NTIA TECHNICAL MEMORANDUM 92-155

PRELIMINARY BUILDING ATTENUATION MODEL

technical memorandum series

U.S. DEPARTMENT OF COMMERCE • National Telecommunications and Information Administration

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PRELIMINARY BUILDING ATTENUATION MODEL

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MAY 1992

ABSTRACT

In this technical report, preliminary graphical models spanning approximately 1 MHz to 30 GHz are developed for commercial and residential building attenuation. The models are least-square fits to the data available from the open literature. An estimate of the mean attenuation through the exterior wall can be made for most of the range of the models.

A measurement plan for verification and improvement of the graphical models is outlined, and an example of its application to residential houses at lower frequencies is provided.

The result of a literature review based on 31 references provides additional information for detailed applications. For this purpose, summarizing tables and figures are cross-referenced to primary sources of measurement data.

KEYWORDS

Building Attenuation Model and Measurements

Lognormal and Rayleigh Distributions

Penetration Losses

Shielding Effectiveness

VHF-UHF Band

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SECTION 1
INTRODUCTION

BACKGROUND

The National Telecommunications and Information Administration (NTIA) is responsible for managing the Federal Government's use of the radio frequency spectrum. Part of NTIA's responsibility is to establish policies concerning spectrum assignment, allocation and use, and providing the various departments and agencies with guidance to ensure that their conduct of telecommunications activities is consistent with these policies.[1]

In support of NTIA's duties, the Spectrum Engineering and Analysis Division (SEAD), Office of Spectrum Management (OSM) has undertaken a number of interference or spectrum sharing studies requiring estimation of the attenuation of radio waves into buildings. This attenuation is often a key factor used in the link equation to determine the compatibility between radio systems. A recent example involved sharing between microwave oven and satellite uplink usage at 2.45 GHz in which the building attenuation factor was required. As spectrum sharing increases, these types of issues will appear more frequently in the future.

The engineering literature includes a relatively large number of studies and measurements of building attenuation for various frequency ranges and coupling conditions. In general, measurement work can be classified into four types of equipment setups depending on the location of the antennas (TABLE 1 and Figures 1 to 4). For each type, an important consideration is building usage (commercial or residential) which largely determines the framework, cladding, and choice of materials (wood, metal, etc.). Setup 3 is often a subset of 2 in a measurement program.

However, no one source of information provides a comprehensive model that covers a wide frequency range, various building types, and statistical parameters. For each new task, a staff engineer often has to undertake an extensive literature search to determine values appropriate for a specific estimate of building attenuation. Also, values for the particular frequencies or conditions of interest are often not available and extrapolation from available data is required. These ad hoc approaches to the problem are expensive in labor and time and may not be fully consistent from study to study. A more comprehensive approach to the issue is needed.

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[1] NTIA, *Manual of Regulations and Procedures for Federal Frequency Management*, U.S. Department of Commerce, National Telecommunications and Information Administration, Washington, D.C., Revised January 1991.

TABLE 1

BUILDING ATTENUATION MEASUREMENT SETUPS

MEASUREMENT SETUPS:	Location of trans. ant.	Location of receiving ant.	Building usage and material
1. Urban and suburban environments.	Far away from building.	Anywhere in building.	Commercial only. Masonry/concrete steel framework.
2. Localized, deep penetration into building.	Outside building.	Anywhere in building.	Commercial: Same as above. Residential: wood, brick, and aluminum sidings.
3. Localized, exterior wall penetration only.	Outside building.	Inside near exterior wall.	Commercial: same as above. Residential: same as above.
4. Localized, wall penetration only.	Just outside wall.	Inside near wall.	Wood-frame wall: brick facing and wood lap siding.

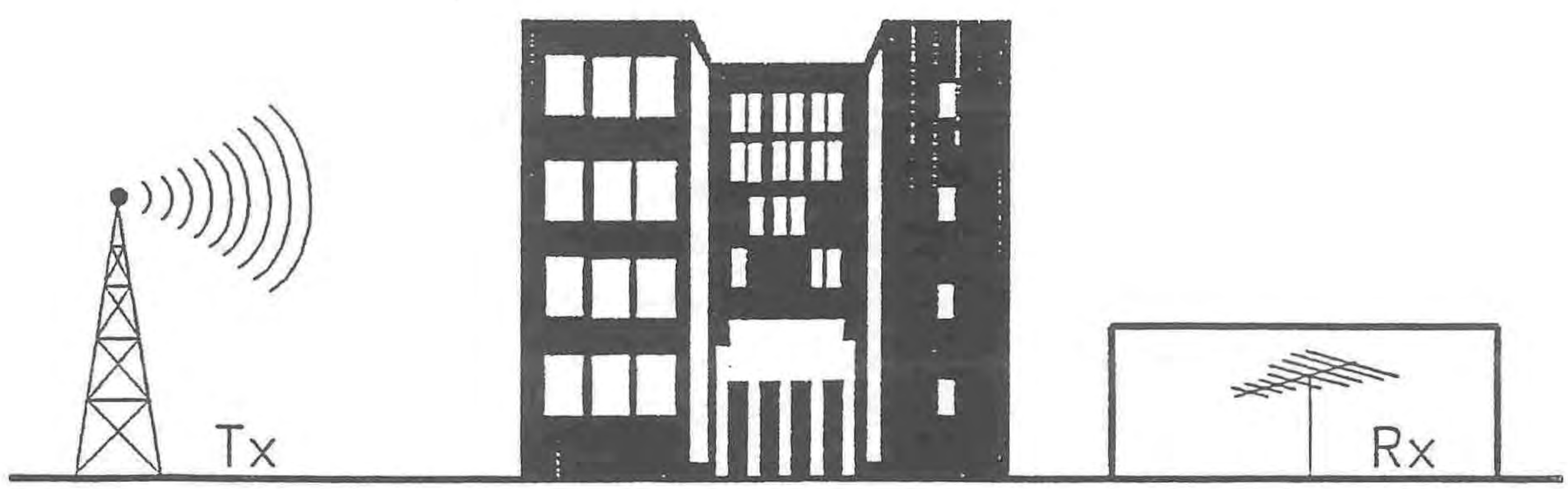

Figure 1. Measurement Setup 1; Urban and suburban environs.

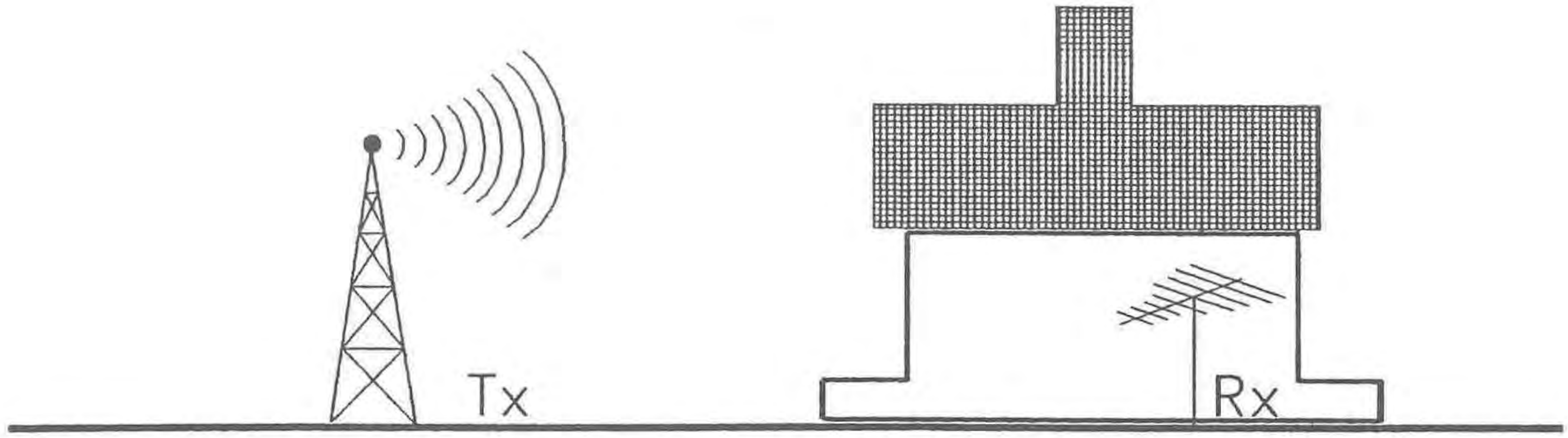

Figure 2. Measurement Setup 2; Localized, deep penetration into building.

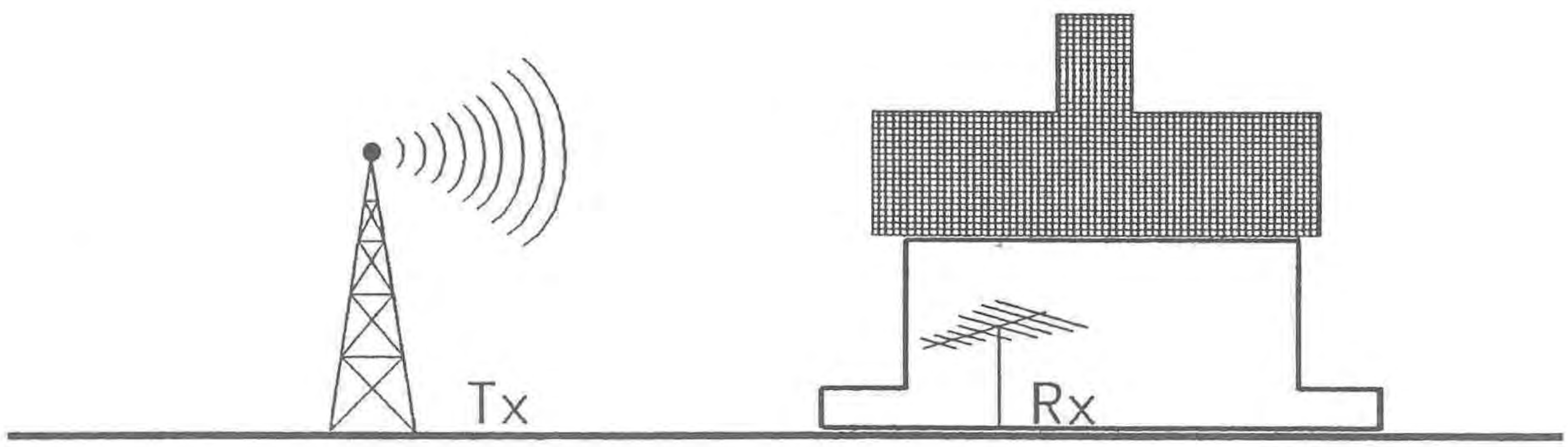

Figure 3. Measurement Setup 3; Localized, exterior wall penetration only.

Figure 4. Measurement Setup 4; Localized, wall penetration only.

OBJECTIVES

The main objective of this task is to

a. Develop a preliminary NTIA model which may be analytic or graphical for attenuation of radio waves into buildings useful for interference or spectrum sharing studies. The model should cover the range of frequencies and building conditions most encountered by NTIA between 1 MHz and 30 GHz.

b. A secondary objective is to furnish a literature review and bibliography useful for focusing research efforts when the user of the model requires more detailed data.

c. A third objective is to present a measurement plan to verify and improve the model over the frequency range and building conditions of its application.

APPROACH

In order to accomplish the objectives, the following steps were undertaken.

1. Conducted and reported on an extensive literature review of RF building attenuation or penetration loss.

2. Determined the frequency range, building types, and building materials most relevant to NTIA's needs.

3. Determined the statistical methods and statistical distributions most encountered in the literature.

4. Developed a graphical model for mean building attenuation as a function of frequency for selected building parameters and assigned standard deviation.

5. Outlined a general measurement plan to verify and improve the graphical model throughout its frequency range and building parameters.

6. Presented a procedure for applying the measurement plan to a portion of the graphical model requiring priority treatment.

SECTION 2
CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

The main objective of this report, to develop a building attenuation model useful for the range of frequencies and building conditions encountered by NTIA, was met as follows.

1. Graphical models spanning approximately 1 MHz to 30 GHz have been developed separately for commercial and residential buildings.

2. The models consist of least-square fits to the data available from the building attenuation literature.

3. Model reliability is best in the UHF band where the majority of the measurements have been conducted.

4. Using the model, an estimate of the attenuation through the exterior wall can be made for commercial buildings.

5. For residential houses, an estimate can be made at UHF and above. The data is very limited below this band and only general trends can be indicated.

6. The graphical model can be improved by follow-through measurements, particularly for residential houses below the UHF band.

The secondary objective, to include a literature review useful for more detailed work, was met as follows.

1. For the reader's convenience, the literature is grouped and reviewed in three areas:
   - UHF measurement work, mainly for cellular radio.
   - Experimental work including earth-satellite links.
   - General measurements across the RF band.

2. The review includes a large bibliography of 31 references. All references are discussed at least once in the text, and are cross-referenced within the text and to tables and figures.

3. Detailed summary tables are presented at the end of the review. References are listed in chronological order with information on building construction, frequency, mean attenuation, and other statistical information. These tables offer a quick way to locate detailed information and to access primary sources.

4. Selected data from the summary tables are presented in graphical form at the end of the review and generally serve to show how building attenuation varies with frequency and building type.

The final objective, to devise a follow-through measurement plan for the preliminary graphical model, was met as follows.

1. A general measurement plan applicable to both commercial and residential buildings was outlined for verification and improvement of the model. The sequence is

   - Measurements within the VHF band to determine the validity of the graphical model and confirmation of the probability distribution best known in the UHF band.

   - Measurements within the HF band for the reasons stated above, with due regard for the scarcity of available data and the high building attenuation.

   - The measurement plan was detailed for residential houses, and the order of priority of the measurements was established.

RECOMMENDATIONS

The following are NTIA staff recommendations based on the findings of this report. NTIA management will evaluate these recommendations to determine if they can or should be implemented from a policy, regulatory, or procedural viewpoint. Any action to implement the recommendations will be via separate correspondence modifying established rules, regulations, and procedures. It is recommended that NTIA:

1. Should utilize the building attenuation graphical models for use in spectrum management with due regard for the limitations imposed upon the models as stated in this report.

2. Address the need for information on building penetration loss set forth at the CCIR 1990 Plenary Session by preparation of a recommendation with supporting details from this report.

3. Conduct a measurement program by the Institute for Telecommunication Sciences (ITS) as outlined in this report in order to verify and improve the building attenuation models.

4. Issue NTIA technical reports for wider dissemination as the models are improved and extended in frequency coverage.

SECTION 3
LITERATURE REVIEW

INTRODUCTION

The attenuation of radio waves passing into and out of buildings and large structures is a subject usually discussed as part of the overall losses in a radio propagation path. As such, it is sometimes included with diffraction and refraction effects. Occasionally, this can lead to misunderstanding by the non-specialist. "Shading," for example, denoting attenuation of a signal passing completely through a building, can be confused with "shadow loss" due to diffraction around buildings.[2]

With the proliferation of hand-held/portable transceivers such as indoor radio, paging devices and cordless telephones, transmitting and receiving antennas of a radio link can no longer be assumed to be outdoors; better estimates of building attenuation or penetration are needed. Unfortunately, the literature surveys for this report and an earlier one by the National Bureau of Standards (NIST)[3] reveal that information dealing directly with this subject is difficult to locate. This difficulty, as mentioned earlier, is due to treating building attenuation as only part of any propagation study. One notable exception is the body of measurements in support of cellular communications, wherein the propagation path is short enough to make building attenuation a key factor.

This literature review will first categorize the heterogeneous collection of materials under building attenuation, then identify common quantifiable parameters, wherever possible, in probabilistic terms.

STUDIES IN BUILDING ATTENUATION

This report includes materials from technical journals and reports, symposium proceedings, and books spanning the past 40 years. The post World War II period was selected as a starting point because it saw the rise of mobile radio and a practical need to understand VHF

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[2] Shepard, N.H., *Radio Wave Loss Deviation and Shadow Loss at 900 MHz*, IEEE Vehicular Technology Group Conference Record, Washington, D.C., March 24-36, 1976, pp. 63-66.

[3] Wyss, J.C., W.J. Anson and R.D. Orr, *Building Penetration Project*, National Bureau of Standards (NIST), NBSIR 84-3009, September 1984.

propagation. Prior to the war, VHF mobile radio in the public safety sector was still in an experimental stage,[4] and few references for radio propagation above 30 MHz can be found from that period. Bullington's much-quoted paper[5] is the seminal work for the postwar years.

Studies in building attenuation appear to fall into the following categories.

- Measurement work for UHF cellular telecommunications.
- Experimental work including earth-satellite links.
- General measurements across the lower radio frequency band.

These overlap somewhat, notably between the last two items. All measuring equipment setups discussed in the INTRODUCTION section are found in these categories. Measurements are usually conducted in the VHF-UHF band between two points at only one or a few frequencies; therefore, the data need to be extended to cover additional frequencies particularly into the kilo- and gigahertz bands. The following discussion will begin with UHF cellular radio where measurements are relatively abundant and end with experimental work extending into the lower frequencies.

Measurement Work for UHF Cellular Telecommunications

Discussion on UHF cellular measurements will center on three contributions of a general nature. The first is a comprehensive paper in cellular radio propagation[6] followed by a summary

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[4] Bryant, J., *Public Safety Credited with Three Milestones*, Mobile Radio Technology, pp. 48-54, July 1988.

[5] Bullington, K., *Radio Propagation at Frequencies Above 30 Megacycles*, Proc. I.R.E.(IEEE), vol. 35, October 1947.

[6] Walker, E.H., *Penetration of Radio Signals Into Buildings in the Cellular Radio Environment*, Bell System Technical Journal, vol. 62, no. 9, pp. 2719-2734, November 1983.

for cellular mobile radio.[7] The third suggests a method whereby empirical models can be derived from measurement data for suburban houses.[8]

Walker

Walker measured penetration losses at 850 MHz in Chicago for one residential home and 14 office and industrial buildings served by a developmental cellular system (Ref. 6). A standard deviation of approximately 9 dB for most points was attributed to variation in building construction (brick, concrete, or steel-glass), building orientation, and other physical conditions. Walker verified his results with those of earlier workers. He found that suburban buildings had 5 dB less attenuation than urban ones on the main floor (TABLE 2). For all buildings, there was a decrease with height of about 2 dB/story for the lower stories. Walker did not account for deep penetration into buildings but was able to show that windows reduced the average loss by 6 dB (sigma = 5.2 dB).

TABLE 2

PENETRATION LOSS
(Ref. 6)

Environment	Floor	Loss(dB)
Urban	1	18.0
Suburban	1	13.1
All	1	14.2
	2	10.6
	3	6.8

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[7] Lee, C.Y., *Mobile Cellular Telecommunications Systems*, McGraw-Hill Book Co., New York, NY, 1989.

[8] Cox, D.C., R.R. Murray and A.W. Norris, *800 MHz Attenuation Measured In and Around Suburban Houses*, AT&T Bell Laboratories Technical Journal, vol. 63, no. 6, July-Aug. 1984 pp. 9-954.

Lee

C.Y. Lee presented empirical charts for estimating 800 MHz penetration loss as a function of floor level in his mobile cellular textbook (Ref. 7). The charts are based on Walker's Chicago data and measurements for urban Tokyo buildings by Japanese investigators. Lee ascribes high Tokyo first-floor losses (nearly twice Chicago's) to the need for more metal in earthquake-resistant buildings, and surmises that cities with few very tall buildings such as Los Angeles would have an intermediate value around 20 dB. However, it is unclear whether the 20 dB includes earthquake design. Lee estimates a constant 2.7 dB decrease per floor and a decrease of 6 dB for the effect of windows.

Cox et al

Cox *et al* measured the level in eight suburban homes at 800 MHz (Ref. 8), and statistically showed that the median signal level varied as a function of siding materials. All regression slopes (slope determines the distance exponent) were found to be statistically significant by the standard F test at the 0.5 percent level. Comparative data are given for basement and each floor and the number of points (measurements) determining each F value. This paper is notable for the way in which the extensive experimental measurements are clearly traceable to the determination and statistical reliability of a distance-exponential model. Cox concluded that the building attenuation appeared to fit a log-normal distribution with a standard deviation of 4.4 dB.

Status of cellular measurements

From the foregoing discussion, we see that in cellular radio propagation where building attenuation measurements are most plentiful and emissions are restricted to the UHF band, accurate predictive modeling has not been fully achieved. The relationship between attenuation loss per floor level and a building's height may differ with building material and frequency. For example, Cox *et al*[9] reported less than 5 dB difference for a two-floor metallic wall building at

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[9] Cox, D.C., R.R. Murray and A.W. Norris, *Measurements of 800 MHz Radio Transmission Into Buildings with Metallic Walls*, Bell System Technical Journal, vol. 62, no. 9, pp. 2695-2715, November 1983.

800 MHz; whereas, Horikoshi et al[10] obtained results closer to 10 dB/story for a four-floor reinforced concrete building at 1.2 GHz. Whether the difference is attributable to building construction or radio frequency, or both, is uncertain.

This section on UHF cellular radio propagation has pointed out the difficulties associated with measuring attenuation within the complex structure of buildings even at one frequency band. In the near future, the within-building environment of cellular cordless telephones must be specified more clearly because of the low power of these devices.[11]

Experimental Work Including Earth-Satellite Links

The review now focuses on experimental work by the U.S. Government and includes earth-satellite paths.

Experiments with stand-alone sections of a brick wall and wood-frame wall typical of residential construction were reported by the National Bureau of Standards (ITS).[12,13] TABLE 3 gives the median of loss due to insertion of a wall. Probability distributions for all five frequencies can be found in the reports. Comparisons are fair with lists published earlier in 1959 (TABLE 4),[14] and more recently in 1988 wherein wood and brick siding had a 2 dB attenuation at 800/900 MHz.[15]

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[10] Horikoshi, J., K. Tanaka and T. Morinaga, *1.2 GHz Band Wave Propagation Measurements in Concrete Building for Indoor Radio Communications*, IEEE Transactions on Vehicular Technology, vol. VT-35, no. 4, November 1986.

[11] Cox, D., *Universal Portable Radio Communications*, IEEE Transactions on Vehicular Technology, vol. VT-34, no. 3, pp. 117-121, August 1985.

[12] Gierhart, G.D., L.G. Hause, J.E. Farrow, and M.T. Decker, *Insertion Loss of a Brick Wall at UHF*, National Bureau of Standards (ITS) Report 7272, Boulder, CO, June 26, 1962.

[13] Gierhart, G.D., L.G. Hause, J.E. Farrow, and M.T. Decker, *Insertion Loss of a Frame Wall at SHF*, National Bureau of Standards (ITS) Report 7273, Boulder, CO, June 26, 1962.

[14] Bachynski, M.P., *Microwave Propagation Over Rough Surfaces*, RCA Review, vol. 20, no. 2, pp. 308-335, June 1959.

[15] IEEE Vehicular Technology Society Committee on Radio Propagation, *Coverage Prediction for Mobile Radio Systems Operating in the 800/900 MHz Frequency Range*, IEEE Transactions on Vehicular Technology, vol. 37, no. 1, February 1988.

TABLE 3

MEDIAN VALUE OF WALL INSERTION LOSS
(Refs. 12 & 13)

WALL TYPE	Freq.(GHz)	Loss(dB)
Brick	0.518 1.5	2.3 2.4
Wood-frame	4.7 9.4 23.0	5.3 3.9 14.2

TABLE 4

WALL ATTENUATION AT 3.26 GHz
(Ref. 14)

WALL TYPE	ATTEN.(dB/cm)
Dry brick	0.5
Dry Wood E-field along grain E-field across grain	 1.1 0.5

Gierhart et al noted that at SHF, significant diffractive and periodic effects were caused by the studs and lap siding of the wooden frame wall. Similar effects were seen in measurements for seventeen masonry buildings in a follow-up study at 180 and 750 MHz.[16] It was found that absorption by brick or sandstone cannot be separated statistically from the effects produced by the gross structural features of the buildings. Standard F and t tests were applied to determine significance.

[16] Snider, J.B., *A Statistical Approach to Measurement of RF Attenuation by Building Materials*, National Bureau of Standards (ITS), NBS Report 8863, July 1965.

The "shielding effectiveness" (conversely building attenuation) of structural materials were compiled for a recent study by the Electromagnetic Compatibility Analysis Center (ECAC), Annapolis, Maryland.[17] Graphs of attenuation (dB/cm) vs. frequency are presented for common building materials, metal sheets, wire mesh and steel girders.

With the advent of portable indoor transceivers communicating with aircraft and earth-orbiting satellites, building penetration at high elevation angles is becoming more important. Among the few sources of information for higher angles is the experimental work of the ITS, NTIA in Boulder, Colorado, on UHF signals from geosynchronous satellites.[18,19] The signal received from the ATS-6 satellite at 0.86, 1.55, and 2.6 GHz (about 45 deg elevation angle) was measured in residential homes in five American cities. The goal was to determine the feasibility of using satellites to broadcast disaster warnings. Homes with wood siding were found to have an average loss of 5.7 dB, whereas wood-siding with brick-veneer homes averaged 6.9 dB.

H. Liebe,[20] also at ITS, studied the problem of potential "hot spots" created within habitable structures exposed to microwaves radiated earthward from the proposed Satellite Power System (SPS). Three coupling mechanisms were considered for penetration of energy into three types of real structures characterized by their main electrical properties. For example, energy may enter a brick house through diffuse-aperture coupling because of the lossy dielectric property of brick. Liebe's approximations for transmission through wood and frame walls (15% and 40% respectively) compare favorably with the 6 dB average (25%) reported by Wells (Ref. 19). Aperture coupling is also mathematically developed and related to building attenuation in Wells et al.[21]

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[17] Barton, M.A., M.C. Fahler, and D.L. Patrick, *EMC Analysis of EMI to Computers and Computer-Associated Equipment Located in a Proposed Building at Carlisle Barracks, PA*, DoD Electromagnetic Compatibility Analysis Center, ECAC-CR-89-013, 46 pages, May 1989.

[18] Wells, P.I. and P.V. Tryon, *The Attenuation of UHF Radio Signals by Houses*, U.S. Department of Commerce, Office of Telecommunications (NTIA), OT Report 76-98, 88 pages, August 1976.

[19] Wells, P.I., *The Attenuation of UHF Radio Signals by Houses*, IEEE Transactions on Vehicular Technology, vol. VT-26, no. 4, pp. 358-362, November 1977.

[20] Liebe, H.J., *Field Maxima Inside Habitable Structures Exposed to 2.45 GHz Plane Wave Radiation*, NTIA Report 80-49, 37 pages, October 1980.

[21] Wells, P.I., D.A. Hill, A.G. Longley, R.G. Fitzgerrell, L.L. Haidle, and D.V. Glen, *An Experiment Design for the Measurement of Building Attenuation*, U.S. Department of Commerce, Office of Telecommunications (NTIA), Technical Memorandum OTR 75-199, 108 pp., May 1975.

Recently, ITS personnel reported measurements of building penetration losses at 0.9, 11.4, and 28.8 GHz for a reinforced concrete building, a brick-veneer wood frame residence, and a metal-sided building.[22] The results generally agreed with those of other investigations in the same frequency range by showing a loss through solid walls with increased frequency (Refs. 16, 18). Comparison was best with Wells and Tryon's data for residential homes (Ref. 18).

Penetration loss into a commercial building is highly dependent on the percentage of window space for frequencies with wavelengths that are not many times larger than the windows (personal communication, R.C. Allen). However, window space appears to vary little in residences and may not be an important parameter.

General Measurements Across the Lower Radio Frequency Band

The typical paper considered thus far in this literature review has been one which covers one to three frequencies in the higher end of the radio band. To expand the discussion, the frequently cited works by Rice at 35 and 150 MHz,[23] and Smith,[24] and Mir and White[25] between 0.1 and 500 MHz will form the basis of the following discussion.

Rice

Rice (Ref. 23) is the earliest paper located in the literature search dealing exclusively with "radio transmissions in buildings." Losses within 11 large buildings of reinforced concrete or brick in New York City were measured at 35 and 150 MHz. The over-all building losses (main floor value referenced to the median field intensity in the street outside) were about 24 dB for 35 MHz and 22 dB for 150 MHz. Figure 5 reproduced from Rice's paper shows his log-normal distribution curves for both frequencies. The large standard deviations are probably due to combining measurements taken throughout a building. Smith and Mir-White (discussed later) grouped measurements according to distance from the exterior wall and have smaller standard deviations.

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[22] Allen, R.C., N. DeMineo, and P.B. Papazian, *Measured Building Penetration Loss at 900 MHz, 11.4 GHz and 28.8 GHz*, Proceedings National Radio Science Meeting, USNG/URSI, Boulder, CO. Jan. 7-10, 1992. (Detailed technical report to be published in the near future.)

[23] Rice, L.P., *Radio Transmission into Buildings at 35 and 150 mc*, Bell System Technical Journal, vol. 38, no. 1, pp. 197-210, January 1959.

[24] Smith, A.A., *Attenuation of Electric and Magnetic Fields by Buildings*, IEEE Transactions on Electromagnetic Compatibility, vol. EMC-20, no. 3, pp. 411-418, August 1978.

[25] Mir, S. and D.R.J. White, *Building Attenuation and the Impact on Product Susceptibility*, IEEE Electromagnetic Compatibility Record, San Francisco, CA, July 16-18, 1974, pp. 76-84.

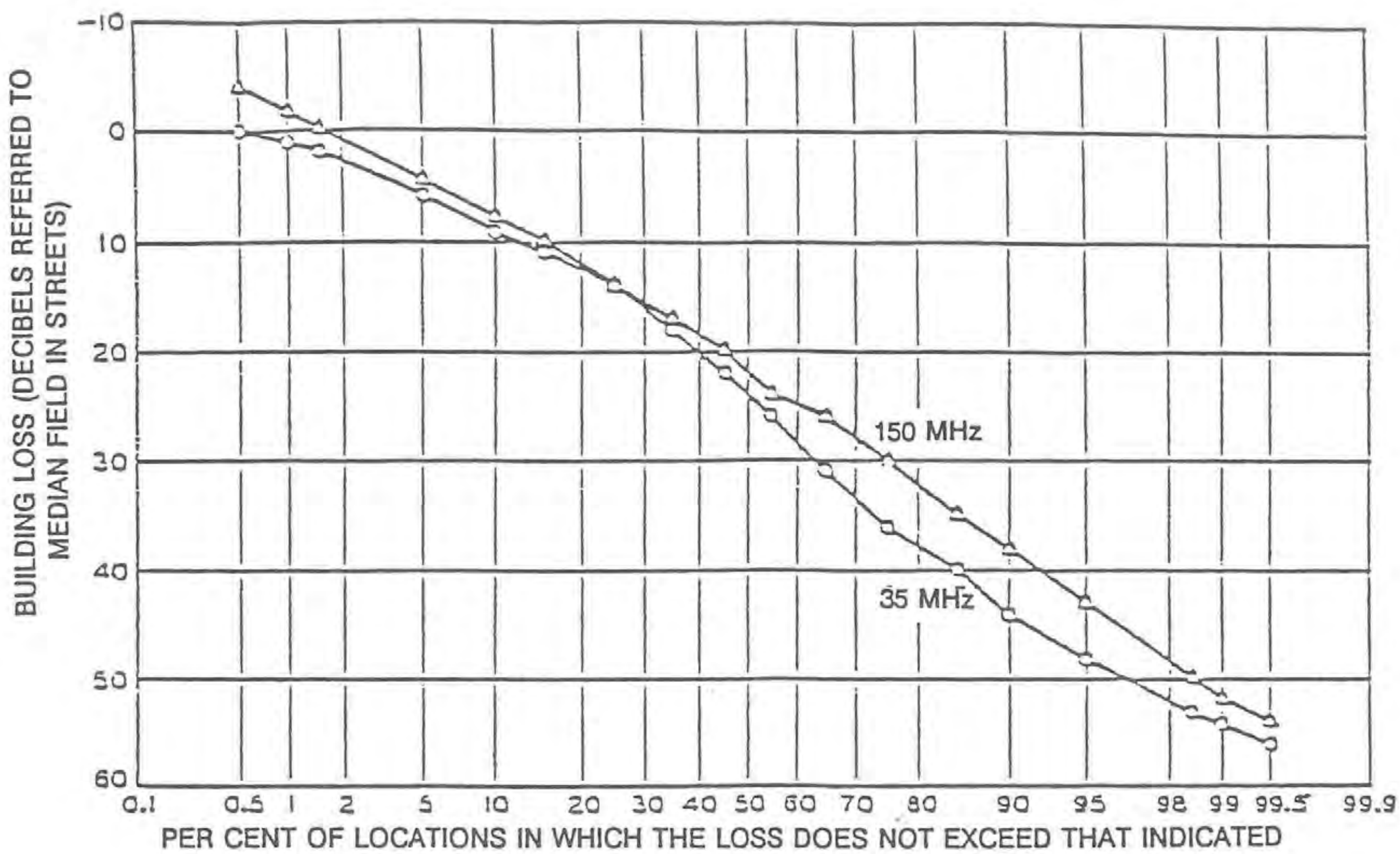

Figure 5. Over-all distribution of building losses at 35 and 150 MHz. (From Ref. 23)

Rice found noticeably less attenuation in buildings with high ceilings. This observation was not pursued by subsequent workers. Rice restricted his measurements to the main floor of the buildings after spot checks on the upper floors showed consistently less attenuation. Loss as a function of height was given for a low-ceiling building where the average loss at 150 MHz was 1 dB per 1.2 m.

Smith

Smith's measurements on electric and magnetic fields of seven buildings from 20 kHz to 500 MHz (Ref. 24) are probably the most quoted data in building attenuation. Selected according to the amount of metal in their construction, the measurement sites ranged from a wood-brick ranch home to a multi-story steel frame office building. Results were given in the form of separate E- and H-field plots of frequency vs attenuation for each building (14 charts total) followed by a discussion of the results. The charts and discussion are difficult to summarize further because the measurements are not done in a consistent manner even for buildings of similar type. For example, a curve is fitted from measured data for a wood-brick sided residence and from mean data for a residence with partial aluminum siding; hence, comparisons are difficult to make.

Mir and White

Mir and White reported on a survey spanning 1 kHz to 500 MHz in five downtown telephone central offices located in three Canadian cities (Ref. 25). The authors undertook this study after noting that earlier ones did not "adequately define a building attenuation model for both periphery and center core locations." All offices were of steel-girder brick or reinforced concrete with few windows. The standard deviation of all measurements just within the outside walls was only about 6 dB attesting to the uniformity of construction. Three attenuation-frequency graphs corresponding to the outside (roof and street), periphery (1.8 m penetration), and core (13.7 m penetration) are presented with mean values and standard deviations for the measurements. Mean values at selected frequencies are listed in TABLE 5.

TABLE 5

BUILDING PENETRATION, MIR AND WHITE
(Ref. 25)

	500 kHz	10 MHz	70 MHz	500 MHz
Difference between outside and 1.8 m inside outer wall	55 dB	25 dB	5 dB	8 dB
Difference between outside and 13.7 m inside outer wall	64 dB	40 dB	16 dB	30 dB

Mir and White conducted all measurements in telephone exchange buildings similar in materials, construction and function, all having little or no windows. From TABLE 5, attenuation is seen to decrease by about 20 dB per decade as expected for iron-grid construction (Ref. 25, p. 77). However, attenuation is dependent on the size of the grid. At 70 MHz where losses are least, the wavelength is equal to the diagonal dimension of the I-beam gridwork of the telephone exchanges.

Status of measurements across the RF band

In closing this discussion on building attenuation across the radio spectrum, we note that measurement difficulties are chiefly related to the great variety of architectural materials and design. These problems encountered earlier in UHF cellular measurements are exacerbated when spanning a wider frequency range. For additional information on this aspect, see pages 5 through 15 of Wells, et al. (See Ref. 21.)

Many of the references cited in this literature review also reported on measurements made in the orthogonal (crosspolar) plane to determine if polarization was important. Most found that although a large difference may be found at one location (10 dB or more) the differences become negligible when the results - usually the median - of several locations are combined. It must be remembered that an uncertainty in the polarization of a incident wave will always contribute a 3 dB mismatch.[26] This gives rise to the interesting possibility that an antenna most resembling an isotropic one (omnidirectional and nonpolarized) would be best for indoor reception (Ref. 23).

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[26] Balanis, C.A., *Antenna Theory: Analysis and Design*, Harper and Row, New York, pp. 51-53, 1982.

Experimental procedure including a detailed treatment of antenna selection and measurement theory for building attenuation studies may be found in Wells *et al* (Ref. 21). Another plan for the frequency range of 10 kHz to 10 GHz is outlined in Wyss et al (Ref. 3).

SUMMARY

Several facts can be gleaned from the foregoing literature survey. These will now be summarized starting with the two basic building types: commercial and residential.

For commercial buildings, attenuation is somewhat greater than for residences at lower frequencies. Presumably this is due to the use of steel frames and thicker walls of masonry or concrete. The steel girder skeleton found in most commercial buildings causes attenuation to vary inversely with frequency at UHF and below. It also contributes resonance and diffraction effects at frequencies above lower VHF. Attenuation decreases with height at about 1 to 3 dB per story and is affected by the total height and the environment of the building.

For single-unit residences, the building attenuation averages to about 6 dB for wood-brick material at VHF-UHF where most measurements are done. The comparable results found among investigators are probably due to the uniformity of wood-frame construction and the minimal use of metals such as structural steel.

The energy transfer or diffusion into a building can be altered by coupling mechanisms of certain architectural features. One important mechanism is aperture coupling which decreases attenuation by about 6 dB in buildings with many windows.

Statistically, signal medians appear log-normally distributed at any one frequency in the VHF-UHF band and decrease exponentially with distance from the signal source. At other frequencies, the signal distribution is less certain. Commercial buildings show more variability because of the greater use of structural and cladding metal, and wall space devoted to windows.

The E-vector polarizations of the incident signal and the receiving antenna appear unimportant provided enough data is taken at several points to remove the uncertainty of a point-by-point comparison.

TABLES 6A and 6B summarize the measurements from the most significant works discussed in this literature review. The table is taken from authors using equipment setups 2 and 3 (TABLE 1), and is in chronological order since authors often refer to the work of earlier investigators. The setups are not listed separately because setup 3 is often a subset of 2 in a measurement program. Allen et al (Ref. 22) had the only setup in which the transmitting antenna is inside the building and the receiving antenna is outside.

TABLE 6A
(page 1 of 2)

COMMERCIAL BUILDING LOSS MEASUREMENT SETUPS 2 AND 3

REFERENCE No., Author and year	FREQ. MHz	BUILDING ATTENUATION mean dB	BUILDING ATTENUATION std dev dB	LABEL Fig. 6A
23. Rice 1959				
11 bldgs, 2 freqs only				
First floor, urban	35	24	14	R
First floor, urban	150	22	22	R
16. Snider 1965				
16 bldgs, 2 freqs only				
Gnd floor, H-polariz.	180	5.5 med.	90%[a]	SN
V-polariz.	180	1.2 med.	90%[a]	SN
Gnd floor, H-polariz.	750	7.8 med.	90%[a]	SN
V-polariz.	750	5.8 med.	90%[a]	SN
25. Mir and White 1974				
5 tel. cent. offices				
most had no windows.				
1.8 m inside outer wall	1.0	51	9	M
within first row of	1.3	45	4	M
girders(various floors)	1.4	45	4	M
	10	27	6	M
	18	16	6	M
	35	15	9	M
	70	2	7	M
	95	2	6	M
	104	8	3	M
	116	7	6	M
	200	4	1	M
	470	8	5	M
13.7 m inside outer wall	0.6	61	16	
within three rows of	1.5	52	12	
girders(various floors)	35	34	2	
	80	16	15	
	100	15	4	
	140	14	6	
	500	30	10	

[a]90% confidence limits: 5.5 med., 24 to -9; 1.2 med., 15 to -10;
7.8 med., 25 to -7; 5.8 med., 20 to -7.

TABLE 6A
(page 2 of 2)

REFERENCE No., Author and year	FREQ. MHz	BUILDING ATTENUATION mean dB	std dev dB	LABEL Fig. 6A
24. Smith 1978				
5 distinctive bldgs.				
4-story steel-frame concrete office bldg.[b]				
1 m from ext. wall	1.0	28		SM
	1.5	24		SM
	1.6	26		SM
	70.0	0		SM
	80	0		SM
	90	1		SM
	100	0		SM
	110	-3		SM
	200	3		SM
	500	3		SM
5 m from ext. wall	1	43		
	1.5	40		
	1.6	38		
	90	2		
	500	14		
6. Walker 1983				
14 bldgs, 1 freq. only.				
First floor, urban	850	18.0	7.7	
First floor, suburban	850	13.1	9.5	
Both of the above	850	14.2	9.3	WA
7. Lee 1989				
Urban, cellular band[c]				
Chicago, 1st floor	800	15		
Tokyo, 1st floor	800	26		
"Intermediate"	800	20		L
22. Allen et al 1992				
3 freqs. measured				
Reinforced concrete building	900	9.4		A
Windowed, outside wall	11400	4.1		A
	28800	5.6		A

[b]Only building with a reported standard deviation (average standard deviation = 9.2 dB, range 0.5 to 19 dB).

[c]Secondary source, measurements not done by author. No standard deviations reported.

TABLE 6B
(page 1 of 2)

RESIDENTIAL BUILDING LOSS MEASUREMENT SETUPS 2 AND 3

REFERENCE No., Author and year	FREQ. MHz	BUILDING ATTENUATION mean dB		BUILDING ATTENUATION std dev dB	LABEL Fig. 6B
18. Wells and Tryon 1976 3 freqs. measured.					
Room with exposed (external) walls[d]					
Worse home type	860	7.5			WE
Best home type	860	2.9			WE
Worse home type	1550	7.8			WE
Best home type	1550	5.0			WE
Worse home type	2569	8.5			WE
Best home type	2569	5.8			WE
24. Smith 1976 2 distinctive homes.					
Wood-brick siding single-unit home.[e]					
	0.1	40[e]			SM
	0.2	26			SM
	0.3	22			SM
	0.4	20			SM
	0.6	28			SM
	0.7	30			SM
	0.9	30			SM
	1.2	13			SM
	1.3	12			SM
	7.0	7			SM
	30	17			SM
	70	3			SM
	80	4			SM
	90	15			SM
	100	5			SM
	105	5			SM
	200	3			SM
	201	0			SM
	203	-3			SM
	500	-5			SM
	500	-2	1.5 mean	6.0	SM
	500	5			SM
	500	8			SM

[d]Measurements on individual buildings of any one type will vary with a standard deviation of 3 dB. For room with no exposed walls, add 0.6 dB to each mean. Standard deviation remains at 3 dB.
[e]Measured data, not mean.

TABLE 6B
(page 2 of 2)

REFERENCE No., Author and year	FREQ. MHz	BUILDING ATTENUATION mean dB	BUILDING ATTENUATION std dev dB	LABEL Fig.6B
6. Walker 1 home, 1 freq. only. Alumin. sided home	850	7.3	6.7	WA
22. Allen et al 1992 3 freqs. measured. House with brick veneer exterior, windowed.	900 11400 28800	3.2 9.7 8.6		A A A

Setup 1 is not included since estimates of path loss encountered before penetrating a building can be found in Bullington (Ref. 5), Bachynski (Ref. 14), and other writings of a general nature. TABLE 7 is for setup 4 where a wall panel was used or where the authors did not specify the building type (commercial or residential). Details necessary for technical applications can be found in the original references in both tables.

In order to examine how building attenuation varies with frequency and building type, selected data from TABLES 6A and 6B are plotted separately in Figures 6A and 6B for commercial and residential buildings. Measurements within several meters of the exterior wall were chosen in order to minimize the effect of internal walls and furnishings, and to make comparisons more equal among the authors.

From the figures, we see that in general, commercial and residential building attenuations are minimum at about 100 MHz, and increase monotonically moving away from this frequency. The attenuation gradient for the higher frequencies appears to be one-half or less than the gradient for the lower frequencies in both figures. Figure 6A tends to confirm the approximate 10-20 dB per decade mentioned earlier for commercial buildings.

For residences, the situation at lower frequencies is still unclear. The data points (X) in Figure 6B by Smith (Ref. 24) are <u>single</u> measurements at discrete frequencies except at 500 MHz for one house (albeit a typical home with wood-brick siding), and may not necessarily indicate that a gradient exists as with commercial buildings. This uncertainty is emphasized in Smith's data for the only other residence he measured: a single-unit home with a aluminum-sided upper story. For this case, a fitted mean curve (not shown in this report) of many <u>averaged</u> points is seen to vary by only +/-3 dB between 1 and 200 MHz (see Ref. 24, Fig. 3).

TABLE 7

EXTERIOR WALL LOSS MEASUREMENT SETUP 4

REFERENCE number, author and year	FREQ. MHz	BUILDING ATTENUATION median dB	BUILDING ATTENUATION confidence level dB
16. Gierhart *et al* 1962: 1 Wall panel, 2 freqs. Brick, wood-frame	 518 1046	 2.3 2.4	 90% (7.0 - 0.1) 90% (4.1 - 1.2)
17. Gierhart *et al* 1962: 1 Wall panel, 3 freqs. Wood, wood-frame	 4700 9400 14200	 5.3 3.9 14.2	 90% (9.5 - 3.4) 90% (7.8 - 0.9) 90% (24.0 - 5.4)
5. Bullington 1977:[a] Brick exterior	 30 3000	 2-5 10-40	
19. IEEE V-T Soc. 1988:[b] Cellular bands. 8" concrete block Wood-brick siding Aluminum siding Metal walls (sic)	 800/900 800/900 800/900 800/900	 7 3 2 12	 σ = 1.0 σ = 0.5 σ = 0.5 σ = 4.0

[a]Secondary source, measurements not done by author.
Numbers are quoted as "typical values."

[b]Secondary source, measurements not done by author.

The foregoing summary of this literature review indicates that building attenuation is best understood at UHF and above, notably in the cellular bands. At lower frequencies, few measurements are available, especially for residential houses. The following section will focus on the development of a provisional building attenuation model using the results of the literature review.

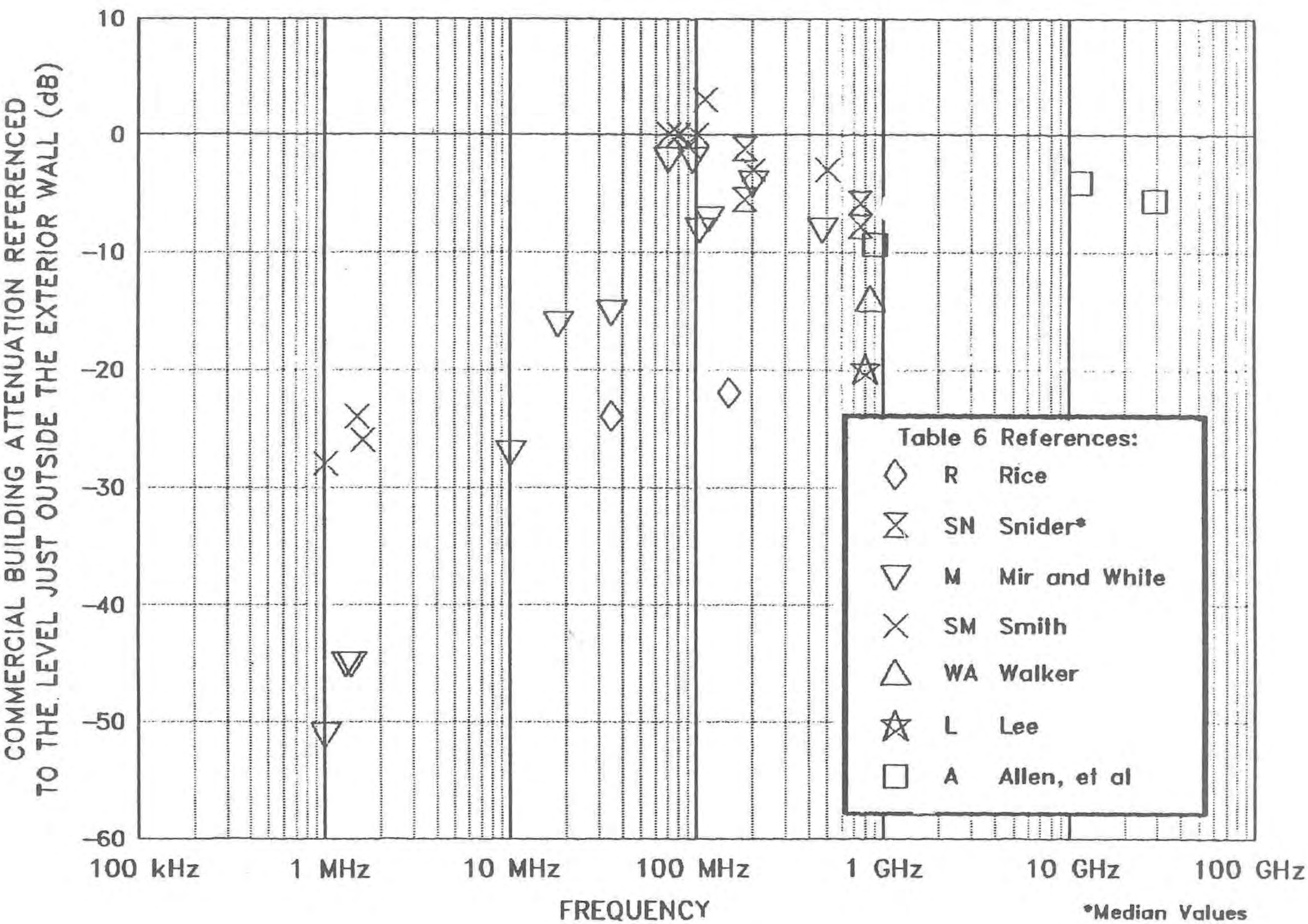

Figure 6A. Commercial Building Attenuation vs. Frequency.

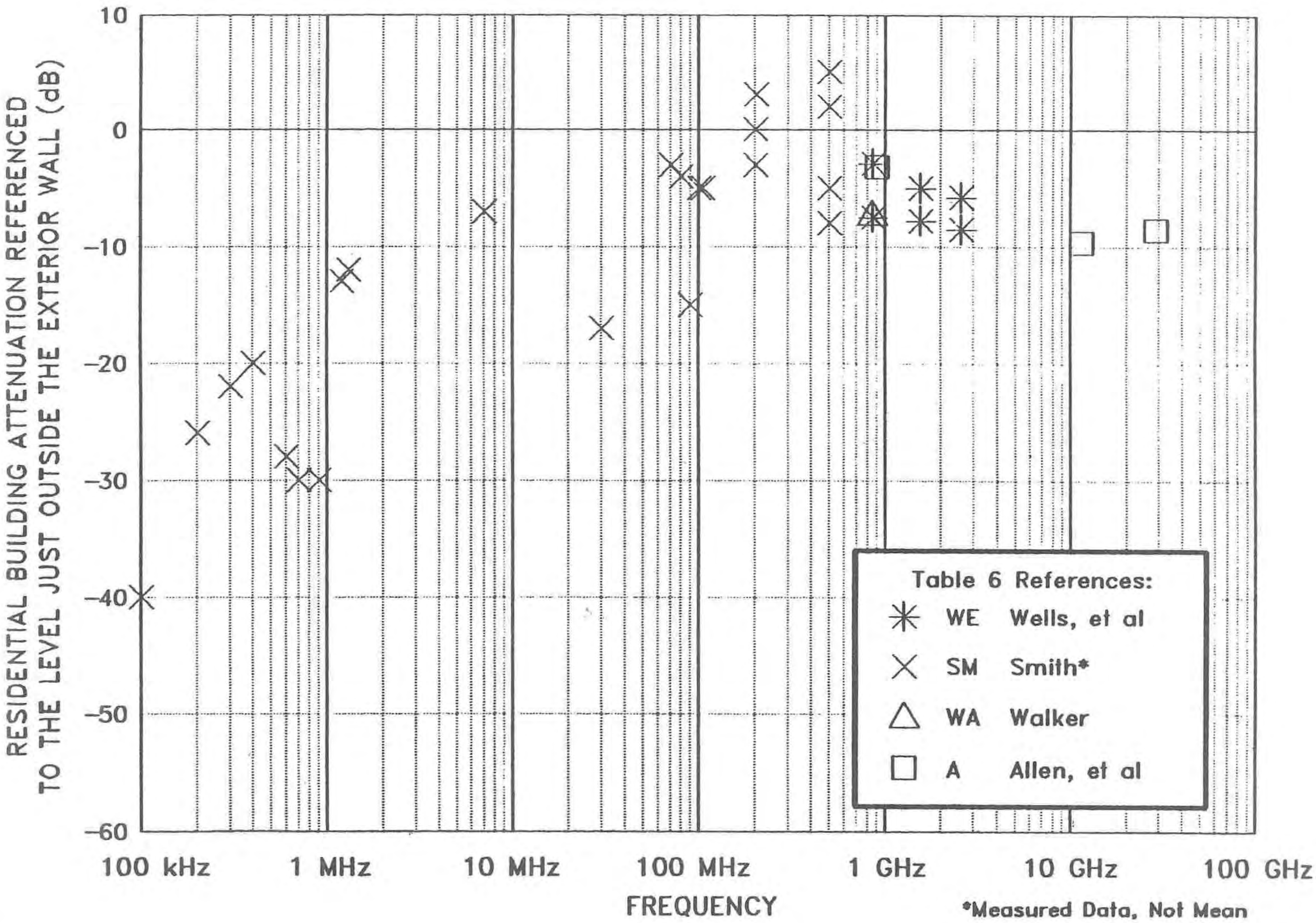

Figure 6B. Residential Building Attenuation vs. Frequency.

SECTION 4
PRELIMINARY BUILDING ATTENUATION MODEL DEVELOPMENT

INTRODUCTION

The development and realization of a building attenuation model depend on the following steps.

1. Identification of the areas in our knowledge where data is available for creating a model. The literature review showed that there are measurable differences in how building attenuation varies with frequency and building types (commercial or residential). Published data has been found to be best for commercial buildings at UHF and poorest for residences below UHF.

2. Creation of a model based on the measurements and statistical models found in the literature.

3. Verification and improvement of the model by field measurements.

The first step has been completed by the summary of the literature review section. The last two steps are the subjects of this section.

SPECIFICATIONS FOR A BUILDING ATTENUATION MODEL

The present model will be in the form of a graph depicting building attenuation as a function of frequency for each of the following cases:

1. Commercial: masonry or concrete with a steel girder framework, and

2. Residential: brick or wood siding with a wood framework.

The graph will follow the accepted practice of plotting relative power loss in dB against frequency on a log scale for a wide frequency band. Most contributions to the study of building attenuation use this form, whether they are primary sources of data (e.g., Refs. 24 and 25) or secondary sources.[27] The model ideally encompasses the range from HF to SHF, the frequency range of principal interest to the telecommunication services.

Separating measurements and their results by commercial and residential building types is a rule followed in most writings on building attenuation measurements. A typical project includes several buildings of one type only, e.g., urban business offices or large telephone central offices (Refs. 23 and 25). The few reports that include both residential and commercial buildings are careful to analyze them separately (e.g., Refs. 6 and 24).

The materials in the cladding and framework for the commercial and residential cases are reasonably clear from the description of buildings in the literature. Most investigators furnish adequate information (sometimes with a photograph and floor plan) of an individual building, even when seven or more buildings are involved in a study (e.g., Refs. 6, 16, 18, and 24). A typical commercial building (taken to be at least three stories high) has a steel girder framework with an outer wall of panels or poured concrete, or masonry consisting of brick or concrete block. By contrast, a typical residential house is a much smaller single-unit, one or two story structure with a wood framework covered by wood, or brick-wood siding. Thus commercial buildings have more metal and thicker exterior walls, and this difference is seen electrically in the somewhat higher penetration loss and steeper gradient loss at lower frequencies (compare Figures 6A and 6B). Also because of their greater size, attenuation with depth of penetration and the number of stories are considered for commercial buildings.

The foregoing discussion has established the graphical representation of the building attenuation model, and the reasons for separating commercial and residential buildings separately. The next step is to outline the form in which data is presented on the graph.

PRELIMINARY BUILDING ATTENUATION MODELS

From TABLES 6A, 6B, and 7 we see that measurement results are usually presented at discrete frequencies as a mean value with a standard deviation or as a median often with confidence limits. The only exception is Smith's measured data points for a wood-brick siding home in TABLE 6B (Ref. 13). Authors often fit a curve to data when values are available across a range of frequencies. Smith for example, employed fifth and third-order polynomial fits to accommodate his widely varying points; whereas, Mir and White applied a simple linear fit to

[27] EMCT Staff, *Electromagnetic Shielding Effectiveness (SE) of Buildings*, EMC Technology, volume 10, number 5, July-August 1991.

their points which had on the average, a smaller standard deviation (compare Refs. 24 and 25, and TABLE 6A).

For our model, the plotted data of TABLES 6A and 6B in Figs. 6A and 6B can be represented by a two-segment straight-line, least-square fit. This appears to be the simplest representation for both commercial and residential building attenuation. Such a model has been proposed for commercial buildings from MF to SHF (Ref. 27). Similarly, Golshan[28] combined results from Wells (Ref. 19) and recent University of Texas experiments to derive a smooth attenuation curve (which plots linear on a log frequency axis). However, Golshan's curve is limited to the higher frequencies, i.e., 700 MHz to 2.6 GHz. In the literature search only Smith appeared to have measurements for multiple frequencies below the UHF band for residential houses (see Fig. 6B in Ref. 24).

Metal-cladded structures are not included in this preliminary model because most authors consider their high penetration loss across the spectrum as nontypical and treat them separately. For commercial buildings, Walker, Cox et al, and Allen et al can be consulted on this aspect (Refs. 6, 8, and 22). For aluminum-sided houses, see Walker, Wells and Tryon, and Smith (Refs. 6, 18, and 24).

Commercial Building Attenuation Model

For the commercial building model (Fig. 7A), least-square fits for Smith's four-story office building and Allen et al's single-story laboratory building from Figure 6A were selected for the following reasons.

1. Buildings are of concrete, steel frame or reinforced, typical of commercial structures.

2. Amount of window area is typical of commercial buildings. Mir and White's telephone central offices were not selected because they have little or no windows. Alan et al's data are for exterior walls with approximately 50% window space.

3. Both have data taken at similar distances within the buildings. Measurements made closest to the outer wall were selected from Figure 6A.

[28] Golshan, N., *DIRECT BROADCAST SATELLITE-RADIO Systems Tradeoff Study*, Interim Report, Jet Propulsion Laboratory JPL D-8615, June 1991.

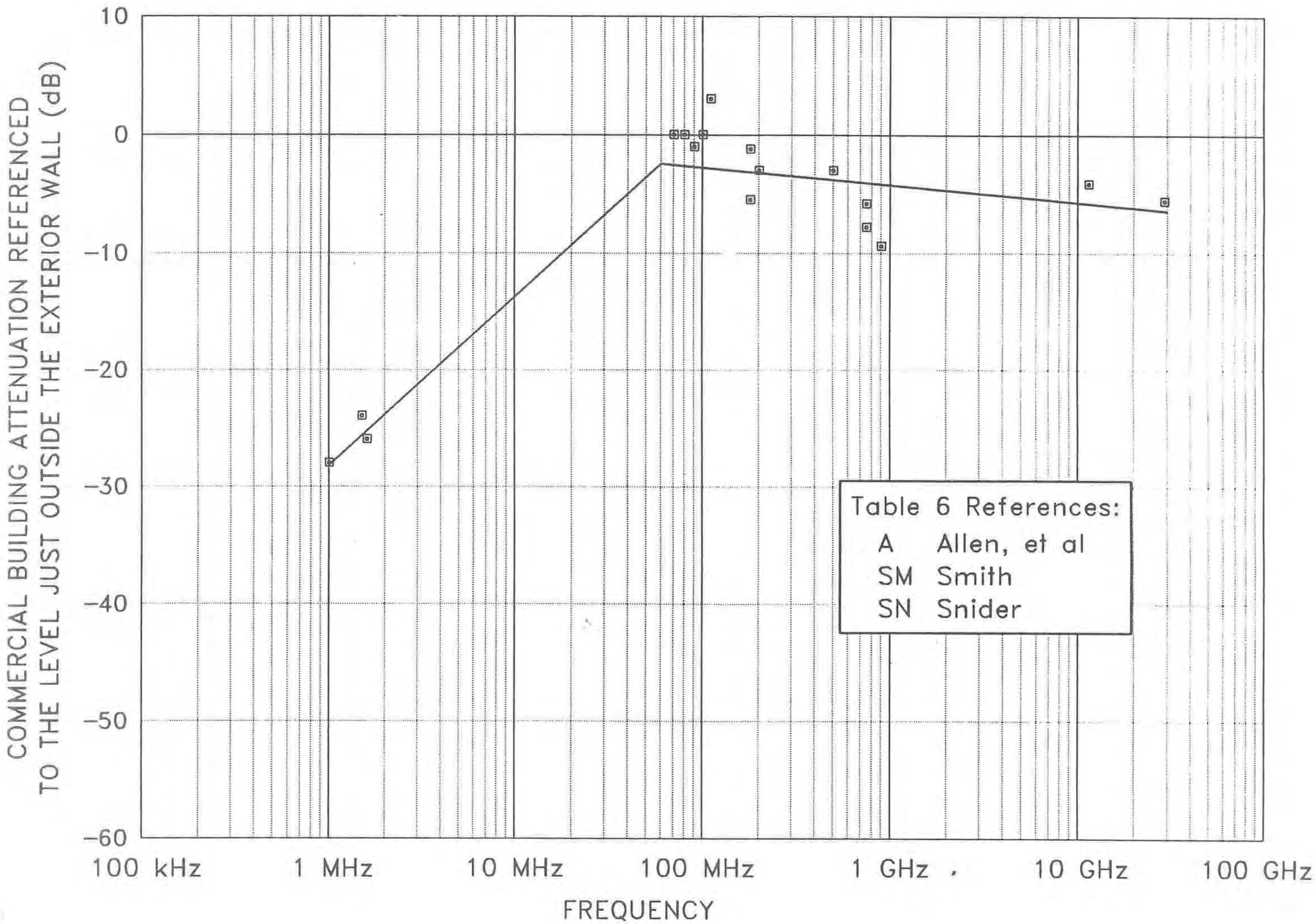

Figure 7A. Least Square Fit to Commercial Building Attenuation Points of Figure 6A.

The intersection of the least-square fit for Smith and Allen et al is at 60 MHz for a minimum attenuation of 2 dB. This frequency corresponds closely to Mir and White's 70 MHz "resonant" frequency for central office buildings (Ref. 25). Snider's results plotted in Figure 6A tends to confirm the model in the UHF region. No estimate of statistical reliability is given since the sources vary in their treatment of the data. If this information is desired, the reader should consult TABLE 6A and the original paper.

The equations for the line segments of Figure 7A are

$$A(f) = -28.6 + 14.9 \log f \qquad 1 < f < 60$$

$$= 1.3 - 1.7 \log f \qquad 60 < f < 30000$$

where $A(f)$ = attenuation in dB,

and f = frequency in MHz.

The reader is cautioned that a direct comparison cannot be made between a straight line, least-square fit on a semilog graph (as in Fig. 7A) and a straight line, least-square fit on a linear graph (not shown in this report). Points for a log axis are fitted by the equation $f(x)' = A' + B' \log x$, and not $f(x) = A + Bx$, resulting in very different curves for $f(x)'$ and $f(x)$.

The mean attenuation can be estimated for a typical situation as follows.

Given: A large steel frame office building several stories high with an outer wall of reinforced concrete.

Problem: Find the building attenuation close to the outer wall at 10 MHz.

Estimation: From Fig. 7A, the mean building attenuation is approximately 15 dB.

The effect of building height may be added to estimates derived from Figure 7A for certain frequency bands where measurements are available. The attenuation decrease per floor for the first few floors can be roughly estimated at -4 dB for VHF and -3 dB for UHF (Refs. 6 and 23) until zero dB is attained. For the 800-900 MHz region, very tall buildings can be accommodated on a graph derived by Lee from secondary sources (Ref. 7). For other frequency bands, the effect of building height is unknown.

Residential Building Attenuation Model

The residential building model (Fig. 7B) has a two-segment least square fit similar to the commercial model with a minimum attenuation of 3 dB at 200 MHz. Data are from Wells and Tryon, Allen et al, and Smith (Refs. 18, 22, and 24) for penetration loss through a wood or wood-brick sided wall of typical wood-frame single-family residences. The equations for the line segments of Figure 7B are

$$A(f) = -23.7 + 8.9 \log f \qquad 0.1 < f < 200$$

$$= 4.0 - 3.1 \log f \qquad 200 < f < 30000$$

where $A(f)$ = attenuation in dB,

and f = frequency in MHz.

The UHF portion of the upper segment is based on the extensive measurements of Wells and Tryon, and Allen, et al, discussed earlier in the literature review. According to Wells and Tryon, their measurements on any one of the buildings of one type vary with a standard deviation of only 3 dB (see TABLE 6B, footnote b). This fact can be used to estimate the confidence level to be placed on the graphical model at these frequencies.

The frequencies below the UHF band are the most poorly measured for residential houses. The least square fit based on data for a single wood-brick siding home from Smith is shown as a dotted line (TABLE 6B and Figure 6B). This line is poor for estimating purposes since measured data rather than averages are given. A comparison with Figure 6A would indicate that in going below UHF, residential building attenuation appears to increase at a somewhat slower rate than for commercial buildings.

Summary of the Preliminary Building Attenuation Model

The commercial and residential models are restricted to penetration loss through the external wall between approximately 1 MHz to 30 GHz. Metal-sheathed buildings require special consideration and are not included in the models.

For typical commercial buildings of masonry or concrete with steel framework or reinforcement, the minimum attenuation is about 2 dB near 60 MHz. From there, it increases

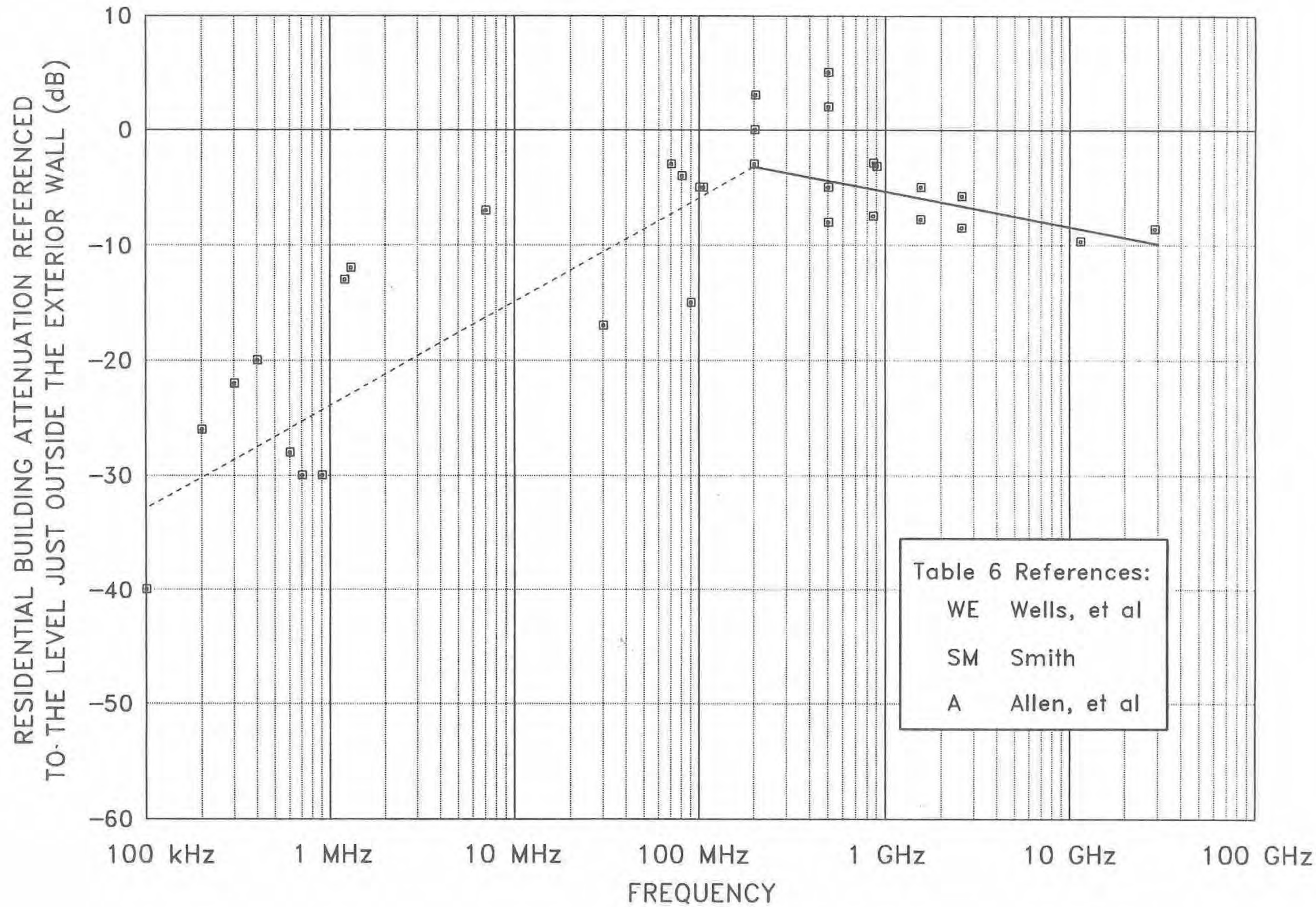

Figure 7B. Least Square Fit to Selected Residential Building Attenuation Points of Figure 6B.

at about 1 to 2 dB per decade toward higher frequencies and 15 dB per decade toward lower frequencies.

For residential houses typically of brick or wood siding with wood framework, minimum attenuation is about 4 dB at 200 MHz. Loss is about 3 dB per decade at the higher frequencies and 9 dB per decade at the lower frequencies. The latter is based on measured data rather than averaged points and should be taken as indicating a trend only.

The reliability of a building attenuation estimate may be obtained in most cases by consulting TABLES 6A or 6B for the standard deviation or confidence level. If these are not listed, the referenced paper itself may be of help. Statistical information is also found in measurements by others not listed in the table at the frequency of interest by consulting the LITERATURE REVIEW and REFERENCES Sections.

The next topic deals with improvements to the preliminary attenuation model by additional field measurements.

VERIFICATION AND IMPROVEMENT OF THE MODEL BY FIELD MEASUREMENTS

Introduction

The graphical model just presented yields preliminary estimates of E-field attenuation for commercial and residential buildings. But the model relies on the measurements of six investigators with confirmation at discrete frequencies by others, and needs to be verified by additional measurements over a wide range of frequencies for both types of building usage.

Statistical verification is also necessary because the contributors are not consistent in the way data are collected and analyzed. For example, Smith presented results differently for buildings of the same type in his report (Ref. 24).

Clearly, the probability distributions encountered in building attenuation measurements need to be identified and related to follow-through measurements in order to establish reliable confidence limits for the model.

Building Attenuation Statistical Distributions

From the discussion on the setups of Figures 2 and 3, the signal received within a building from an external source nearby is attributable to

1. a direct wave associated with attenuation through walls, ceilings, and floors of different materials, and

2. indirect waves of reflected and scattered energy from internal walls, partitions and objects in the vicinity of the receiving antenna.

The APPENDIX shows that the total probability distribution function (PDF) of the E-vector of the received signal is a combination of a lognormal PDF for the direct wave and a Rayleigh PDF for indirect waves. Mathematically, for large field amplitudes the lognormal PDF prevails and the direct wave is dominant. The converse holds for small-scale amplitudes where the Rayleigh PDF and indirect waves prevail.

The foregoing implies that for a sufficient number of large-scale amplitude measurements, the direct wave attenuation can be modeled as a random variable with a lognormal distribution. Then, the attenuation expressed in dB would have a normal distribution.

Measured Data and the Lognormal-Rayleigh Probability Distribution

Building attenuation measurements have tended to support the lognormal PDF model described above for certain VHF-UHF frequencies. Lognormal distributions were reported over 30 years ago by Rice for reinforced concrete and brick buildings at 35 and 150 MHz (Fig. 1). More recently, Cox et al's exhaustive studies made within suburban houses and metal buildings at 800 MHz concluded that large-scale signals were lognormally distributed (Refs. 8 and 9). Parsons and Gardiner in their 1989 summary of cellular radio measurement work stated that "...in general, the small-scale signal variations follow a Rayleigh distribution, and the large-scale variations are lognormally distributed, with a standard deviation related to the frequency and the transmission conditions relevant to the area under investigation..."[29]

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[29] Parsons, J.D. and J.G. Gardiner, *Mobile Communication Systems*, Halsted Press, Glasgow and London, UK, 1989.

Smith is the only author encountered in the literature review (SECTION 3) who assumed that the lognormal distribution was applicable over a wide frequency range (i.e., from HF to UHF). However, this was stated without any statistical qualification (Ref. 24).

A General Measurement Plan for the Attenuation Model

The fact that large-scale signals received through the exterior wall of a building are most probably lognormally distributed suggests the following general steps in a measurement plan for verifying and improving the attenuation model.

1. Measurements at a few frequencies within the VHF band to determine if the graphical model (Figs. 7A and 7B) and the lognormal PDF are still valid. More reliable confidence limits could be assigned to the model from these measurements.

2. Measurements at a few frequencies within the HF band for the same reasons stated above. Measurements should be made carefully because of the scarcity of data at these frequencies and the high building attenuation.

3. Measurements above the UHF band for the reasons stated above. Here some data are available for comparative purposes, and the attenuation is not as high as in the lower bands.

A Measurement Plan for Residential Houses, UHF and Below

The application of the general measurement plan described below is for residential houses; commercial building measurements would follow similar lines. The signal could come from sources set up for the measurements (Ref. 8), or from existing broadcast stations (Ref. 24).

1. Measurements in the VHF band.

Measurements begin at a frequency near 300 MHz, then at 100 and 30 MHz. According to Rice (Fig. 5 and Ref. 23) probability distributions are lognormal at 35 and 150 MHz; however, this lognormality is for commercial buildings, and should be verified for residential houses.

The following measurement procedure is a modification of those utilized by Cox et al and Wells and Tryon. An unobstructed signal from a transmitting antenna is measured at paired locations on each side of an exterior wall, and the average and mean signal strength (in dB) in a horizontal 2 m square area, 1 m height determined at each location. Measurements are done for two location pairs per room for three rooms. At least four typical houses (as described by Wells and Tryon) are surveyed for a minimum of 24 paired measurements.

From the results of Cox et al, we would expect the small-scale signals in each square to be approximately Rayleigh distributed and the large-scale distribution of the small-scale medians to be approximately lognormal. The latter is a normal distribution if measured in dB; therefore, we can obtain the mean and standard deviation required to check the graphical model and to express confidence levels. The probability distributions can be verified following the procedures detailed in Cox et al (Refs. 8 and 9).

2. Measurements in the HF band.

The measurement procedure above is also followed for frequencies near 1, 3, and 10 MHz, but with additional care because of the expected high building attenuation. Mir and White used high-powered AM broadcasts for their commercial building measurements (Ref. 25). The statistical distribution will be difficult to estimate if small and large-scale amplitudes are not readily separable.

Summary and Order of Priority for the Measurement Plan

A measurement plan has been outlined for verification and improvement of the preliminary building attenuation model. Verification starts in the UHF band where the average building attenuation and probability distributions are best known. Then measurements are extended to lower frequencies where data are scarce. As an example, a measurement plan for residential houses has been detailed.

The literature review has revealed where measurements are scarce and the model requires improvement. In order of priority, these are as follows.

1. Residential houses of brick or wood siding with a wood framework at frequencies below UHF.

2. Residential houses of aluminum siding with a wood framework at 1 MHz to 30 GHz.

3. Commercial buildings: penetration loss as a function of distance deep into the building at 1 MHz to 30 GHz.

APPENDIX

BUILDING ATTENUATION STATISTICS

A theoretical approach to characterize the electromagnetic field distribution after signal penetration of an enclosure such as a building has been examined by NBS (NIST) at Boulder, CO.[30] The E-vector of the received signal is represented as the summation of a direct wave through the outer wall, plus indirect waves from reflection and scattering effects. The vector amplitude E is expressed as

$$E = A_o e^{j\phi} + \sum_{i=1}^{N} A_i e^{j\phi_i} \qquad (1)$$

where A_o = amplitude of the direct wave, A_i = Amplitude of the ith reflector or scatterer, ϕ = phase, and N = total number of objects.

Direct path statistical distribution

A signal penetrating a building passes through layers of materials having certain definable properties, such as attenuation factor and thickness. The direct wave term in equation 1 is modeled in a form analogous to the effect for a transmission line as

$$A_o = K_o \exp \left[- \sum_{i=1}^{M} \delta_i \, d_i \right] \qquad (2)$$

where K_o = amplitude factor, M = number of layers, δ_i = is the attenuation constant for the ith layer, and d_i is the thickness or depth for the ith layer. The summation in the exponent is then

[30] Kanda, M., J. Randa, and N.S. Nahman, *Possible Estimation Methodologies for Electromagnetic Field Distributions in Complex Environments*, National Bureau of Standards (NIST), NBS Technical Note 1081, March 1985.

modeled as a random variable with a normal distribution by assuming a sufficient number of layers (Central Limit Theorem). This results in the direct wave attenuation, a power ratio, modeled as a random variable with a lognormal distribution. Attenuation expressed in dB would then have a normal distribution.

Indirect path statistical distribution

The second term in equation 1 superposing the effect of indirect waves presents difficulty, particularly for multiple scatterers. The conventional approach (also followed by Kanda et al) is to assume that the scatterers are widely dispersed so no mutual coupling exists, and are randomly oriented so that their phase distribution is uniform and independent of their amplitudes. Then the attenuation factor of the indirect wave superposition can be modeled as a random variable with Rayleigh distribution. This result also relies on the Central Limit Theorem to represent the net vector components as normal random variables to obtain the Rayleigh amplitude. Therefore, a large number of indirect paths is implicitly assumed.

Combined direct and indirect paths

The total probability distribution function (PDF) is given as a combination of the lognormal and Rayleigh distribution by Kanda et al (Ref. 30, equation 2.15). The authors go on to show that for large values of the field amplitude, the direct wave dominates and the total PDF reduces to a lognormal function. Conversely, for small field amplitudes, indirect waves dominate and the PDF becomes Rayleigh-distributed. One supporting measurement involving building attenuation was given by Kanda et al. This was a graph showing lognormal distribution for large field occurrences within a metal-wall building by Cox et al (Ref. 9).

The lognormal and Rayleigh probability distributions occur frequently in radio propagation statistics. For a general treatment of these PDFs which complements the special application by Kanda et al presented here, the reader should consult a recent report by the CCIR.[31]

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[31] CCIR, *Probability Distributions in Radio Wave Propagation*, Report 1007, vol. 5E, Reports of the CCIR, 1990, Annex to Volume V, Propagation in Non-Ionized Media, Geneva, 1990.

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FORM NTIA-29
(4-80)

U.S. DEPARTMENT OF COMMERCE
NAT'L. TELECOMMUNICATIONS AND INFORMATION ADMINISTRATION

BIBLIOGRAPHIC DATA SHEET

	1. PUBLICATION NO.	2. Gov't Accession No.	3. Recipient's Accession No.
	NTIA TECHNICAL MEMORANDUM 92-155		

4. TITLE AND SUBTITLE
PRELIMINARY BUILDING ATTENUATION MODEL

5. Publication Date
MAY 1992

6. Performing Organization Code
NTIA/OSM/SEAD

7. AUTHOR(S)
Herbert K. Kobayashi, Gary Patrick

8. PERFORMING ORGANIZATION NAME AND ADDRESS
National Telecommunications and
and Information Administration
179 Admiral Cochrane Drive
Annapolis, MD 21401

9. Project/Task/Work Unit No.
29012171

10. Contract/Grant No.

11. Sponsoring Organization Name and Address
U.S. Department of Commerce/NTIA
179 Admiral Cochrane Drive
Annapolis, MD 21401

12. Type of Report and Period Covered
TECHNICAL

13.

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.)*

In this technical report, preliminary graphical models spanning approximately 1 MHz to 30 GHz are developed for commercial and residential building attenuation. The models are least-square fits to the data available from the open literature. An estimate of the mean attenuation through the exterior wall can be made for most of the range of the models.

A measurement plan for verification and improvement of the graphical models is outlined, and an example of its application to residential houses at lower frequencies is provided.

The result of a literature review based on 31 references provides additional information for detailed applications. For this purpose, summarizing tables and figures are cross-referenced to primary sources of measurement data.

16. Key Words *(Alphabetical order, separated by semicolons)*

Building Attenuation Model and Measurements;
Lognormal and Rayleigh Distributions;
Penetration Losses; Shielding Effectiveness
VHF-UHF Band

17. AVAILABILITY STATEMENT	18. Security Class. *(This report)*	20. Number of pages
☒ UNLIMITED.	UNCLASSIFIED	47
	19. Security Class. *(This page)*	21. Price:
☐ FOR OFFICIAL DISTRIBUTION.	UNCLASSIFIED	