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Satellite Sound Broadcast Propagation Measurements

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***Abstract*-Power transmitted from atop a 17.9 m tower in simulation of a satellite signal, emitted by a tone generator sweeping from 700 to 1800 MHz,was received using a 90° beamwidth linearly scanning antenna at many locations inside six buildings of solid brick, corrugated sheet-metal, wood-frame, mobile home, and concrete wall construction. The signal levels were found to have much structure in the spatial and frequency domain, but were relatively stable in time. Typically, people moving nearby produced less than 0.5 dB variations, whereas a person blocking the transmission path produced 6 to 10 dB fades. Losses, which at an average position in a room increased from 6 to 12 dB over 750 to 1750 MHz, could be mitigated to 2 to 6 dB by moving the antenna typically less than 30 cm. Severe losses (17.5 dB, mitigated to 12.5 dB) were observed in a concrete wall building, which also exhibited the longest multipath delays (>100 ns). Losses inside a mobile home were even larger (>20 dB) and independent of antenna orientation. The losses showed a clear frequency dependence.**

I. Introduction

Several efforts [1]-[3] are underway to develop systems for direct broadcasting of radio programs from geostationary satellites (BSS-Sound) to inexpensive personal receivers in houses and cars. Such features as a shareable space-segment in a safe location, tailored footprints from global to local using multiple spot-beams, and flexible sound quality through digital signal processing combine to make this an attractive technology. Three potential frequency bands for BSS-Sound have been proposed by the FCC: 728-788 MHz, 1493-1525 MHz, and 2390-2450 MHz. This paper reports on signal strength measurements made inside six buildings over the 700-1800 MHz band, using a tower-mounted transmitter in simulation of a satellite. Radio wave building attenuation measurements were reported [4] at 860, 1550, and 2569 MHz, using the ATS-6 geostationary satellite as a source platform. The average attenuation into wood-frame houses with and without brick veneer was found to be 6.3 dB for elevation angles from 36° to 55° and increasing by 3 dB from 860 to 2569 MHz. The widelyspaced, single frequency results presented were spatially averaged, however, allowing no conclusions about the fine structure of signal levels within a room. The experiment described here has been carried out to determine the excess path loss associated with reception inside buildings. Such information is needed for the preparation of international standards [5].

II. Experimental Aspects

A. Instrumentation

The measurement system makes use of an erectable 17.9 m tall tower attached to a van which has been outfitted with radio transmission and reception equipment as well as a data acquisition and control computer. Continuous wave (constant frequency or swept) signals from a tracking generator synchronized to a microwave spectrum analyzer are fed through a cable to the top of the tower, amplified, and transmitted towards the location under test. There they are received by an antenna which is mounted to a linear positioner about 1.4 m above ground and pointed towards the transmitter . After amplification the received power is conducted through an 80 m cable back to the spectrum analyzer in the van. The positioner can be manually oriented to allow computer controlled antenna motion along any arbitrary axis. For the measurements presented here the receiving antenna position was varied in 16 steps of 0.05 m, resulting in a total scan distance of 0.8 m along either the vertical direction or in the horizontal plane parallel with or at right angles to the propagation path.

The measurement system, shown as a block diagram in Figure 1, functions like a scalar network analyzer. It is capable of determining transmission loss over a maximum frequency span from 700 to 1800 MHz with a resolution bandwidth of between 10 kHz and 1 MHz and an overall accuracy of better than 0.5 dB. By varying the transmitter to receiver range from 15 to 75 m, elevation angles of 12° to 48° can be obtained. Both antennas are circularly polarized cavity-backed spirals with 90° half-power beamwidth and gain increasing from -2.5 to 4.5 dB over the 700 to 1800 MHz frequency range. They were chosen because of their wide bandwidth and relatively constant directivity characteristics. The pertinent system parameters are summarized in Table I below.

Table I: Pertinent System Parameters

Frequency	
Coverage:	700 MHz to 1800 MHz
Span:	0 Hz to 1100 MHz
Resolution:	1 MHz to 10 kHz
Amplitude	
Range:	45 dB
Resolution:	0.2 dB
S/N Ratio:	>45 dB
Error:	<0.5 dB
Antennas	
Type:	Cavity Backed Spiral
Polarization:	Right-hand Circular
Beamwidth:	90° (3 dB)
Gain:	-2.5..+4.5 dB
Elevation Angle:	12° to 45°

B. Calibration Method

The system was calibrated to power levels relative free space with height-gain measurements performed over the entire 1100 MHz frequency range at distances from 15 to 75 m in a flat open field. In this situation the received signal mainly consists of a combination of two waves: the direct wave and the specular ground reflection. Increasing the height of the receiver causes additional delay of the reflected relative to the direct wave and changes the pattern of con- and destructive interference as a function of frequency. Typical peak-to-peak received power variations in a full frequency sweep were 10 dB at 75 m and 1.5 dB at 15 m. The free space level was determined by linearly averaging the composite maximum and minimum of the power levels versus frequency obtained at 16 vertical positions from 2.0 to 2.8 m.

An example of such a procedure for the distance of 25 m (elevation angle 32°) is depicted as Figure 2. The vertical scale has been adjusted relative to free space using the overall calibration results. Absolute power levels consistent with propagation loss calculations and with errors of typically less than 0.5 dB for all frequencies and distances were obtained. Some of the remaining ripple is due to the residual impedance mismatch between the receiving antenna and the cable to the low-noise amplifier.

C. Measurement Sites

The measurement campaign covered six locations and many positions at each location. The characteristics of the receiving locations are as follows:

BRC 16-4: A corner room office (about 6x7 m) with two large windows in a single story building. The exterior walls are of concrete-block masonry. They are covered with plasterboard on the inside. The ceiling is formed by acoustic tiles suspended at 3 m height from metal hangers. The double-glazed reflective window in the wall exposed to the transmitter has a modern aluminum frame, but no screening, and takes up about 3/8 of the wall. The roof of the building is flat, consisting of concrete panels supported by steel beams. The room contains wooden office furniture and two large plants. Trees and shrubs on the outside of the building did not obstruct the line-of-sight (LOS) between transmitter and receiver. The transmitter was at a distance of 33 m from the closest inside receiver location, resulting in an elevation angle of 27.5°. The azimuth angle between the wall and the line-of-sight was 50°.

BRC 15-24: A small room (about 3x4 m) with two windows taking up about 5/8 of the exterior wall. A cable chase separates the two windows. The construction is similar to that of BRC 16-4. The room is furnished with metal filing cabinets. The location was illuminated over the top of several trees at an elevation angle of 18° from a distance of 52 m, but the LOS between transmitter and receiver was clear. The azimuth angle between the wall and the LOS was 50°.

Commons: A 5x5 m corner foyer with a large reflective glass door taking up half of one outside wall. Wooden double doors lead from this room to the interior of the building. The external walls are of concrete tilt-wall construction; internal walls have metal frames covered with plasterboard. The ceiling consists of acoustic tile suspended at 3.5 m height. Several small trees in front of the measurement location did not shadow the propagation path. The transmitter was 57 m from the building at an azimuth angle of 45°, making both sides of the outside corner visible. The elevation angle was 16°.

Metal Shack: A 3x6 m shack (approximately 2.5 m high) with corrugated sheet-metal walls and roof on the outside and plywood on the inside. The shack stands in an open field. It has one small, unscreened window on each of the two narrow sides and a metal covered door centered between two windows (also unscreened) on one of the long sides, which was in the direction to the transmitter. The distance to the transmitter was 35 m, the elevation angle 25°, and the azimuth angle between the wall and the LOS was 60°.

Farm House: An 1870 vintage restored and furnished 2-story ranch house with wood siding. The walls are filled with rock wool and covered with sheetrock on the interior and wood siding on the exterior. No metallic heat-shield is installed. The attic is insulated. The gabled roof is covered with wood shingles. Windows have wooden sashes and are not covered with metallic screens. There are two large trees near the house, but the propagation path was not shadowed. Measurements were made in two rooms on the ground floor and one room on the second level. The distance to the transmitter was 35 m, the elevation angle 25°, and the azimuth angle between the wall and the LOS was 45°.

Mobile Home: A 40'x8' empty mobile trailer home with sheet-metal exterior and aluminum frame windows with metal screens. The distance to the transmitter was 35 m, the elevation angle 25°, and the azimuth angle between the wall and the LOS was 45°.

III. Measurement Results

A. Data Examples

An example of the power received versus frequency from 700 to 1800 MHz during a vertical position scan near a window in BRC 15-24 is given in Figure 3. The two outside traces in the plot are the composite maximum and minimum signal levels measured at 16 positions with 5 cm spacing. The trace meandering between the outside two represents the received power versus frequency at just one of the positions. At best, the signal was attenuated by 0 to 5 dB; at worst troughs of over 20 dB were found. Figures 4 and 5 more clearly show signal levels in this scan at two positions separated by 50 cm. In the first case, the deepest troughs happen to be located near 800 and 1100 MHz; in the second case one is close to 1400 and another to

1500 MHz. Over a frequency span of about 25 MHz, from 725.3 to 749.5 MHz, a trough near the center position of the scan changes its location and depth only slightly, as depicted in Figure 6.

Taken in a different building, the Metal Shack, two frequency sweeps from a horizontal position scan which were separated by 50 cm are shown in Figures 7 and 8. In contrast to the similarity of the two previous scans, these two scans are quite dissimilar. At position 2 the receiving antenna was looking through the open door, at position 12 it was shielded by the wall between the door and the window, resulting in the loss of most of the direct signal and consequently greater variations due to multipath scattering across the entire frequency span. A scan taken in Commons in the vicinity of the window at a position where the LOS penetrated the exterior wall is shown in Figure 9. As in Fig. 8, the average attenuation was 15 to 20 dB, but the variations with frequency are faster, indicating multipath contributions arriving from greater distances. Moving the antenna by 50 cm resulted in a LOS path through the window, and as can be seen in Figure 10, the signal level increased across the band, with some frequencies being enhanced to above the free space level by constructive interference, probably from the specular ground reflection. Figure 11 illustrates the high degree of correlation with frequency for a span of 25 MHz at 1500 MHz over an 80 cm motion, except at very low signal levels.

It is easy to calculate that in the case where both a direct wave and a reflected wave are received, the resulting linear power has a sinusoidal variation across the bandwidth of the receiver with a frequency-periodicity that is inversely proportional to the delay of the reflection relative to the direct path. The periodogram of the signal level versus frequency, therefore, represents an estimate of the time delay spread spectrum. This has been determined for the scans of Figs. 4, 8, and 9, and the results, shown in Fig. 12, give the percentage of the delayed power with delays less than the abscissa. The small room, BRC 15-24, suffered the shortest delays with 95% of the multipath power delayed by less than 15 ns. In the Metal Shack, the percentage increased rapidly after about 17 ns, which corresponds to the turn-around time between the receiver and the walls. In the Commons building, a large structure, more than 10% of the multipath power was received with delays greater than 80 ns (24 m distance).

B. Time Variations

In order to assess the time-variability of the received power, repeated frequency sweeps were obtained at many measurement locations while keeping the receiving antenna stationary. Statistics of amplitude changes at each frequency were determined from 99 sweeps taken over a period of about 6.5 minutes, with each sweep lasting 1 s. Some typical results are shown in Figs. 13 and 14, which give the maximum, average, and minimum power versus frequency and the standard deviation versus the average, respectively. The gross structure of the losses remains quite stable, whereas the standard deviation increases with falling average power level, presumably as more distant and variable multipath components become effective.

By making single frequency measurements over durations of 100 seconds, it was determined that power variations within the 1 s full sweep time of the receiver tended to be smaller than the 0.5 dB measurement accuracy of the equipment to signal levels of about -15 dB. Variations brought about by scattering from people walking in the vicinity of the receiving antenna were also quite small, except when someone moved directly into the LOS, in which case fades of 6 to 10 dB were observed. We conclude that time variations of near free-space-level power levels transmitted into buildings are not of primary importance in characterizing the transmission channel.

C. Losses

In each of the six buildings, at between eight and twenty locations, horizontal and vertical scans were taken. The power levels obtained were analyzed to derive losses at the average and at the best position in the scans for bandwidths of 1, 2, 5, 9, 18, 45, and 90 MHz from 700 to 1800 MHz. As no bandwidth dependence of the losses was found, Figure 15 gives probability contours for the signal level being less than the ordinate at 99, 90, 50, 10, and 1% at the average position in the scan for BRC 15-24 averaged over all the bandwidths listed above. The median loss increased from 5 dB at 750 MHz to 13 dB at 1750 MHz. Assuming that the receiving antenna was placed at the best position in a scan, the median losses were reduced, varying from 1.5 dB to 7 dB over the same frequency span. The central percentiles at that position show less variability than those at the average position, especially at the low frequency end. Table II summarizes the losses observed in all buildings. By moving from the average position to the best position, the signal level can be improved by about 3 to 6 dB. The trend is for higher frequencies to suffer more attenuation when losses are moderate. In Commons losses are rather uniformly high across the full frequency span.

Table II: Median Power Levels as a Function of Frequency.

Building	Average Position 750...... 1750 MHz	Best Position 750...... 1750 MHz
BRC 16-4	-5..........-11 dB	-2............-6 dB
BRC 15-24	-5..........-14 dB	-2............-5 dB
Metal Shack	-9..........-11 dB	-5............-6 dB
Commons	-17..........-18 dB	-12..........-13 dB
Farm House	-5..........-11 dB	-3............-5 dB
Mobile Home	-20........<-24 dB	-16..........-22 dB

After averaging over all frequencies, the probability distribution functions (PDF) at the average and best positions were calculated for each building and the results for the Metal Shack have been plotted against a normal probability scale in Figs. 17 and 18. The means and standard deviations derived with linear regressions are summarized in Table III.

Table III: Signal Distributions at the Average and Best Position.

Building	Average Position Mean..........STD	Best Position Mean..........STD
BRC 16-4	-7.9 dB ....5.5 dB	-4.2 dB ....4.2 dB
BRC 15-24	-9.1 dB ....4.4 dB	-5.4 dB ....3.7 dB
Metal Shack	-9.7 dB ....6.3 dB	-5.2 dB ....4.9 dB
Commons	-15.4 dB ....8.4 dB	-9.7 dB ....6.7 dB
Farm House	-9.0 dB ....4.5 dB	-5.4 dB ....3.7 dB
Mobile Home	-24.9 dB ....3.8 dB	-19.8 dB ....3.4 dB

In the first three buildings all distributions deviate from normal at the upper signal level tails, as can be seen in the examples of Figs. 17 and 18; in Commons the fit is poor across the entire range. Loss measurements performed at 900 MHz [6] into a well shielded metal building have shown the signal amplitudes in a multipath environment to be Rayleigh distributed, but all amplitude data collected in this experiment except for the Mobile Home case were obtained under less severe attenuation conditions and the Rayleigh distribution did not provide a better fit than the normal one.

For each building, using all the data collected, the percentage of positions P (%) at which the average received power was less than a given threshold THR (from -3 to -18 dB) has been determined. For example in the Metal Shack as a function of frequency F (in GHz) from 50 to 65 percent of positions had signals lower than -9 dB. At all six buildings P can be approximated by the relations:

$$P = A + B*F, \quad (1)$$

where

$$A = A0 + A1*THR, \quad (2)$$

and

$$B = B0 + B1*THR. \tag{3}$$

Table IV summarizes the coefficients derived for the six buildings, including the rms error of P in percentage points.

Table IV: Fit Coefficients for the % Positions at Which the Signal is Below a Threshold

Building	A0	A1	B0	B1	RMS-Error
BRC 16-4	66.2	5.3	16.0	-0.54	4.0
BRC 15-24	74.1	7.0	20.3	-1.2	8.4
Metal Shack	97.8	6.2	-3.8	-1.5	3.4
Commons	105.7	3.1	-7.8	-0.34	2.8
Farm House	67.2	5.2	24.9	-0.1	6.1
Mobile Home	61.9	-1.3	11.1	-0.02	13.2

IV. Summary and Conclusion

The experiment described has been performed to allow a more detailed description of radio wave propagation into buildings than has been hitherto available in the literature. Such comprehensive information is needed for the design of BSS-Sound systems, which will have to mitigate unfavorable propagation characteristics with additional power, coding, or space- and frequency-diversity. Although measurements were made into dissimilar buildings of brick, metal, wood-frame, or concrete construction, many similarities among the results were uncovered. Temporal variations at levels within about 15 dB of the free space value were only of the order of 0.5 dB. Only in one of the buildings were delays greater than 50 ns of importance. The predominating effects of short delays for satellite systems have previously been observed in the land mobile case [7] and are a feature of near free-space propagation.

Losses increased with frequency, although many specific counter examples could be found. In light of the demonstrated frequency insensitivity of multipath effects, increased losses at higher frequencies are believed to be due to greater absorption by the walls of the buildings studied. By moving the receiver to a position of a signal strength crest, losses could be reduced.

References

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[7] Vogel, W. J. and Hong, U.-S., "Measurement and Modeling of Land Mobile Satellite Propagation at UHF and L-Band," IEEE Trans. on Ant. and Prop., Vol. AP-36, No. 5, May 1988, pp. 707-719

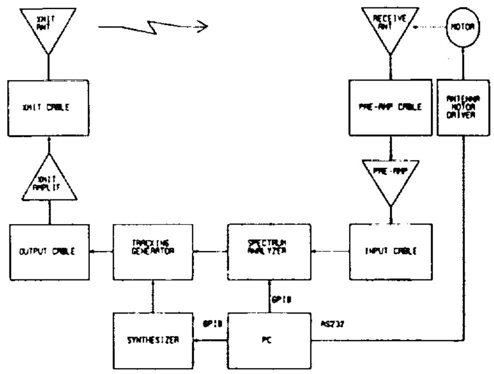

Fig. 1. The DBS-R measurement system functions like a scalar network analyzer in the 700-1800 MHz frequency range.

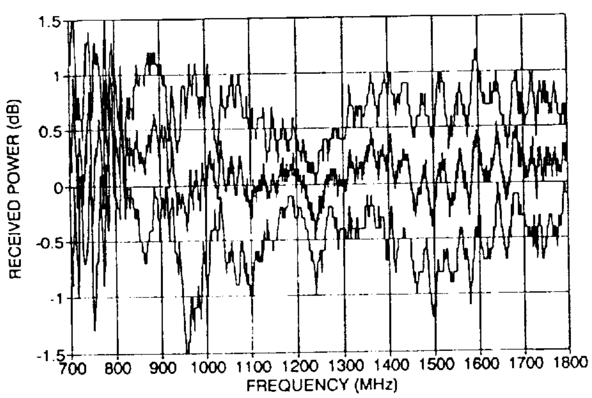

Fig. 2. Equipment calibration to 0.5 dB accuracy accounts for specular ground reflections observed in an open field.

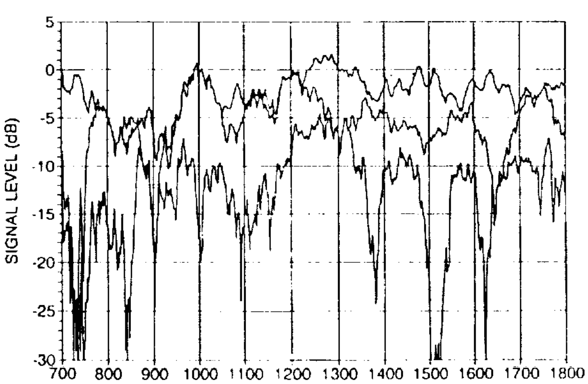

Fig. 3. The composite maximum and minimum of the received power in a vertical position scan near window in BRC 15-24, and a single position trace.

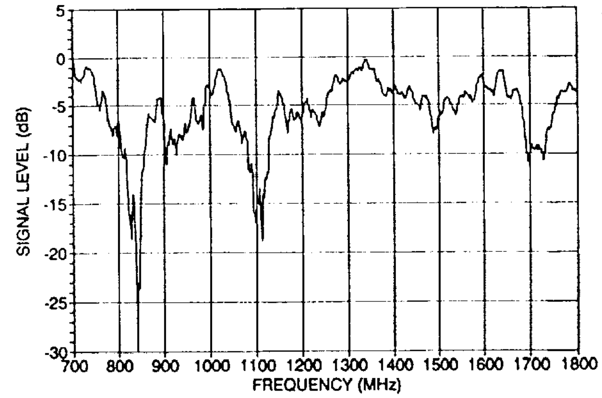

Fig. 4. The received power at one position in the vertical scan of Fig. 3 shows the deepest fade troughs near 850 and 1100 MHz.

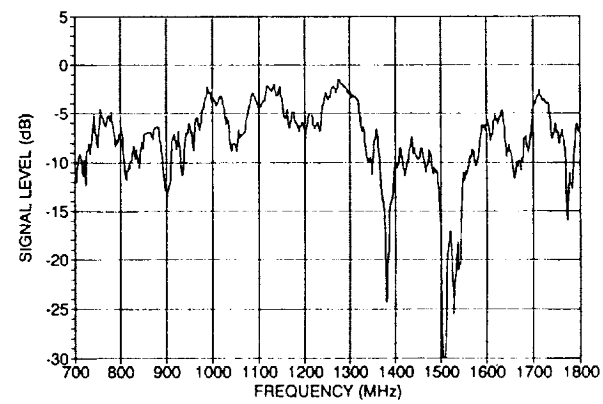

Fig. 5. At another position, some 50 cm higher than in the previous figure, the deepest fade troughs appear close to 1400 and 1500 MHz.

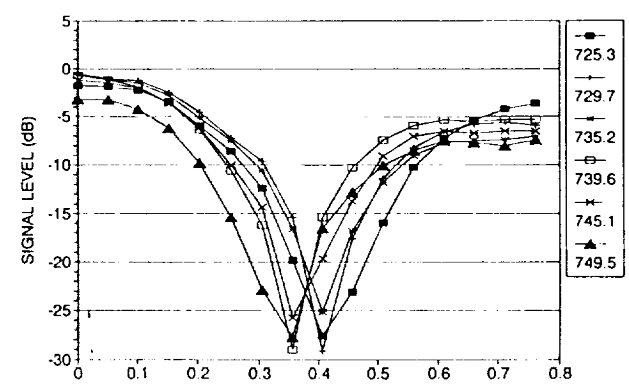

Fig. 6. The received signal level in a fade trough versus distance at six frequencies from 725.3-749.5 MHz spaced by about 5 MHz. The scan is same as shown in Fig. 3.

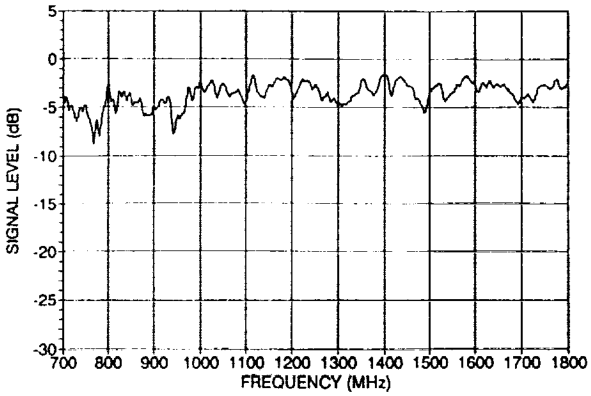

Fig. 7. The signal level observed at position 2 during a horizontal position scan near the open door, but inside of the Metal Shack.

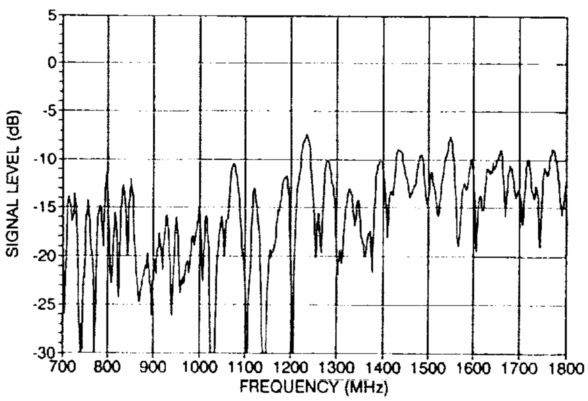

Fig. 8. The signal level observed at position 12, 50 cm from the previous location, with the path now obstructed by a corrugated sheet-metal wall.

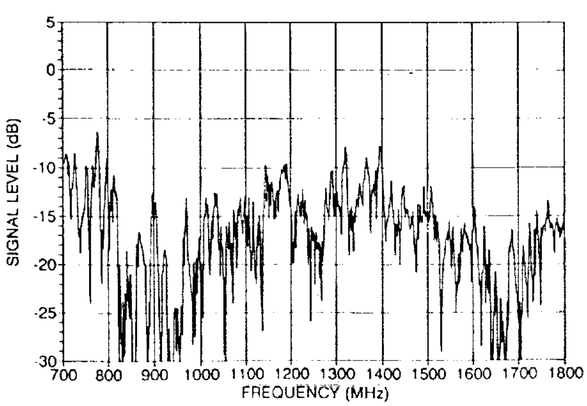

Fig. 9. A frequency sweep taken in Commons in the vicinity of the large window, but where the line-of-sight path penetrated the exterior concrete wall.

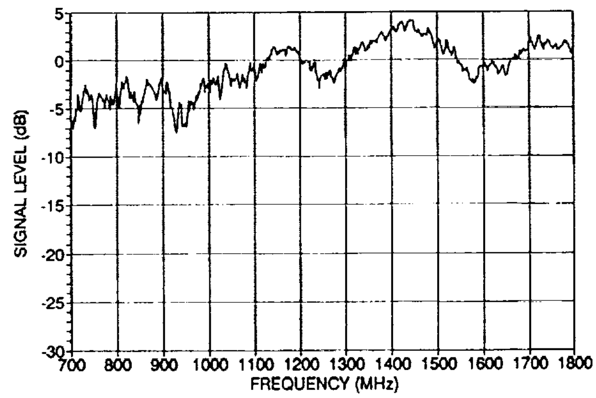

Fig. 10. A frequency sweep taken in Commons 50 cm from the previous example, but now the line-of-sight path penetrated the window.

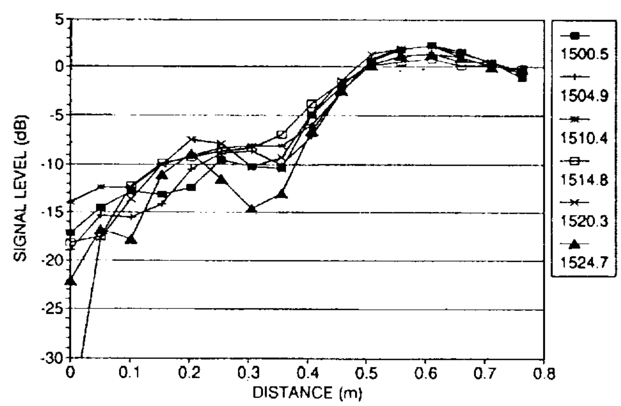

Fig. 11. The signal level versus distance, at six frequencies from 1500.5-1524.7 MHz. The receiver LOS moves from behind the wall of Commons to the window.

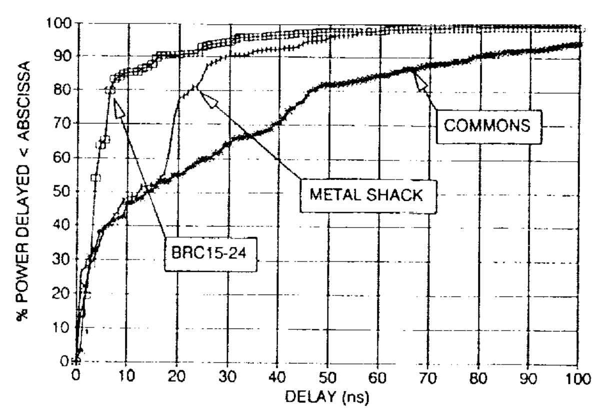

Fig. 12. The CPF of time delay spread at one position in three buildings. The most lossy structure, Commons, had the longest delays.

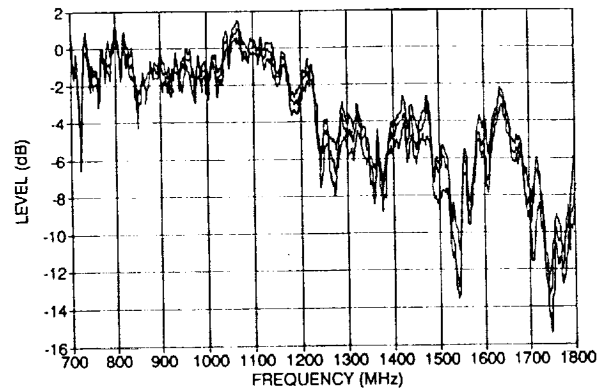

Fig. 13. Maximum, average, and minimum for 99 frequency sweeps taken in BRC 16-4 over a period of about 6.5 minutes, with each sweep lasting one second.

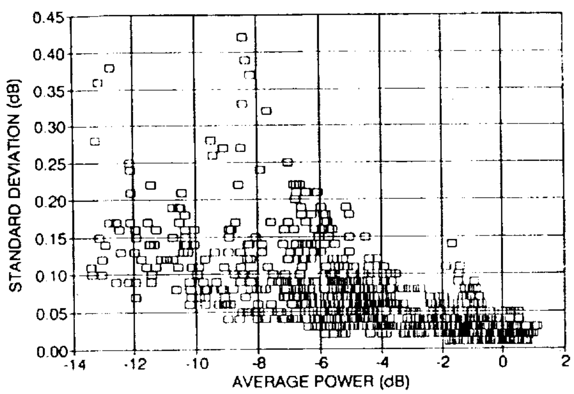

Fig. 14. The standard deviation of time variations gets larger in the deeper fade troughs, where more distant and variable multipath components become relevant.

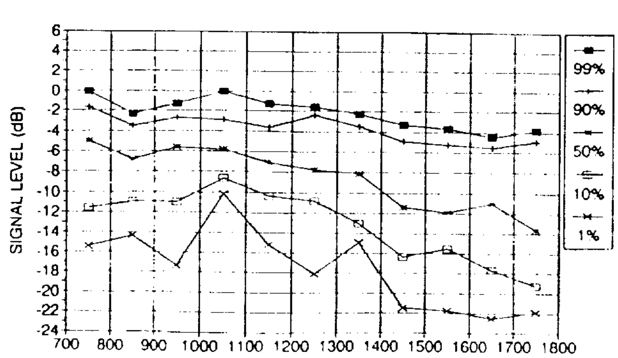

Fig. 15. Probability contours for the signal level being less than the ordinate at 99, 90, 50, 10, and 1% at the average position in the scan for BRC 15-24.

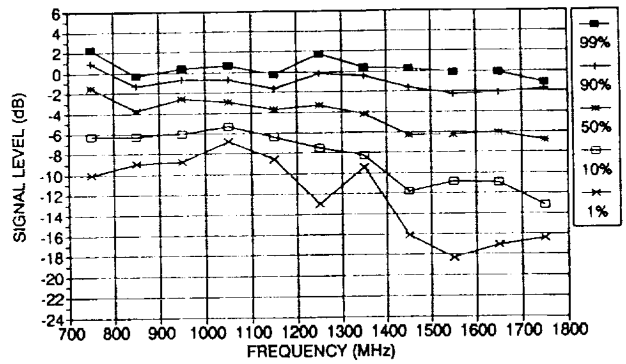

Fig. 16. Probability contours for the signal level being less than the ordinate at 99, 90, 50, 10, and 1% at the best position in the scan for BRC 15-24.

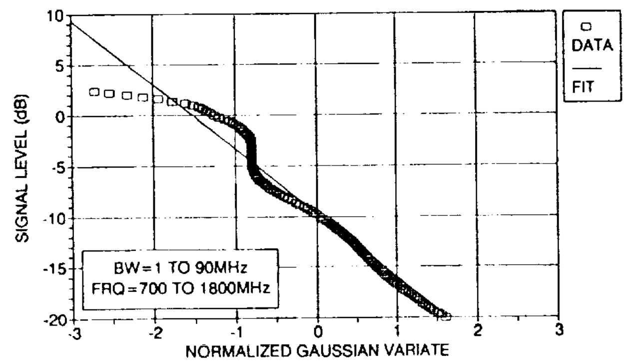

Fig. 17. Gaussian scaled distribution of the signal level at all average positions in the Metal Shack, with a mean of -9.7 dB and a standard deviation of 6.3 dB.

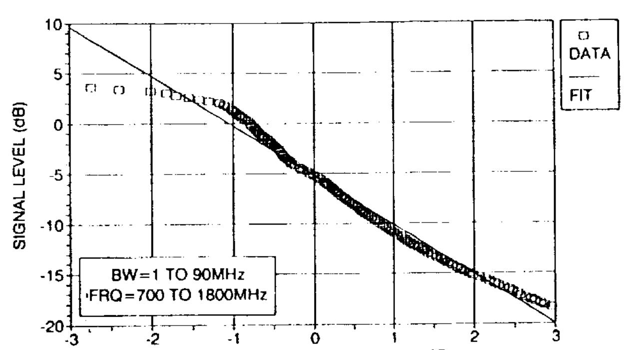

Fig. 18. Gaussian scaled distribution of the signal level at all best positions in the Metal Shack, with a mean of -5.2 dB and a standard deviation of 4.9 dB.