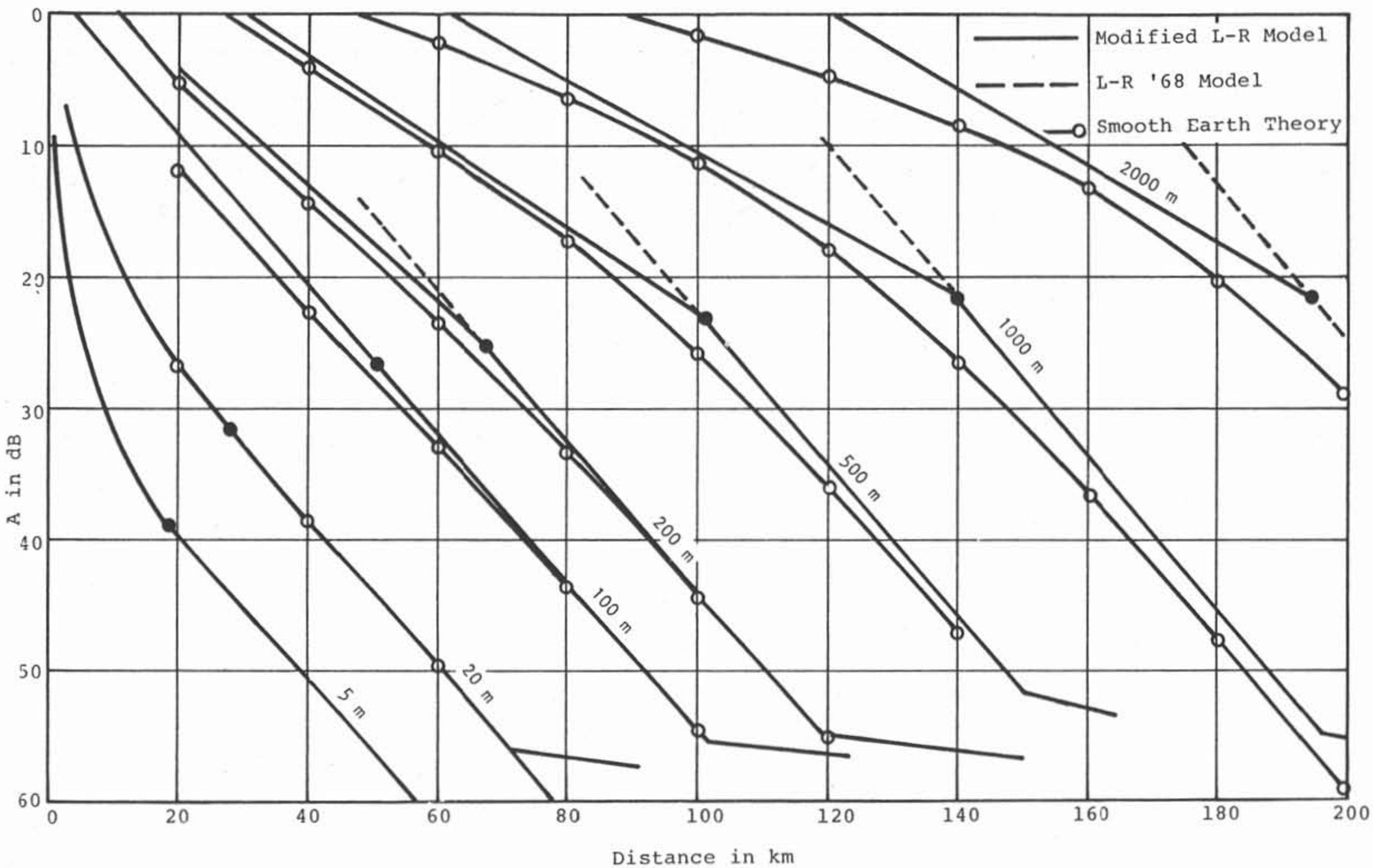

Figure A-3. Attenuation relative to free space as a function of distance over a smooth homogeneous earth. Frequency 300 MHz, $\varepsilon = 15$, $\sigma = 5$ mS/m, $h_1 = 5$ m, $h_2 = 5$ to 2000 m.

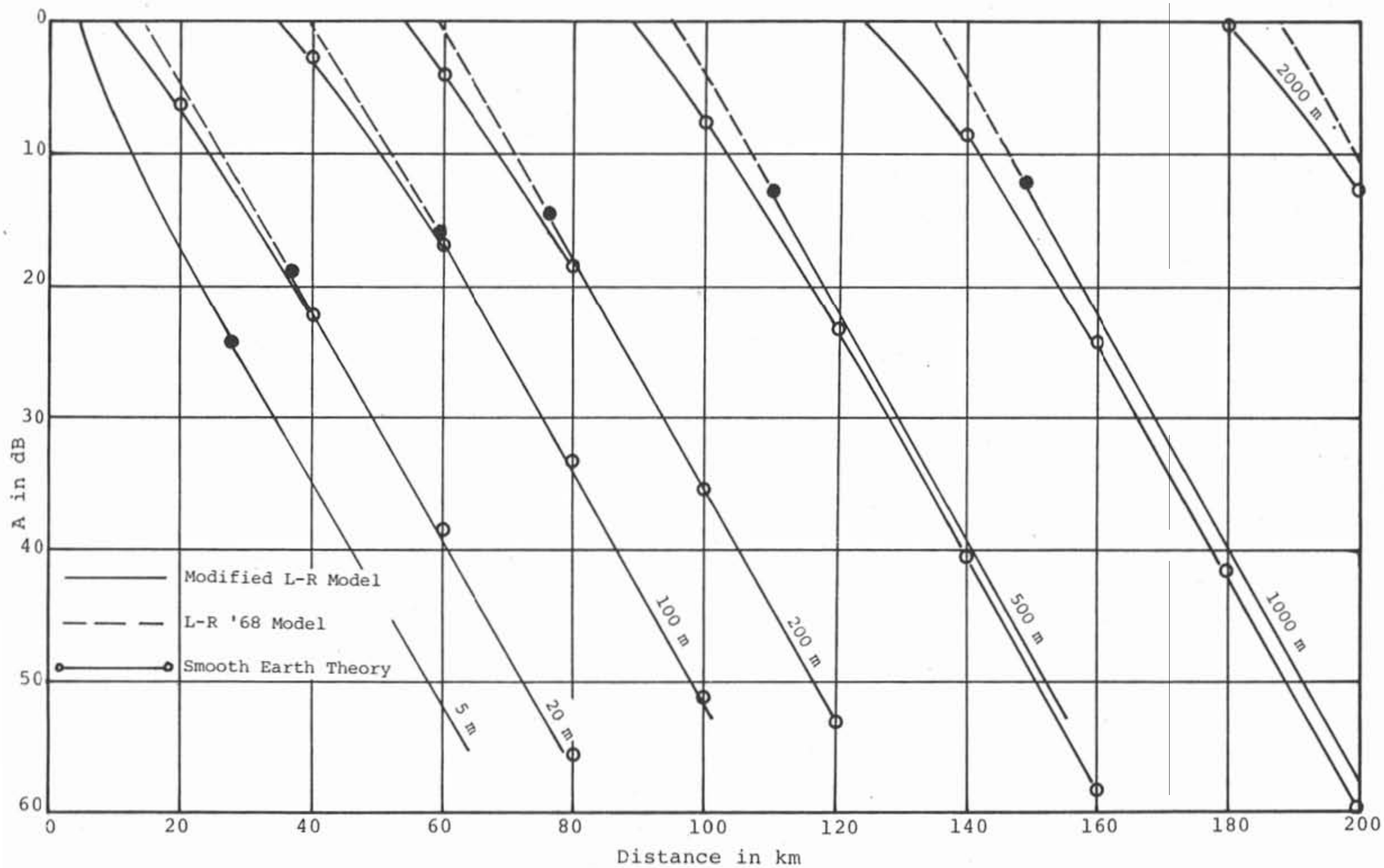

Figure A-4. Attenuation relative to free space as a function of distance over a smooth homogeneous earth. Frequency 1000 MHz, $\varepsilon = 15$, $\sigma = 5$ mS/m, $h_1 = 20$ m, $h_2 = 5$ to 2000 m.

FORM OT-29
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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.)*

This report reviews much of the earlier work on radio propagation in urban areas, including a good deal of data from measurement programs, careful studies of multipath propagation, and techniques to reduce multipath fading. A number of investigators have also developed propagation models for use in urban areas. Most of these are largely empirical, and are presented as curves with various correction factors for antenna height, frequency and terrain irregularity.

The present report describes a model, intended for use with a digital computer, which provides a rapid means for calculating both the median attenuation and the location variability expected in urban areas. The model has been tested against measured values and is applicable for a wide variety of conditions.

16. Key Words *(Alphabetical order, separated by semicolons)*
Broadcast systems; irregular terrain; land-mobile systems; location variability; radio propagation; urban communications.

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