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800-MHz Attenuation Measured In and Around Suburban Houses

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The signal levels around and within eight suburban houses were measured at 800 MHz. These measurements are needed in refining the requirements for portable-radio communication systems that can accommodate low-power radiotelephone sets. The measurements were made from an instrumentation van having an erectable 27-foot-high antenna. Large-scale distributions of the small-scale signal medians are approximately log normal. The decrease in median signal level with distance ranges from d^{-3} to $d^{-6.2}$ for the eight houses. Signal decreases as $d^{-4.5}$ for the overall data set. At 1000 feet, regressions to signal levels range from 12.5 to 37.1 dB below free-space propagation levels for locations outside and locations inside on first and second floors. In basements, regression levels at 1000 feet range from 29 to 48.2 dB below free space. For the overall data set, regression signal levels at 1000 feet are 27.7 dB below free space. For all the basements, this value is 39.6 dB. Other signal statistics are given in this paper.

I. INTRODUCTION

Portable radiotelephones that are small, sophisticated, and low power are feasible because of advances in solid-state integrated-circuit technology. The performance of systems that operate with such radiotelephones strongly depends on the attenuation of radio signals propagating into buildings. Portable radiotelephone systems may operate at frequencies near 800 MHz.

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Suburban residential areas, characterized by discrete houses with densities ranging from less than one house per acre to several houses per acre, comprise an important environment for portable radiotelephones. In the residential environment, fixed radio terminals that communicate with portable handsets could be placed outside houses at convenient locations. Such fixed terminals are referred to as portable radiotelephone terminals (PORTs).

Measurements of attenuation in and around three small buildings and a house were described in an earlier paper.[1] This paper describes attenuation measured in and around eight suburban houses. The measurements were made from an instrumentation van parked at different locations ranging from 250 to 2500 feet from the houses. A 27-foot-high erectable antenna on the van simulated an unobtrusive PORT antenna. Signal levels were received and recorded in the van from a portable signal source moved in and around the houses. Figure 1 depicts the measurement configuration.

Section II of this paper describes the instrumentation and measurement procedures. Section III contains the statistical results from the measurements.

II. THE EXPERIMENT

2.1 Instrumentation

2.1.1 Signal source

The portable signal source is the transmit section of a modified 815-MHz* handie-talkie. The transmitting antenna is a half-wavelength coaxial sleeve dipole attached to the top of the hand-held unit. Dc power is provided by a self-contained nickel-cadmium battery through a series voltage regulator. The regulator minimizes the output power drift due to normal battery discharge. The transmitter output is 0.8 watt. The output varies less than 0.3 dB and 700 Hz over continuous 1-hour periods that include ambient temperature changes of 0°C to 25°C.

2.1.2 Instrumentation van

The instrumentation van (movable PORT) is a modified motor home, containing a 5-kW ac generator. An uninterruptible power supply isolates the instrumentation from generator voltage fluctuations that otherwise could affect measurement accuracy. The van is shown in Fig. 2.

Two 27-foot antenna masts are installed in pivoting mounts so they

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* The actual frequency of the measurements is 815 MHz; however, the statistical results are not sensitive to small changes in frequency. Therefore, when frequency is referred to relative to the measurements, it will be rounded to 800 MHz.

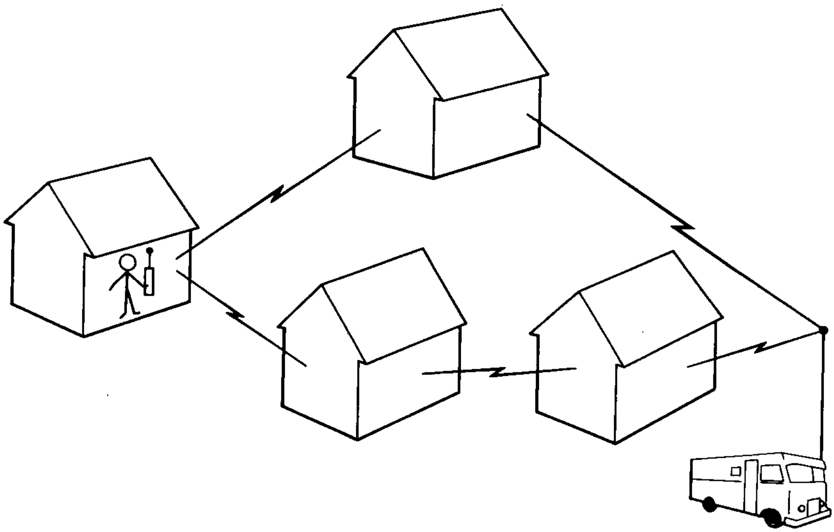

Fig. 1—Pictorial representation of the measurements.

can be stored horizontally for transport and easily erected at the test site. They are 14.2 feet apart and are adjusted to vertical using built-in bubble levels. An 815-MHz collinear receiving antenna is mounted on one mast. A bracket on the other mast holds the 815-MHz signal source at the same height to provide a reference signal for calibration purposes. The centers of the two antennas are at the same height when erected.

2.1.3 Measuring receiver

The measuring receiver is an 815-MHz FM communications receiver modified to detect the received signal envelope. The receiving antenna is a collinear array (4 dipole elements, 5.8-dB gain over dipole, 18-degree vertical beamwidth) mounted vertically at the top of the tilt-over mast on the instrumentation van. In the receiver modification, as shown in Fig. 3, an 11.7-MHz Intermediate Frequency (IF) output is extracted before the limiter, converted down to 13 kHz, bandpass filtered (BW_{3dB} = 8 kHz), and linearly detected. Figure 4 shows the modified receiver input/output characteristics. The modified receiver has a −123 dBm sensitivity for 0-dB output signal-to-noise ratio (s/n) from the linear envelope detector and a 45-dB measuring range between levels 6 dB above the noise level and 3 dB below saturation. This characteristic is linear within ± 1 dB over 35 dB. The input/output characteristics were measured before and after the field measurements to show the long-term variations in receiver performance. The standard deviation of the receiver noise level is also shown. The

Fig. 2—The instrumentation van with the receiving antenna mast and the reference signal mast erected. The center of the four-element collinear receiving antenna is 27 feet above ground at the top of the mast mounted on the right side of the van near the front. The signal source is at the top of its reference mast mounted on the left side near the rear. The center of the signal-source dipole is also 27 feet above ground.

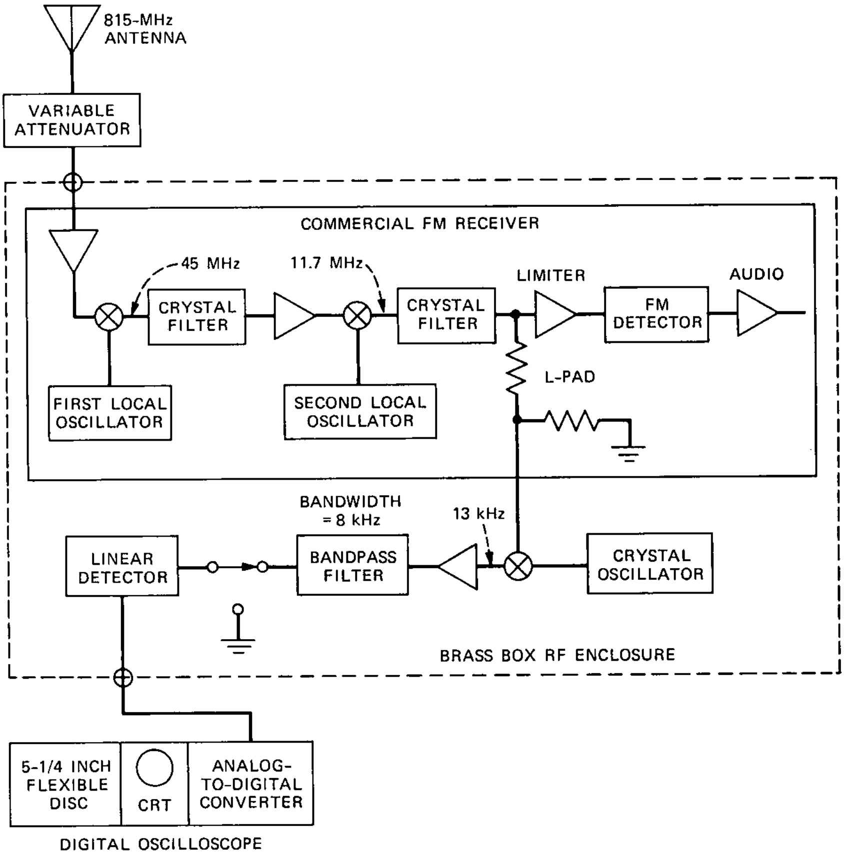

Fig. 3—Block diagram of the measuring receiver illustrating the modification to the commercial FM receiver. Also shown is the storage oscilloscope with the integral flexible-disk drive used for data acquisition.

entire receiver is enclosed in a sealed brass box to provide Radio Frequency (RF) isolation. A variable RF attenuator (see Fig. 3) reduces the input signal level in 1-dB steps to prevent overloading of the receiver.

2.1.4 Data acquisition

The analog receiver output drives a 12-bit resolution digital-storage oscilloscope and an integral 5-1/4 inch flexible disc drive for data storage. The oscilloscope is set to record 2048 samples in a 20-second measurement period. On each disc are recorded 16 tracks of 2048 samples each. Data for each parked position of the van, i.e., one PORT location, are stored on a separate disc.

The recorded data are transferred to a desktop computer. At the

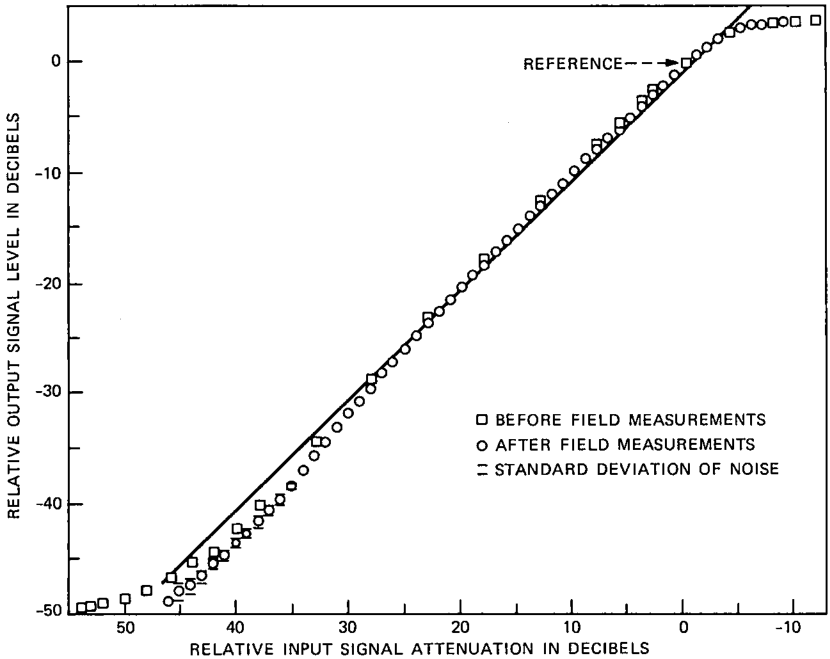

Fig. 4—Input-to-output characteristic of the modified receiver. The data from after the field measurements include the analog-to-digital conversion in the digital-storage oscilloscope. The data from before the field measurements were measured with an analog voltmeter at the output of the linear detector.

time of transfer the following steps are performed: (1) Hand-recorded log information is appended to the signal-strength data. The log information includes such items as the address of the house, the position of the van, the path azimuth, the path length, and the received input attenuator setting. (2) The data are scaled to convert the recorded signal voltages to decibels relative to 0 dB at the reference location 14.2 feet from the receiving antenna. The scaling takes into account recorded dc offsets, recorded reference levels and the received input attenuator settings. (3) Medians and cumulative distributions of signal level are calculated from the scaled data. (4) The scaled data are stored on flexible discs within the computer for further analysis.

2.2 Signal reference

For calibration purposes, both pivoting masts on the instrumentation van are used. The received signal level from the source at the reference distance is used as a calibration level to which all subsequent data measurements are referenced. The distance represents a realistic compromise between near-field antenna interactions and physical limitations on reference mast mounting.

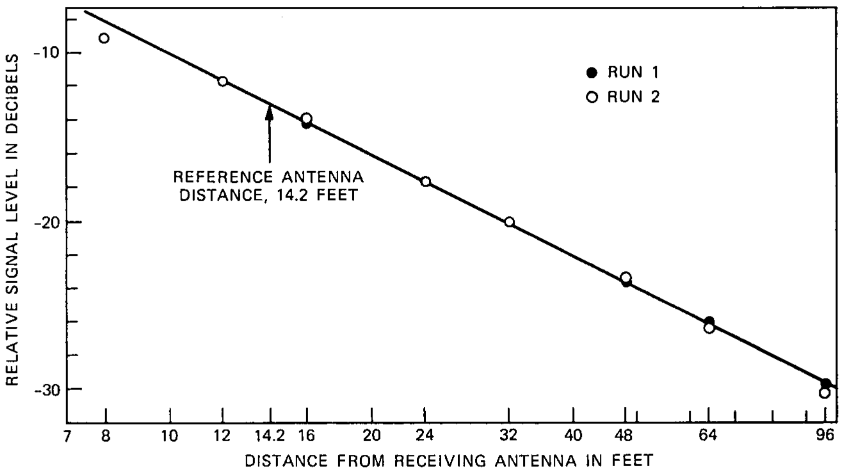

Fig. 5—Relative received signal level as a function of distance, d, between the signal source on top of a building and the receiving antenna mounted on the 27-foot van mast shown in Fig. 2. The measurements were made in an open area free of obstructions.

Relative ratio of signal level to distance from the receiving antenna is plotted in Fig. 5. The van with the receiving antenna erected was moved away from a fixed point supporting the signal source. Both antennas were at the same height. At the reference antenna distance, the received signal decreases at the $1/d^2$ rate of free-space propagation. The rate of change of the signal departs from $1/d^2$ at shorter distances because of near-field effects. At longer distances, ground reflection becomes significant.

2.3 Procedure

Van locations were selected using tax maps covering the immediate vicinity of the houses. Points were chosen approximately equally spaced in azimuth around each house for each of three radii at about 400, 800, and 1600 feet. Road layout and terrain irregularities influenced the final choices of vehicle placement.

Measurements were coordinated between the van and the measurement location over a 450-MHz voice link. The voice link comprises a 25-watt FM transceiver in the van and a 2-watt handie-talkie carried by the person making the measurements.

A typical procedure for measuring a house starts with the van parked at an appropriate position. The van location must be fairly level. If necessary, wooden ramps are put under wheels to aid in leveling. The portable transmitter is installed on its mast as a local reference source. The mast is erected and is plumbed to vertical. Similarly, the receiving antenna on the opposite side of the vehicle is erected and plumbed. Keeping both masts plumbed on the level van assures a fixed distance between the reference and receiving antennas for calibration purposes. The linear detector Intermediate Frequency (IF) input is grounded, and the dc level is adjusted and recorded on a disc track. Next, the detector input is ungrounded and the receiver RF attenuator is adjusted so the RF reference level is within the receiver operating range. This level, which serves as a calibration reference at the fixed 14.2-foot distance, is then recorded.

The signal source is removed from the mast and taken to the house for signal level measurements. The unit is hand-held[2] at arm's length for a scan height of 4.5 feet. At a selected location either outside or within the house, a 20-second raster scan[2] is made by moving the transmitter in a horizontal plane at 2.5 ft/s. The 4-foot-square scanned area consists of 12 parallel linear scans separated by 4-inch increments. During the scan period, 2048 data points are taken at a rate of 100 samples per second.

During that period, the oscilloscope is monitored to see that signal amplitudes are within the receiver operating range. If they are not, the RF input attenuation is adjusted and the scan is repeated. The remaining locations within the house and immediately outside are similarly scanned and recorded. Upon completion of the measurements, the transmitter is reinstalled on the reference mast, erected and plumbed, and the dc level and RF-signal reference level are again recorded. The closure error between beginning and ending reference-level recordings is usually less than 0.5 dB. If the closure error exceeds 1 dB, the measurements are repeated. Such high closure error occasionally occurs when the transmitter battery has discharged below the regulation limit of the voltage regulator.

2.4 Received signal characteristics and definitions

Motion of the continuous wave (CW) signal source through the 4-foot-square areas inside and outside of houses results in small-scale signal variations. The variations are caused by multipath propagation.[2,3] Inside houses and in areas shadowed from the van, where propagation is dominated by reflection and scattering, the variations in the received signal envelope are approximately Rayleigh distributed.[1,2,4,5] Received signal minima are separated by the order of one-half wavelength.[2] The medians (or means) of these small-scale variations are approximately stationary over the small areas, but the medians for areas in different rooms in a house or in different houses can be significantly different. Thus, the signal statistics can be modeled as a combination of a small-scale quasi-stationary process (multipath) superimposed on a large-scale process (shadowing). This model is like the models used for mobile radio propagation.[3,6]

The received signal $y_c(t)$ can be represented as

$$y_c(t) = L(t)R(t)e^{j\omega_c t + j\phi(t)}, \tag{1}$$

where $\omega_c = 2\pi \times 815$ MHz and t is time. Since a number of paths that are many wavelengths long are involved, as in mobile radio, it is reasonable to expect any value of $\phi(t)$ to be equally likely, i.e., $\phi(t)$ is uniformly distributed from 0 to 2π.

The envelope $R(t)$ is Rayleigh distributed with a stationary mean (or median) over small-scale areas. The median of $R(t)$ is normalized to unity.[1,2,4,5] From Ref. 1, small areas for which $R(t)$ departs significantly from Rayleigh are those with strong signal, often with no houses between the van and the measurement areas. These are areas for which $L(t)$ is large. However, low signals are the ones that limit radio system performance and are thus of most concern. Therefore, departures from Rayleigh for large signal areas will not affect the accuracy of the model for most system-analysis applications.

The large-scale random variable $L(t)$ varies from room to room, from house to house and from van location to van location. Reference 1 and Section III show that the distribution of the random variable $U(t)$, defined by

$$U(t) = 10 \log_{10} L^2(t), \tag{2}$$

can be approximated by a Gaussian (normal) distribution for most random collections of small areas; that is, $L(t)$ is log-normally distributed. Thus, the probability density of $U(t)$ is

$$f_U(u) = \frac{1}{\sigma\sqrt{2\pi}} \exp[-(u - m)^2/2\sigma^2], \tag{3}$$

where the standard deviation, σ, is in decibels. Reference 1 and Section III also show that the mean, m, varies with distance, d, between the van and the small area as

$$m \propto 10 \log_{10}(d^n), \tag{4}$$

where n is the distance dependence exponent.

Only a single parameter is needed to describe the small-scale Rayleigh-distributed signal variation. The median can be determined if somewhat over half of the samples are above the measurement threshold. The mean, however, is biased by the receiver noise level unless significantly more than half the samples are above the threshold. Therefore, medians of received signal variations for the 4-foot-square areas characterize the small-scale signal variations at different measurement locations. The lowest median signal measured was 17 dB above the receiver noise level for the data presented in Section III. The second- and third-lowest median signals measured were 19 dB and 19.5 dB above the receiver noise. All other medians were more than 20 dB above, with most around 40 dB above the noise.

III. THE MEASUREMENT RESULTS

3.1 Measurement areas

Characteristics of the houses measured are summarized in Table I. A brief description of the houses follows.

Figure 6 shows the first house, on Rambling Brook Drive. It is a 2-story English Tudor style with a full basement. The house is centrally located on a level 250- by 200-foot lot. House densities in this area are generally one per acre. This house is 5 years old, has aluminum siding on three sides, and has nonmetallic composition siding on the front. Aluminum combination storm window and screens are on all window and door openings. The metal screen covers only one-half of the area of each window opening. This house has full, foil-backed insulation in the walls. Outside this house are numerous low foundation trees. There is a dense row of 15-foot-high evergreens along the west property line, and a few large trees within an 800-foot radius. These measurements were made in April 1982.

Figure 7 shows the second house, on Winding Brook Way. It is located on a slightly raised mound on a 1-acre lot. It is a bilevel ranch house. The basement is half above ground and is part of the living area. The house has all wood siding and nonmetallic wall insulation. House densities in this area are one per acre. This house is 15 years old. Most trees and plantings in this area are the same age. The foundation plantings are medium density, with the exception of several large evergreens on the corners and in the rear near the property line. Metal screening covers all the window openings halfway. These measurements were made in May 1982.

House number 3, on Valley Point Drive, and shown in Fig. 8, is a very large, new, 2-story colonial with vinyl siding covering foil-faced sheathing. All windows are full-metal screened with the exception of sliding glass doors located in the rear. This house has a full concrete block basement and is located on a mostly level 1-acre lot. There are very large trees completely covering the rear property line, which drops off sharply into a ravine. The ravine is filled with large trees. All other houses in this area, although different in style, are constructed on 1-acre lots. For the most part, there are very few trees, except for the dense woods running behind the house and adjacent houses. These measurements were made in late May to mid-June 1982.

Figure 9 shows the fourth house, on Courtland Lane. It is an L-shaped ranch house without a basement. It is on a 75- by 100-foot lot. All surrounding lots and houses are similar, with a housing density of

Table I—Characteristics of houses in study

House	Lot Size (ft)	House Densities in Area	Exterior-Side Material	Density of Foundation Plants	Large Shrubs or Trees in Area	Metal-Window Screening	Wall-Insulation Backing
Rambling Brook	250 by 200	1 per acre	3 aluminum 1 composition	Avg.	Few	Half	Foil
Winding Brook	200 by 200	1 per acre	Wood	Avg.	Avg.	Half	Paper
Valley Point Drive	200 by 200	1 per acre	Vinyl over foil	Avg.	Many in rear	Full*	Foil
Courtland Lane	75 by 100	5 per acre	3 asbestos 1 wood	Avg. to high	Avg.	Half	Paper
Alden Lane	175 by 250	1 per acre	All brick	Avg. to low	Few, some large	Half	Paper
Monmouth Ave.	100 by 200	0.5 to 2 per acre	All brick	Avg.	Few, very large	None	Metal lath under plaster
Tallen Drive	75 by 110	5 per acre	3 asbestos 1 wood/brick	Avg.	Few	Full	Paper
Rutledge Drive	50 by 150	1 to 5 per acre	All wood	Avg.	Few	Half	Unknown

* No metal screens on rear sliding doors.

Fig. 6—The house on Rambling Brook Drive.

Fig. 7—The house on Winding Brook Way.

Fig. 8—The house on Valley Point Drive.

Fig. 9—The house on Courtland Lane.

Fig. 10—The house on Alden Lane.

about five per acre. This house has wood siding on the front and composition siding on three sides. Half of each window opening is covered with a metal screen. Wall insulation is nonfoil glass wool. There are some fairly large shrubs along the foundation and some medium-sized trees on the lot. These measurements were made in August 1982.

Figure 10 shows house number 5, on Alden Lane. It is an all-brick construction with a full basement. It is centrally located on a level lot. This house does not have foil-backed insulation and has metal half-screened windows throughout the house. It has two large, unscreened windows, one front and one rear. House densities in this area are generally one per acre. There are medium-height foundation plantings and some medium to large trees near the house. There is a large open area behind a 100-foot strip of heavy woods to the back. This strip is perpendicular to the lot. These measurements were made in late August to early September 1982.

Figure 11 shows house number 6, on Monmouth Ave. It is a large, all-brick, 2-story colonial with a full basement and is on a half-acre lot. This is an older house with metal-lath plaster walls. Vegetation density is medium around the house. The property has numerous large trees in the rear and one or two large trees in the front. Most streets in the area are tree-lined with older shade trees. This house has full-metal screening on its average-sized windows, but two very large front first-floor windows are unscreened. House densities in this area vary

Fig. 11—The house on Monmouth Avenue.

Fig. 12—The house on Tallen Drive.

considerably, but generally run from one-half to two per acre. These measurements were made in October 1982.

Figure 12 shows house 7, on Tallen Drive. It is located on a 75- by 110-foot lot in an area of homes that are all on quarter-acre lots. Siding on this house is wood and masonry on the front and asbestos on three sides. This house has full-metal screening on the front windows and partial screening on the few side windows. Wall insulation has no foil backing. Most of the foundation plantings are average-sized, and there are a few trees across the rear property line. The surrounding properties generally have a few medium-sized trees, which had just dropped their leaves. These measurements were made in mid-November 1982.

The last house measured, on Rutledge Drive, is shown in Fig. 13.

Fig. 13—The house on Rutledge Drive.

This is a very old house located on a 50- by 150-foot lot. It is a wood-sided 2-story colonial with a partial basement. Wall insulation material is unknown, but there are suggestions that the newer two-thirds of this house may have foil-backed insulation. Window sizes in this house are average and all are covered halfway with metal screening. House densities in this area are generally two or three per acre. This house has medium-to-large foundation plantings. It also has a few large trees on the property and in the area. There are two 30-foot evergreens, very dense, directly in front and a large wooden 2-car garage directly across the back of the house. These measurements were made in mid-December 1982 to January 1983.

3.2 Large-scale statistics of small-scale medians for individual houses

The data points in Figs. 14 through 21 are the medians of the measured signal envelopes from small-scale areas for each of the eight houses. That is, the data points are samples of the random variable $L(t)$ in eq. (1). Each data point represents the median level of 2048 samples of $R(t)$ taken within a 4-foot-square area at a particular location. The signal levels are in decibels relative to 0 dB at the van reference. The medians are plotted versus the distance between the van antenna and the area. Note that the independent variable, distance, is on the ordinate. The dotted line on each figure represents free-space (FS) propagation (d^{-2}) relative to 0 dB at the van reference. The measurement locations are outside (OS) the houses, in rooms on the first (1) and second (2) floors, and in the basements (B), as indicated by the different symbols on the figures. The outside locations are about 5 to 10 feet in front of the midpoints of the four outside walls of the houses.

A strong dependence of signal level on distance is evident in the data in all the figures. The straight lines, except for the free-space line, are linear-least-squares regression lines through the different groups of data as indicated. The regression lines are determined using distance as the independent variable. These lines are a good quantitative measure of the strong distance-dependent trends. The regression slopes yield the distance-dependence exponents, n, in eq. (4). One average of the median signal level for each grouping of data is given by the level at 1000 feet taken from each regression line. The distance-dependence exponents and the levels at 1000 feet are indicated on each figure. The exponents and the 1000-foot levels with the −37 dB free-space level removed are summarized in Table II.

Table II—Parameters for individual houses (vertically polarized, 27-foot antenna height)

Floor	Distance Exponent	1000 ft to Relative Free Space (dB)	1000-ft Building Attenuation (dB)	σ (dB)	F	No. of Points
Rambling Brook Drive						
OS*	−4.6	−12.5	—	8.8	51	35
1	−4.0	−18.6	6.1	7.3	54	36
2	−3.0	−16.6	4.1	4.8	54	27
B†	−3.2	−29.0	16.5	5.4	13	9
Winding Brook Way						
OS	−3.4	−20.7	—	6.2	55	40
1	−3.7	−24.0	3.3	5.4	42	20
2	−3.3	−21.4	0.7	6.0	55	40
Valley Point Drive						
OS	−5.3	−16.4	—	9.9	37	20
1	−6.2	−28.5	12.1	7.3	65	15
2	−5.7	−26.6	10.2	6.4	104	21
B	−5.5	−37.7	21.3	6.3	16	5
Courtland Lane						
OS	−6.1	−31.6	—	5.5	220	36
1	−6.0	−34.6	3.0	5.3	341	54
Alden Lane						
OS	−5.8	−32.7	—	6.0	260	40
1	−5.8	−37.1	4.4	6.6	251	50
B	−6.2	−48.2	15.5	5.0	89	10
Monmouth Avenue						
OS	−4.8	−27.6	—	5.5	115	36
1	−4.6	−32.9	5.3	6.7	34	18
2	−5.2	−35.4	7.8	6.3	77	27
B	−4.2	−42.6	15.0	6.0	16	9
Tallen Drive						
OS	−4.7	−27.7	—	5.1	165	40
1	−4.7	−30.5	2.8	4.6	202	40
B	−4.7	−39.7	12.0	4.1	121	20
Rutledge Drive						
OS	−4.1	−23.5	—	5.1	91	35
1	−4.2	−29.1	5.6	4.3	107	27
2	−3.8	−24.6	1.1	5.7	32	18
B	−4.3	−38.7	15.2	3.6	44	9

*OS = Outside.
†B = Basement.

An average attenuation at 1000 feet attributable to a building can be defined as the difference between the regression-line value outside and the regression-line value for the particular grouping of the data inside. For example, from Fig. 14 and Table II, the signal level outside at 1000 feet is −49.5 dB and the level inside for the first floor is −55.6 dB. Thus, the building attenuation for the first floor for the house on Rambling Brook Drive is 6.1 dB. Building attenuation values are also summarized in Table II.

After the regression-level trend values are subtracted from each data point in Figs. 14 through 21, there is still considerable scatter in the resulting signal-level residuals. The standard deviations, σ, of the residuals after removal of the trends are listed in Table II.

The distance dependences and signal levels are different for each floor of the same house and are significantly different between houses. Because of these differences and the considerable scatter in the data, it is reasonable to question whether the regression lines are meaningful or are only a manifestation of statistical fluctuation. This question is addressed in the next section.

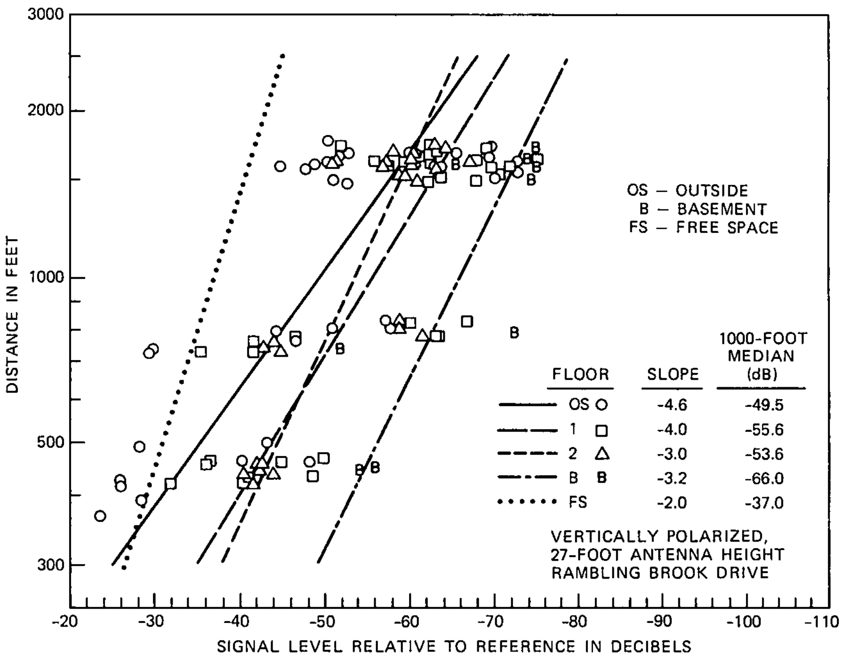

Fig. 14—Medians of the small-scale signal envelope variations for different measurement locations plotted versus distances between the locations and the van antenna. The locations are inside and outside a house on Rambling Brook Drive.

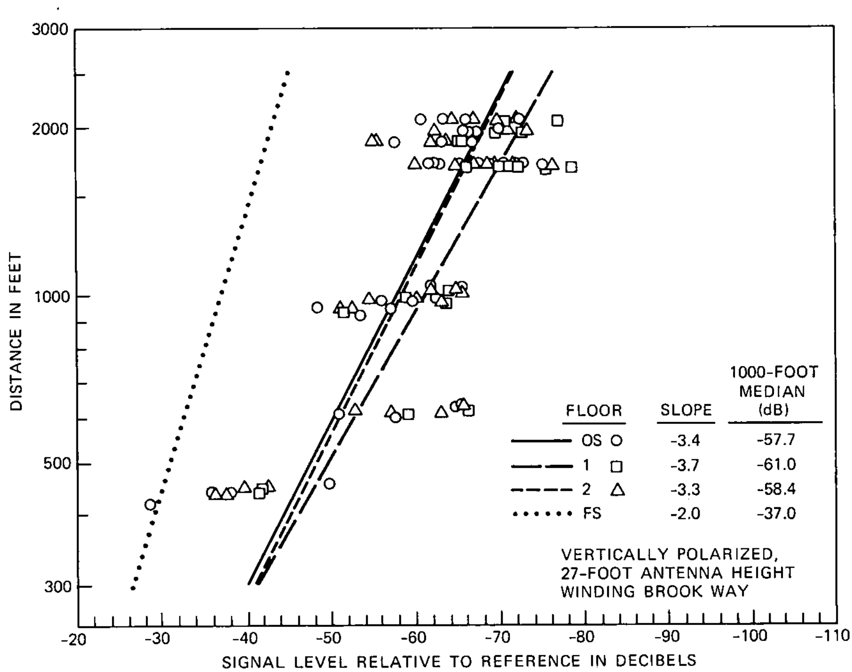

Fig. 15—Signal envelope medians and regression lines for the house on Winding Brook Way similar to those in Fig. 14.

3.2.1 Statistical significance

The statistical significance of the regression lines can be assessed using the well-known "F" test. The F values determined during the regression calculation indicate the likelihood that the line could be the result of statistical fluctuation in a sample of the same number of points taken from uncorrelated data, i.e., that the result is due to chance. In general, the larger the F number, the more significant the result. Also, for larger numbers of points, the result has the same significance at lower F numbers. Values of F and the number of data points (medians) included in the regression are also shown in Table II.

All of the F values in Table II have a very high degree of significance, except for three of the basements. The likelihood of the result being due to chance is much less than 0.1 percent for all but the three basement cases, i.e., they are significant at 0.1 percent or better. The results are significant at 0.5, 1, and 5 percent for the basements on Monmouth Avenue, Rambling Brook Drive, and Valley Point Drive, respectively. The lower significance for these three basements is largely due to the smaller number of measurements taken in them. Thus, in general the regression lines are statistically significant, that is, if more measurements were made in the same houses from different

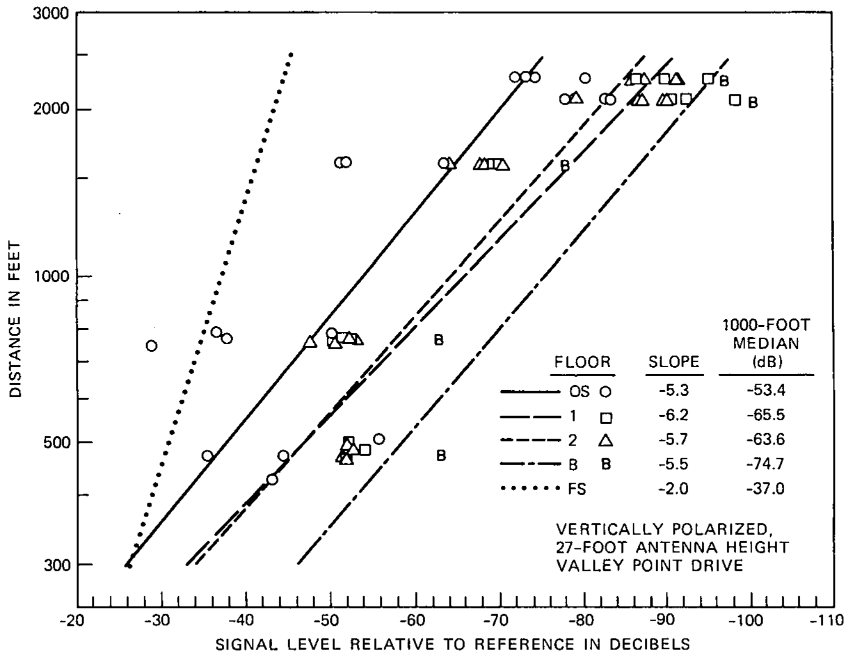

Fig. 16—Signal envelope medians and regression lines for the house on Valley Point Drive similar to those in Fig. 14.

van locations or in similar houses in similar areas, the regression lines would remain essentially the same. The differences in the parameters for the different houses must then result from actual differences in construction and in the environments around the houses. This situation indicates that the combined statistics from the eight houses will be nonhomogeneous and will depend on the number of measurements included from each kind of house and environment. It also indicates that portable-radiotelephone systems should have coverage-area sizes and possibly frequency-reuse factors tailored to fit the particular environments that are encountered. However, to make overall estimates of these system parameters, combined statistics for the eight houses are still useful.

3.2.2 The effect of the ground

Most of the distance-dependence exponents in Table II are less than −4. However, in free space the signal level would decrease as d^{-2}. Some of the additional rate of decrease can be accounted for by the presence of the ground.

For the distances involved here, the earth's curvature is negligible. At 800 MHz, the reflection coefficient phase is approximately 180 degrees for all polarizations for small angles between the propagation

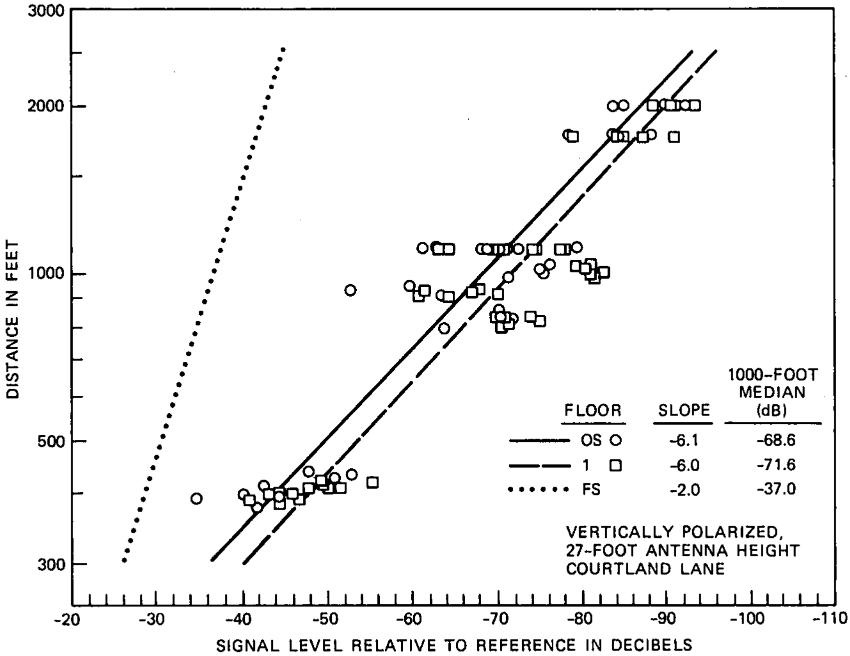

Fig. 17—Signal envelope medians and regression lines for the house on Courtland Lane similar to those in Fig. 14.

direction and the ground.[7] For propagation between two points separated a distance d and at heights h_r and h_t above flat ground, the field amplitude at one point E_r relative to the transmitted field amplitude E_t is given by[7]

$$\frac{E_r}{E_t} = \frac{2}{d} \sin \left[\frac{2\pi h_r h_t}{\lambda d} \right], \tag{5}$$

where λ is the wavelength. For large d, this approaches $E_r/E_t \; a \; d^{-2}$ or, for power, this becomes $P_r/P_t \; a \; d^{-4}$. The approximation d^{-4} is good for the parameters $h_t = 4.5$ feet, $h_r = 27$ feet, $d \gtrsim 1000$ feet, and a frequency of 800 MHz. These parameters are appropriate for the measurements outside houses and on some of the first floors. The effective exponent becomes a little greater than -4 for distances less than 1000 feet. For second floors and for short distances, not only does the approximation of the sine with its argument break down, but also the reflection coefficient angle may depart significantly from 180 degrees for some ground conditions.

All of the outside and first floor exponents in Table II are less than -4 except for one. The house on Winding Brook Way is a little higher than some of the surrounding ground. Thus, even its outside measure-

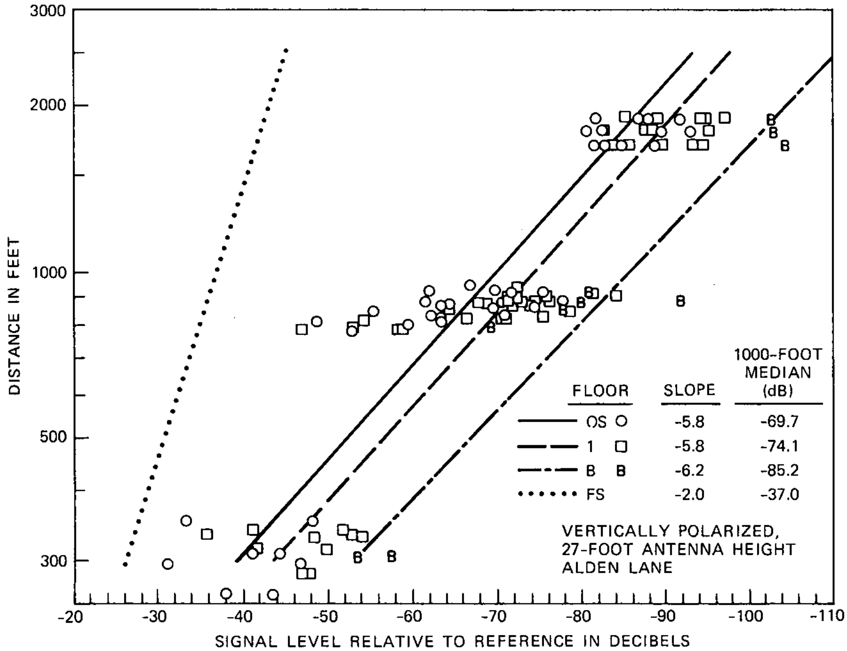

Fig. 18—Signal envelope medians and regression lines for the house on Alden Lane similar to those in Fig. 14.

ments could be more than 4.5 feet above ground. The first floor of this house is at ground level at the back side and underground at the front. For some directions, the first floor is more like a basement. Thus, the trends in the distance-dependence exponents for all the houses are consistent with the presence of the ground. The medians that are above the free-space level on some of the figures are also consistent with the presence of the ground. [Note the factor of 2, i.e., 6 dB, in eq. (5)]. The fact that some of the exponents are considerably less than −4 is probably due to the additional attenuation experienced in reflecting from and propagating through intervening houses and trees.

3.2.3 Discussion

From Table II and Figs. 14 through 21 it is evident that the attenuations into basements are significantly greater ($\approx$ 10 *dB*) than the attenuations into first and second floors. This suggests that, if basements are to be served by a portable radiotelephone system, the attenuations into basements will dominate the radio-link gain requirements.

Attenuations into the houses generally follow expectations based on the metallic content of the walls and other wall construction features. The house on Valley Point Drive, with aluminum foil in the walls and

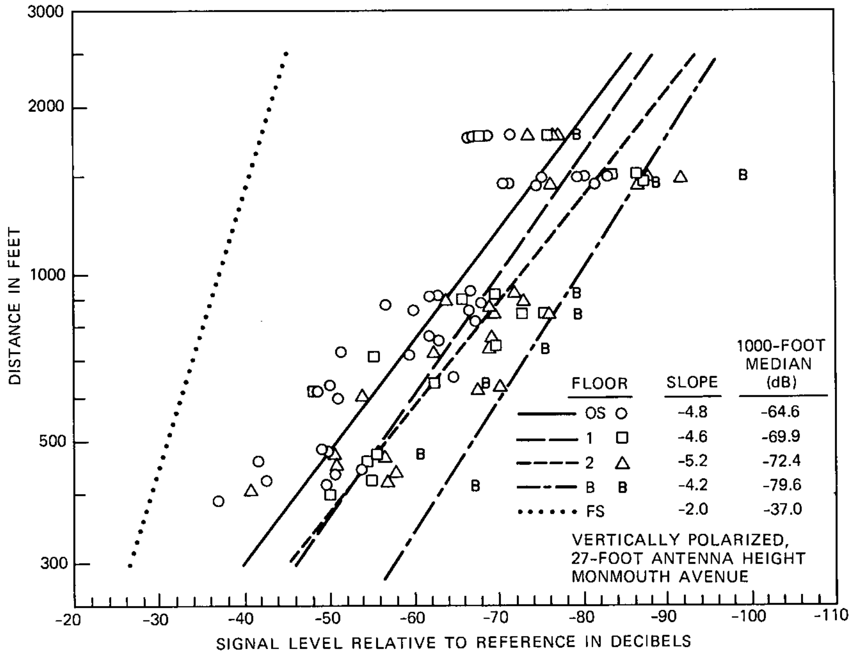

Fig. 19—Signal envelope medians and regression lines for the house on Monmouth Avenue similar to those in Fig. 14.

full metal screens, has the largest attenuations for all floors. The houses on Rambling Brook Drive, Rutledge Drive, and Monmouth Avenue form an attenuation grouping with about 6 dB less attenuation into the first floors. Two of these houses definitely have metal in their walls, with Rambling Brook having half metal screens, and Monmouth Avenue having full screens except for two very large, unscreened picture windows. Uncertainty in the construction of the older house on Rutledge Drive does not help in the attempt to explain its higher attenuation. The second-floor and basement attenuations generally follow the first-floor trends, except for the somewhat higher second-floor attenuation on Monmouth Avenue, and a somewhat higher basement attenuation on Alden Lane. All of the second-floor windows at the Monmouth Avenue address have full metal screens except for two unscreened windows in two sundeck doors. The Alden Lane basement appears to be lower in the ground than the other basements. These factors probably account for the higher attenuations. The attenuation for the first floor of the partially-screened brick house at Alden Lane is about midway between the attenuations for the metallic-walled houses and for the wooden- and composition-walled houses. The dense brick walls seem consistent with this observation. The three houses with wooden and composition walls on Winding Brook Way,

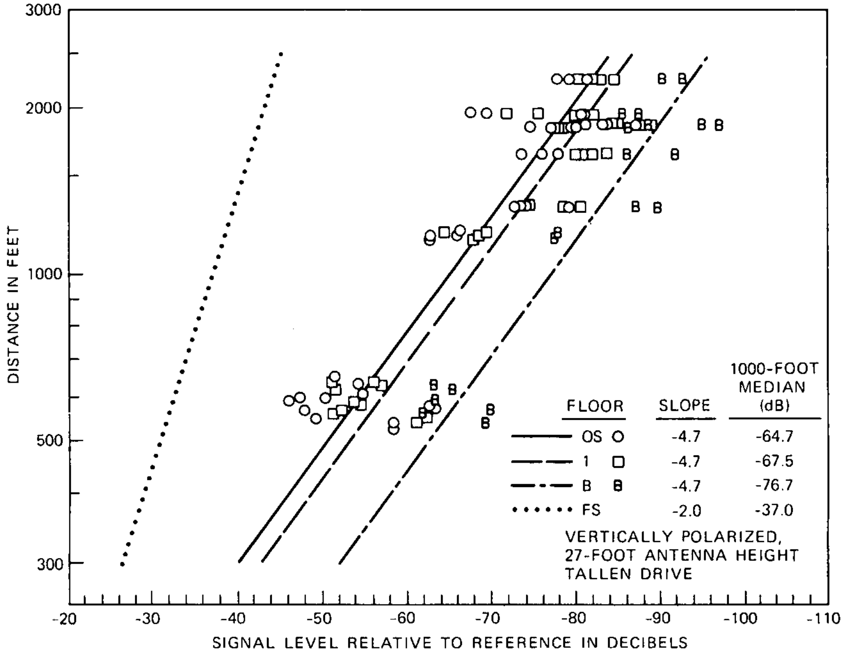

Fig. 20—Signal envelope medians and regression lines for the house on Tallen Drive similar to those in Fig. 14.

Courtland Lane, and Tallen Drive form a low attenuation group with only about 3-dB attenuation into the first floors. The second-floor attenuation on Winding Brook Way and the basement attenuation at Tallen Drive are also lower than the similar attenuations for the other houses.

The median signal levels at 1000 feet both outside and inside are not well correlated with the attenuations into the houses, i.e., with the differences between outside and inside levels. External environmental factors appear to affect the signal levels as much or more than the house constructions. For example, signal levels were lowest at Alden Lane, the brick house with only moderate attenuation. Signal levels were highest at Rambling Brook Drive, the second-highest attenuation house. The two houses in high-density housing areas, the Courtland Lane, and Tallen Drive locations, have low-signal levels. The houses with the higher-signal levels are generally in the least dense housing areas that are not heavily wooded. The significance of these general trends is difficult to assess with a small sample of eight quite different housing environments. It appears reasonable, however, that attenuation would be greater (signal levels lower) for propagation through areas with greater house densities.

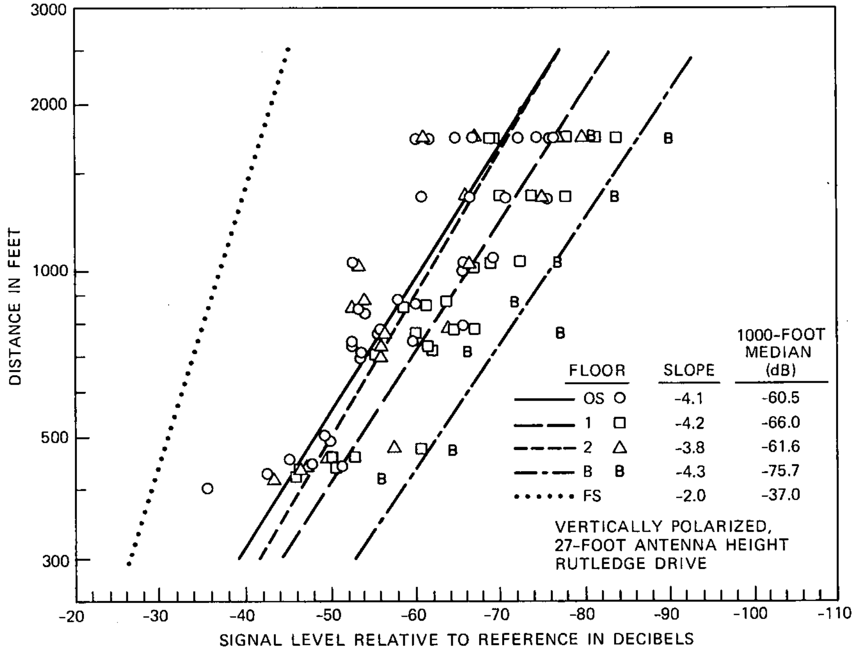

Fig. 21—Signal envelope medians and regression lines for the house on Rutledge Drive similar to those in Fig. 14.

3.3 Large-scale statistics of small-scale medians for all eight houses for different groupings of the data

3.3.1 Parameters for groupings by floors

The signal medians and distances from Figs. 14 through 21 are combined and separated into groups for outside, first floors, second floors, and basements in Figs. 22 through 25. Each symbol of these figures represents data from one of the houses, as indicated in Table III. The straight solid lines are the least-squares regression lines for all the data on a given figure. The longer dashed lines are regression lines for all the data between distances of 250 and 1250 feet. Similarly, the shorter dashed lines are regression lines for all the data between distances of 690 and 2300 feet. The dotted lines are, again, free-space lines. A regression for all the first- and second-floor data for all distances, i.e., from 250 to 2300 feet, is plotted as a long and short dashed line and a dashed and dotted line on Figs. 23 and 24 for comparison with the line for the individual floors. The nonhomogeneity of the data discussed in Section III is evident in Figs. 22 through 25.

The distance-dependence exponents, the signal levels at 1000 feet and the building attenuation at 1000 feet are listed in Table IV for the

Table III—Symbol legend for Figs. 22 through 25

Symbol	House under test
○	Rambling Brook Drive
□	Winding Brook Way
△	Valley Point Drive
*	Courtland Lane
●	Alden Lane
■	Monmouth Avenue
▲	Tallen Drive
+	Rutledge Drive

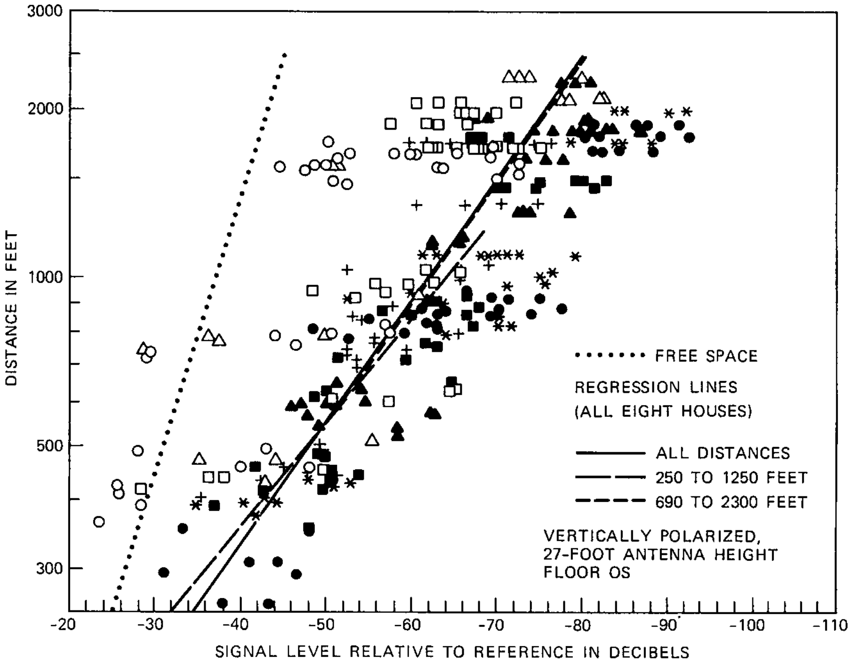

Fig. 22—Medians of the small-scale signal envelope variations for different measurement locations plotted versus distances between the locations and the van antenna. The locations are outside of the eight houses. Signal levels are with respect to 0 dB at the signal reference. Regression lines are drawn for all the outside data from all eight houses for all distances and for two subsets of the outside data.

regression lines in Figs. 22 through 25. The small negative values for building attenuation at 1000 feet for the second floors merely indicate that the average of the median signal levels for the second floors were slightly larger than the average of the levels outside at 4.5 feet above ground. This is reasonable since the second floors are less obstructed by intervening houses and are affected somewhat differently by the ground [see eq.(5)]. The F parameter and number of data points in

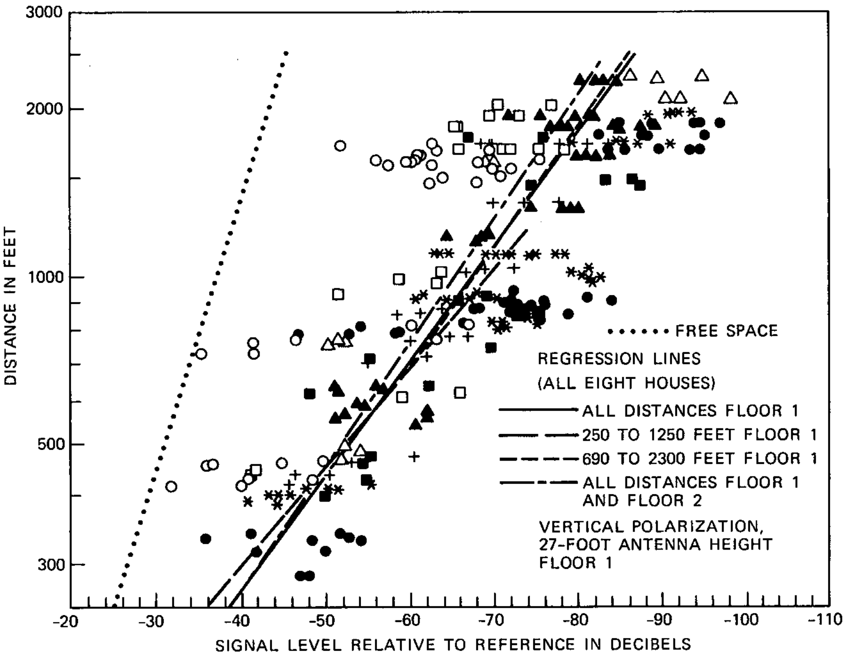

Fig. 23—Signal envelope medians and regression lines for the data from the first floors for all eight houses similar to those in Fig. 22. In addition, the regression line is included for all the first- and second-floor data combined.

each regression are also listed in the table. For these data groupings by floors, the regression is significant well below the 0.1-percent level readily available in F tables.[8] Thus, even though the data sets are nonhomogeneous, the regressions to the data appear very good. Table IV also includes the standard deviations, σ, of the residual signal levels after subtracting out the regression-line values at the same distances, i.e., after removing the trends.

All the signal medians for all houses and all floors (including outside data) are plotted in Fig. 26. Because of the high density of points, no attempt has been made to separate any of the data groupings in that figure. The solid regression line is for all the data. The dashed line is for all of the floors for distances between 250 and 1250 feet. The regression line for all floors and for distances between 690 and 2300 feet is indistinguishable from the solid line for all the data. Parameters for all the floors combined are also listed in Table IV. The F values for these data groupings are also significant well below 0.1 percent.

The distance-dependence exponents are generally less than −4 and range down to −5.5. The overall value for all the data is −4.5. In general, for all the groupings by floors, the signal levels decrease faster with distance for the first few hundred feet than for the greater

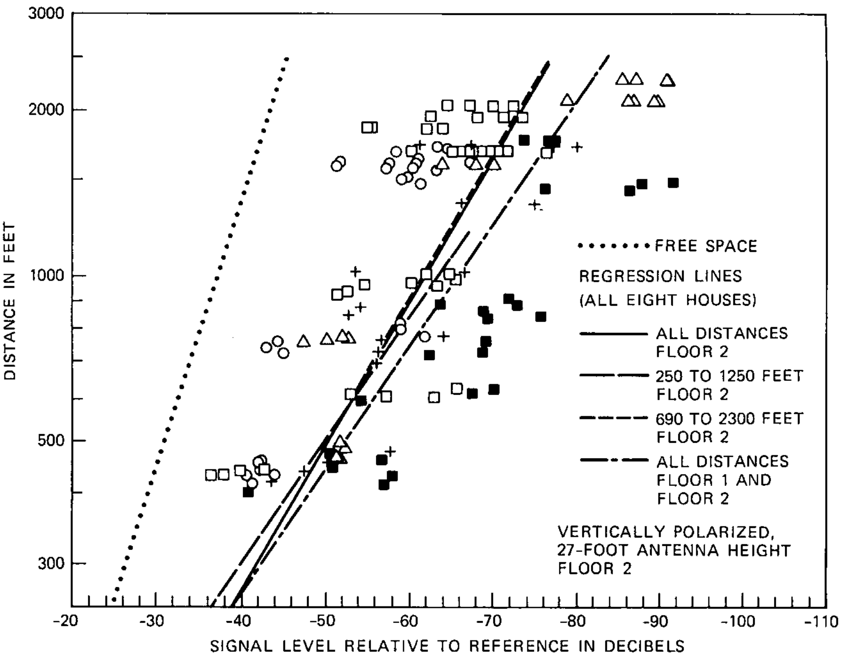

Fig. 24—Signal envelope medians and regression lines for the data from the second floors for the five houses that have second floors. The figure is similar to Fig. 22. In addition, the regression line is included from Fig. 23 for all the first- and second-floor data combined.

distances. This is reasonable since there are few, if any, intervening houses and trees in the first few hundred feet from a house. After several hundred feet there are many intervening houses and trees.

It is evident from Table IV and also generally from Table II that the signal levels and building attenuations for the various floors are different. As we discussed earlier, the second floors generally experience higher signal levels and lower attenuations than the first floors. The basements experience much lower signal levels and much higher attenuations than first floors. In fact, the basement attenuation is so much greater that basements will probably need to be treated separately in considering portable-radio-system performance.

The standard deviations of the residual signal levels are generally between 7.5 dB and 10.5 dB for the groupings in Table IV. The purpose of removing the trends for the data groupings is to reduce the standard deviations of the scatter in the signal levels, and thus, to permit tighter estimates of system performance. In general, removal of the regression line trends from these groupings significantly reduces the standard deviations. For example, before the trend is removed from the group containing all the data, the standard deviation was 14.9 dB. After removal of the trend it is the 10 dB listed in Table IV. This significant

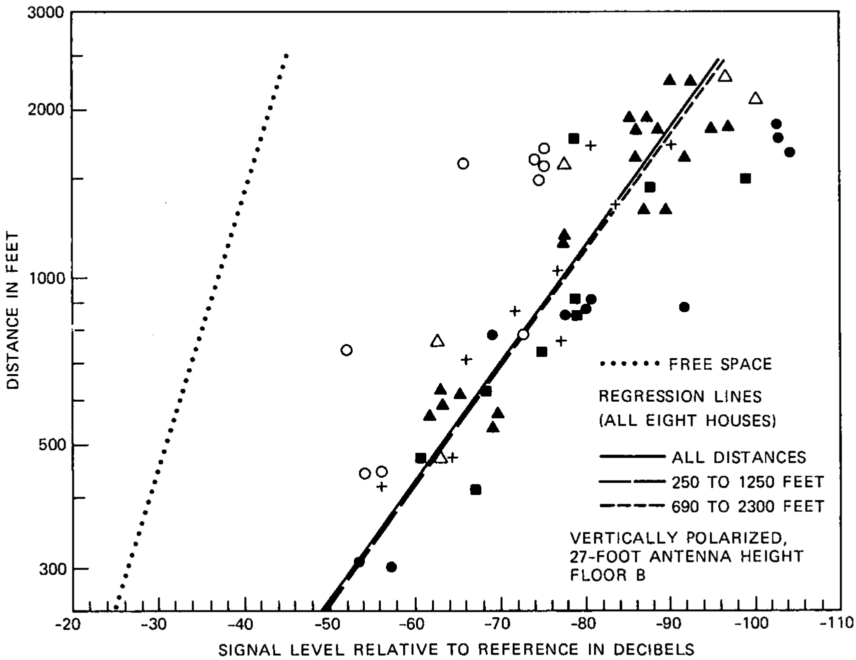

Fig. 25—Signal envelope medians and regression lines for the data from the basements for the six houses that have basements. The figure is similar to Fig. 22.

reduction in standard deviation is essentially the fact indicated by high significance of the F parameter.

3.3.2 Cumulative distributions for different floors and distance groupings

The solid lines in Figs. 27 through 30 are the cumulative distributions of the residuals for all houses and all distances for the floor groupings indicated. The residuals are the levels remaining when the regression-line trends are removed from the signal medians, as we discussed earlier.

Also plotted in Figs. 27 through 30 are distributions for two other distance groupings of the data. These other two groupings contain the residuals for the shortest distances, i.e., between 250 feet and 690 feet, and for the longest distances, i.e., between 1250 feet and 2300 feet. For these distance groupings, and for the intermediate distances of 690 feet to 1250 feet, the distance-dependence trends removed were those trends determined for all distances for the appropriate floor groupings. That is, the trends removed were the solid lines on Figs. 22, 25, and 26 for outside, for basements and for all data and the dashed and dotted lines on Figs. 23 and 24 for first and second floors combined. The straight lines drawn on Figs. 27 through 30 represent log-normal distributions having the standard deviations of the various

Table IV—Parameters for all eight houses (vertically polarized, 27-ft antenna height)

Floor	Distance Exponent	1000 ft Relative to Free Space (dB)	1000-ft Building Attenuation (dB)	σ (dB)	F	No. of Points
All Distances						
OS	−4.5	−24.4	—	9.4	381	282
1	−4.8	−30.2	5.8	8.7	463	260
2	−3.7	−24.5	0.1	9.0	126	132
B	−4.6	−39.6	15.2	7.6	129	62
1 and 2	−4.4	−28.2	3.8	9.3	504	392
OS, 1, 2, B	−4.5	−27.7	3.3	10.0	844	736
250 to 1250 ft						
OS	−5.6	−27.0	—	8.4	179	158
1	−5.5	−32.0	5.0	7.6	217	153
2	−4.4	−26.0	−1.0	7.6	39	66
B	−4.7	−40.0	13.0	6.0	44	33
1 and 2	−5.3	−30.5	3.5	7.8	247	219
OS, 1, 2, B	−5.3	−29.9	2.9	8.8	373	410
690 to 2300 ft						
OS	−4.2	−25.0	—	9.8	94	215
1	−4.5	−30.7	5.7	9.3	113	199
2	−3.8	−24.2	−0.8	9.5	39	101
B	−4.6	−39.7	14.7	8.5	33	46
1 and 2	−4.1	−28.7	3.7	10.0	124	300
OS, 1, 2, B	−4.2	−28.1	3.1	10.6	217	561

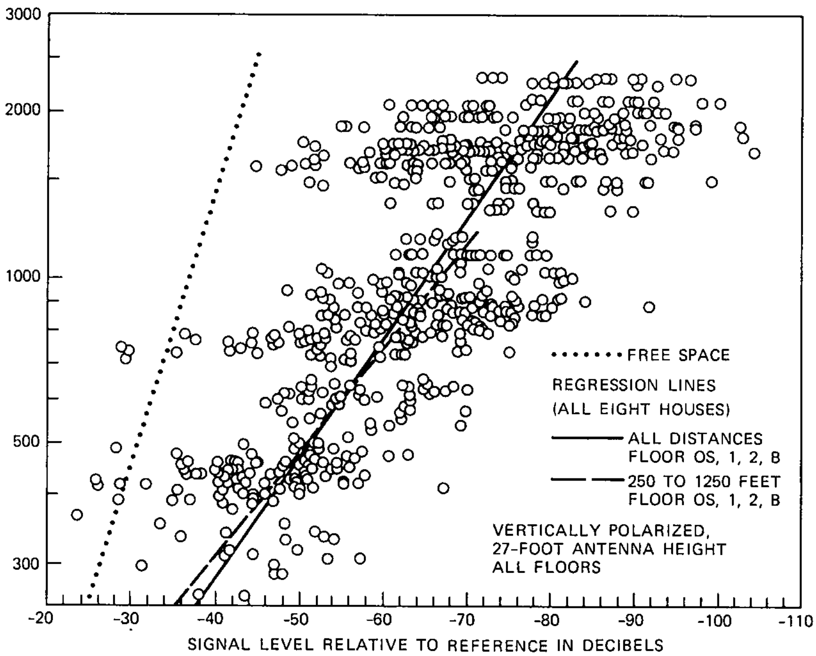

Fig. 26—Signal envelope medians and regression lines for all the data from all the houses for all the floors and outside combined. All the medians are plotted as "o" with no distinction as to house.

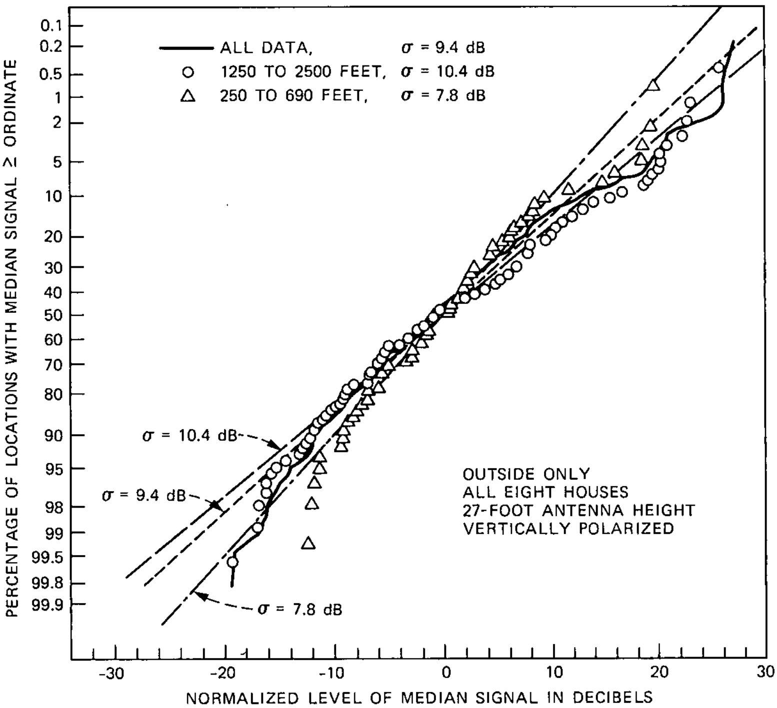

Fig. 27—Cumulative distributions of the medians of the small-scale signal envelope variations for outside locations after the trend values for the solid regression line in Fig. 22 are subtracted out.

data groupings. Standard deviations for the three distance groupings with the overall trends removed are listed in Table V.

The mean value will be zero for the residuals of a data set after removal of the regression trend for that particular data set. The mean of the residuals of a subset of a data set after removal of the trend of the entire set will not necessarily be zero. The closeness of the mean of the subset residuals to zero is an indication of how well the trend of the entire set represents the trend remaining in the subset. The means of the various distance groupings (subsets) after removal of the trend for all distances (sets) are also listed in Table V. Most of the means are less than 1 dB, with the largest being 1.5 dB. Considering the much larger standard deviations, these small means indicate that the overall trends are quite applicable to the distance groupings also.

The cumulative distributions of the measured data in Figs. 27 through 30 are all within ±2 dB of the associated log-normal distribution with the same standard deviation for the range from 10 percent to 90 percent. Most of the measured distributions are within ±1 dB over the 10-percent to 90-percent range. The fit of the measured distributions is worse in the tails, where statistical fluctuations are

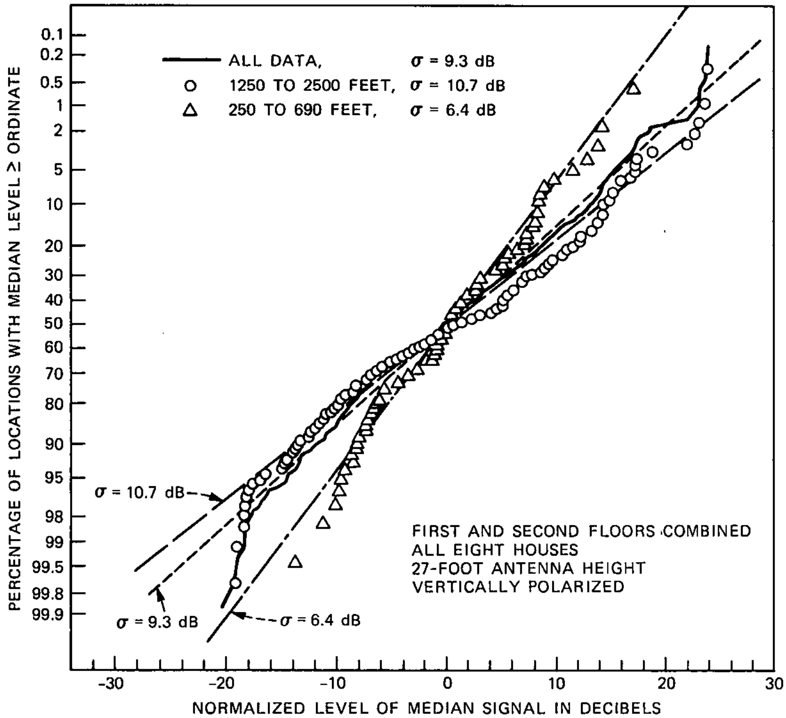

Fig. 28—Cumulative distributions for first- and second-floor locations combined similar to those in Fig. 27. The regression trend removed was the dashed and dotted line in Figs. 23 and 24.

expected to be worse, because of the small number of samples. Thus, log-normal distributions are good descriptions for the various groupings of the data.

For the different distance groupings in Table V, the standard deviations for all the groupings by floors increase with increasing distance. The increase is small but is very consistent across all the different groupings. Therefore, increase in standard deviation with distance probably represents an actual characteristic of the propagation environment.

IV. SUMMARY

Signal levels were measured within and around eight suburban houses from various locations of an instrumentation van. The van locations ranged from 250 to 2500 feet from the houses. Median signal levels were determined for the small-scale signal variations in 4-foot-square areas. Parameters describing the variation of these small-scale medians over large-scale changes for the eight individual houses are summarized in Table II. Parameters describing large-scale changes for

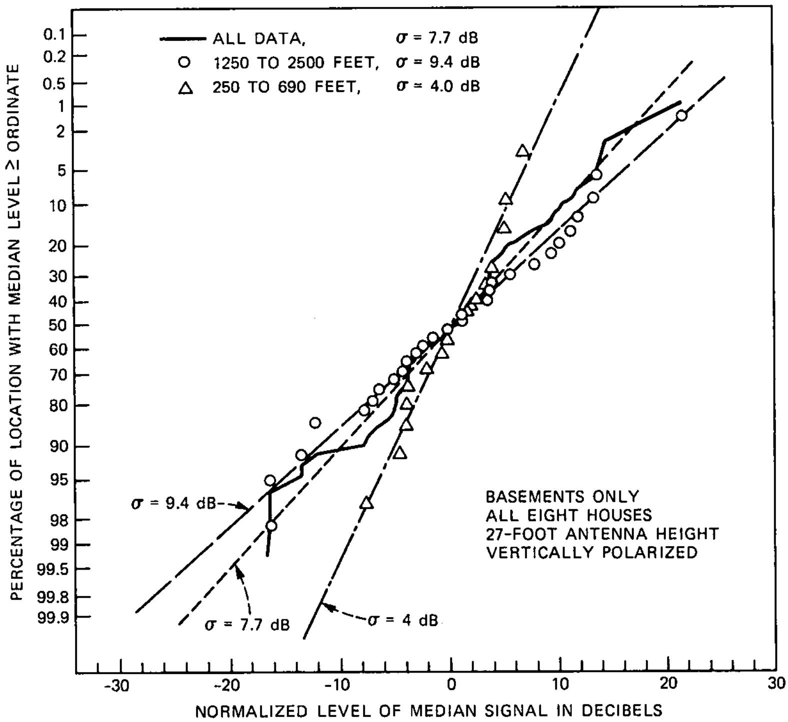

Fig. 29—Cumulative distributions for basement locations similar to those in Fig. 27. The regression trend removed was the solid line in Fig. 25.

Table V—Parameters for all eight houses (vertically polarized, 27-foot antenna height)

Floor	σ Trend Removed (dB)	Mean Trend Removed (dB)	No. of Points
250 to 690 ft			
OS	7.8	0.4	67
1	6.1	0.6	61
2	7.2	−0.7	31
B	3.9	0.2	16
1 and 2	6.4	0.4	92
OS, 1, 2, B	8.0	0.3	175
690 to 1250 ft			
OS	9.0	−1.5	91
1	8.5	−1.5	92
2	8.0	−0.2	35
B	7.4	−0.5	17
1 and 2	8.8	−1.5	127
OS, 1, 2, B	9.5	−1.3	235
1250 to 2300 ft			
OS	10.3	0.9	124
1	9.8	0.9	107
2	10.3	0.4	66
B	9.0	0.2	29
1 and 2	10.7	0.9	173
OS, 1, 2, B	11.2	0.8	326

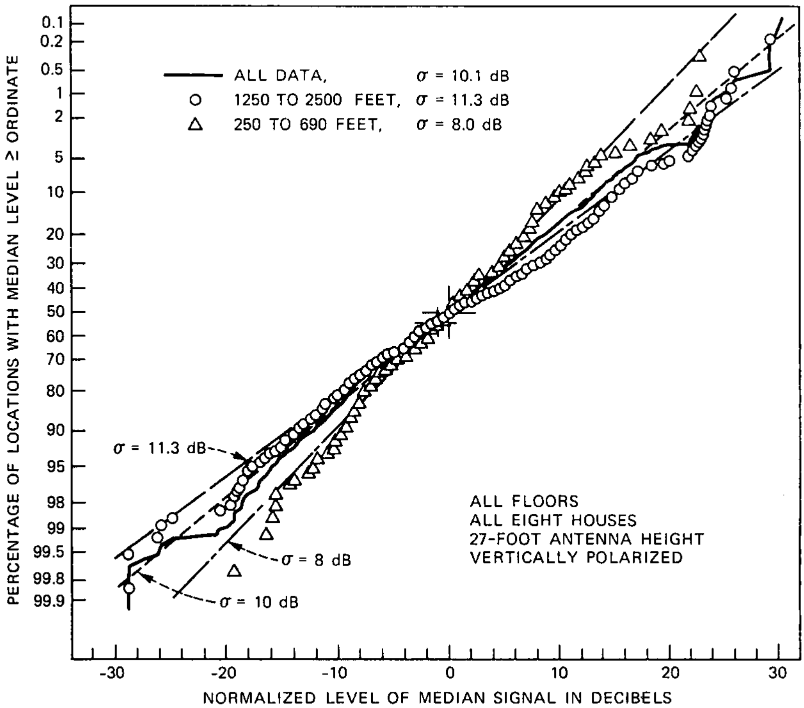

Fig. 30—Cumulative distributions for all floors and outside combined similar to those in Fig. 27. The regression trend removed was the solid line in Fig. 26.

different groupings of the data from all eight houses are summarized in Tables IV and V. Effects of house construction and the environment are discussed in Section 3.2.2.

V. ACKNOWLEDGMENTS

We wish to thank those people who allowed us to make the measurements in their houses that are reported in this paper; without their patience and tolerance this needed set of data could not have been obtained. The continued support of L. J. Greenstein and D. O. Reudink is also greatly appreciated.

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