Propagation in Suburban Areas at Distances less than Ten Miles

By William Daniel and Harry Wong

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INTRODUCTION

In several recent rulemaking proceedings, it has been necessary to estimate the potential interference between devices operating in the same or adjacent frequency bands at relatively short distances. This was true, for example, in the recent revision of Part 15 of the Rules governing the operation of Radio Frequency Devices without an individual license (General Docket 87-389) and in the proceeding considering amendment of the Rules to provide for interactive video and data services (RM-6196). In these proceedings it has been necessary to estimate the interference potential between equipment operating in difference services at separation distances ranging from a few feet to several miles. Existing field strength prediction models are generally intended for use at greater distances and were based on, and verified with, empirical data from these greater distances. Those that do cover shorter distances generally revert to classical free space or plane earth propagation equations at these shorter distances. In the past, the Commission has usually based interference criteria on these free space and plane earth calculations, recognizing that the results would be, in most cases, very conservative.

As new services compete for scarce radio spectrum, the benefits to be gained by basing technical rules on more realistic estimates of service and interference increase. This report describes the development of a new mathematical model for predicting field strength levels within ten miles of a transmitter, taking into consideration frequency, distance, transmitting and receiving antenna heights, and building penetration losses. The model is intended as a general planning and allocation tool for frequencies between 40 and 1000 MHz. It assumes average conditions for a typical U.S. suburban area.

DERIVATION

For convenience of application, the model was developed in terms of field strength. Field strength values can be readily converted to transmission loss or receiver input power with equations provided.

A search was made for data at relatively short distances and relatively low antenna heights with the appropriate environment. Only a few surveys with directly applicable data were found. Added insight was gained from a review of theoretical propagation models and pertinent aspects of various propagation models and data for the broadcast and mobile radio services.

Theoretical models

For line-of-sight paths, with first fresnel zone clearance between the transmitting and receiving antennas, free space propagation can usually be assumed. Signals reflected from distance objects may produce delayed signals or ghosts. When the antenna heights are such that first fresnel zone clearance is not present for the entire path, the resultant signal is the sum of the direct and reflected ray. The amplitude and phase of the reflected ray depends on the path length, angle of reflection, ground constants and surface irregularities. At short distances lobing occurs with changes in distance or antenna height as the direct and reflected signals alternately add in and out of phase. At greater distances the signal monitonically decreases with distance. At still greater distances the curvature of the earth may become a significant factor. The distances at which these phenomena occur is a function of frequency and antenna heights. Hills, trees, buildings, etc., produce excess attenuation by absorbing, reflecting and scattering the signal.

The free space field strength in volts/meter is given by equation (1).

$$E_o = \frac{\sqrt{30Pg}}{D} \qquad (1)$$

where,

E_o = free-space field intensity in volts per meter,
D = distance in meters,
P = radiated power in watts
g = gain of transmitting antenna

Setting g = 1.64, gain of a half-wave dipole over an isotropic antenna, allowing for conversion factors for different units and taking 20 times the logarithm of each side, equation (1) can be converted to equation (2), which gives the field strength in a more convenient form.

$$F = 147.2 - 20\log(D) + 10\log(P) + G \qquad (2)$$

where,

F = field strength in dBu/m,
P = effective radiated power in Watts
D = distance in feet
G = gain of transmitting antenna with respect to $\lambda/2$ dipole.

Equation (3a) gives the plane earth field intensity in terms of the free space field intensity:

$$\frac{E}{E_o} = 2\sin\frac{2\pi H_1 H_2}{\lambda D} \qquad (3a)$$

where,

E = field intensity,
E_o = free space field intensity,
D = separation distance,
λ = wave length in free space,
H_1 and H_2 = centers of antennas above ground,
H_1 , H_2 ,D and λ in same units.

At small grazing angles, the sin can be replaced by its argument.

$$\frac{E}{E_o} = \frac{4\pi H_1 H_2}{\lambda D} \qquad (3b)$$

Multiplying both sides of equation (3b) by E_o , substituting 300/f for λ , and converting H_1 , H_2 and D to feet we get an expression for field strength in microvolts per meter.

$$E = \frac{88\ f\ H_1\ H_2}{300\ D^2}\sqrt{P} \times 10^6 \qquad (4)$$

where,

E = field intensity in microvolts per meter (uV/m),
P = effective radiated power in Watts,
f = is frequency in MHz,
H_1 and H_2 = centers of antennas above ground in feet,
D = distance in feet.

Overall trends

A review of material mentioned above led to a working hypothesis that the model should have the following characteristics:

no frequency trend,
a log-linear trend with distance,
a log-linear trend with antenna heights.

Further evaluation, as described below, established quantitative slopes for these trends as follows:

distance	$E \propto 1/D^2$	uV/m	or	$F \propto 40\log(D)$	dB
antenna heights	$E \propto H_1 \times H_2$	uV/m	or	$F \propto 20\log(H_1 x H_2)$	dB.

Egli[1] and Okumura[2] found trends with distance and antenna height to be independent of frequency for distances well within the radio horizon.

Egli, using data from an RCA survey[3] in the New York City area and data and analysis from Fine[4] (40 to 1000 MHz, distances 10 to 30 miles), compared measured signal levels with those predicted by the theoretical plane earth equation. He concluded that increasing losses due to terrain and ground cover (buildings, trees, etc.) offset the increase in field strength with increasing frequency predicted by the equation.

We note at this point that, while the data considered by Egli were taken at much greater distances and antenna heights than we are concerned with here, for analytical purposes it may be considered equivalent in certain respects. Taking the earth's curvature into account, the signal from a 500-foot transmitting antenna would have the same angle of arrival at 15 miles that a 30-foot antenna would at one mile. Provided the distant signal is not blocked by terrain or large buildings, one might expect to find similar trends with distance, frequency, local antenna height variations, local shadowing due to trees and houses, and building penetration losses.

Allsebrook & Parsons[5] reported mobile measurements in England which included extensive data for suburban areas at 86, 167, and 441 MHz (distances from 1 to 10 km). They concluded that their results "appeared to indicate that an inverse fourth power range law would provide a good estimate of the path loss values, and a model of the form proposed by Egli would be appropriate."

Cox, et. al.[6] made transmission loss measurements in and around four suburban single-family dwellings using a handheld transmitting antenna and a truck mounted receiving antenna at 12.5 and 27 feet above ground (frequency 815 MHz, distances 300-2300 feet). They compared the resulting data with theoretical plane earth calculations and concluded that the height dependence was "consistent with a simple model of reflections from the ground" and that the plane earth height-gain relationship appeared to be appropriate for relatively level terrain at small grazing angles where the sin can be replaced by its argument.

Short range data

Table I summarizes pertinent information on four studies which involved measurement data for the short distances and low antenna heights in which we were interested. Based on the antenna height trends described above, the data were adjusted to a common antenna height product (27 x 4.5 = 121.5) and effective radiated power (1 watt ERP). In some cases other adjustments were made as described below. The adjustments are also shown in Table I. The data, before and after adjustment, are plotted in Figures 1 and 2, respectively. Each point on the two graphs represents many individual measurements.

Cox, et.al.[7] made extensive measurements at 815 MHz in and around eight single-family houses in a suburban residential area of New Jersey. Transmission loss data were recorded at a mobile van located at various distances (from approximately 300 to 2300 feet) from each house. The transmitter was a handheld portable. Data were recorded for various rooms inside each house, including those on the basement and second floor levels where present, and for outside locations on all four sides of each house. The receiving antenna was mounted at 27 feet above ground and the portable was always scanned over a 4X4-foot area 4.5 feet above the ground or floor level.

The eight houses used in the Cox, et.al. study included a mix of single, two-level and split-level houses, with a variety of sidings and insulation types, on one-to-an-acre to five-per-acre lots, some with trees and some without trees. The data were extensively analyzed by Cox, et.al. on a house-by-house and cumulative basis.

In the present study, the Cox, et.al. data were considered to most nearly represent a typical U.S. suburban area and were used as a hallmark with which to compare the other data.

Based on the combined data shown in Table 1, the trend with distance was verified and the frequency variable was replaced with a constant. The result is shown in Equation (5).

$$E = \frac{11.6 \times H_1 H_2}{D^2} \sqrt{P} \quad \times 10^6 \qquad (5)$$

where,

E = field intensity in microvolts per meter,
P = radiated power in Watts,
D = distance in feet,
H_1 and H_2 radiation centers of antennas in feet.

The final expression for the median field strength is shown in equation (6), which was derived by converting equation (5) to dB above one microvolt per meter (dBuV/m) and adding a parameter for building penetration loss. Equation (6) with appropriate values for the various parameters is plotted on Figure 2.

$$F = 141.4 + 20 \log H_1 H_2 - 40 \log D + 10 \log P + B \qquad (6)$$

where,

F = field strength in dBuV/m
H_1, H_2 = antenna height in feet
D = distance in feet
P = effective power in watts
B = building penetration loss in dB.

As can be seen from Figure 2, there is close agreement between the final equation and the available data. When the field strength predicted by Equation (6) is greater than that predicted for free space propagation, the free space value from Equation (2), should be used. Equation (2), with appropriate values for the various parameters, is also plotted on Figure 2.

The antenna heights used in these equations are the heights of the antenna radiation centers above ground. Strictly speaking, the applicable range of equation (6) is one mile, but it can be assumed to be approximately valid for distances up to 10 miles. The upper limit on antenna height is 300 feet or until the free space field strength is reached. At short distances with one antenna appreciably higher than the other, the slant distance should be used with free space loss minus building attenuation. Equations (2) and (6) together provide an estimate of the median field strength value. Data measured over individual paths may vary considerably from the median.

Building penetration loss

The median value of building penetration loss for a typical suburban residential house is given in Equation (7).

$$B = -5.75 + 4.5 \log(f) \qquad (7)$$

where,

B = building penetration loss in dB
f = frequency in MHz

Figure 3 shows the data used to derive the building penetration loss, B, as a function of frequency. The value of B is always zero when both antennas are out of doors. If both antennas are located in separate houses, the value of B should be doubled. Again, B, represents a median value for a typical suburban, single family home. Measured values on individual house may vary over a wide range (0 to 22 dB were found during this study), depending on building material, size and location of windows, etc.

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TABLE I: Field Strength Data

Survey	Location	Reference	Smybol	Frequency (MHz)	Distance (feet)	H_1 (ft)	H_2 (ft)	$H_1 x H_2$	Field Strength (dBu)	Adjustment for Ant Ht (dB)	Adjusted Fld Str (dBu)
A	New Jersey	7	△	815	300	4.5	27	121.5	86.4	0	86.4
				"	1000	"	"	"	62.8	"	62.8
B	Tokyo	8	+	250	300	5	8	40	[illegible].7 74.5 *	9.7	84.2
				"	1000	"	"	"	41.2 53.6	"	63.3
			⁎	400	300	5	8	40	73.7 77.5	"	87.2
				"	1000	"	"	"	52.8 56.6	"	66.3
C	Red Bank	9	◊	850	262	5.9	30	177	87.8	-3.3	84.5
				"	656	"	"	"	68.7	"	65.4
D	McLean		○	218	400	7	7	49	71.2	7.9	79.1
				"	800	"	"	"	58.7	"	66.6
				"	1320	"	"	"	48.3	"	56.2

* [illegible]

Figure 1: Field Strength Data

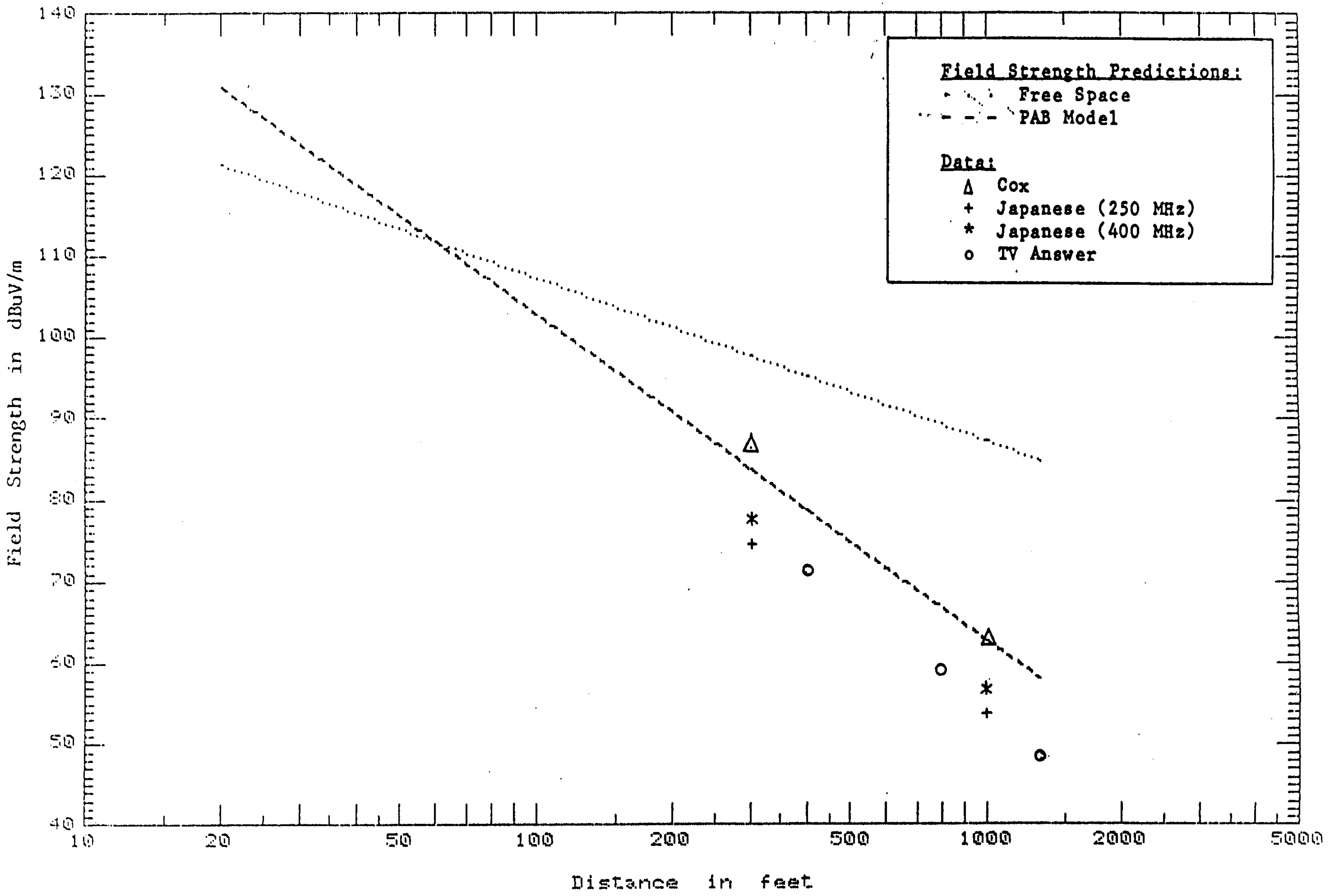

Figure 2: Field Strength Data with Adjustments

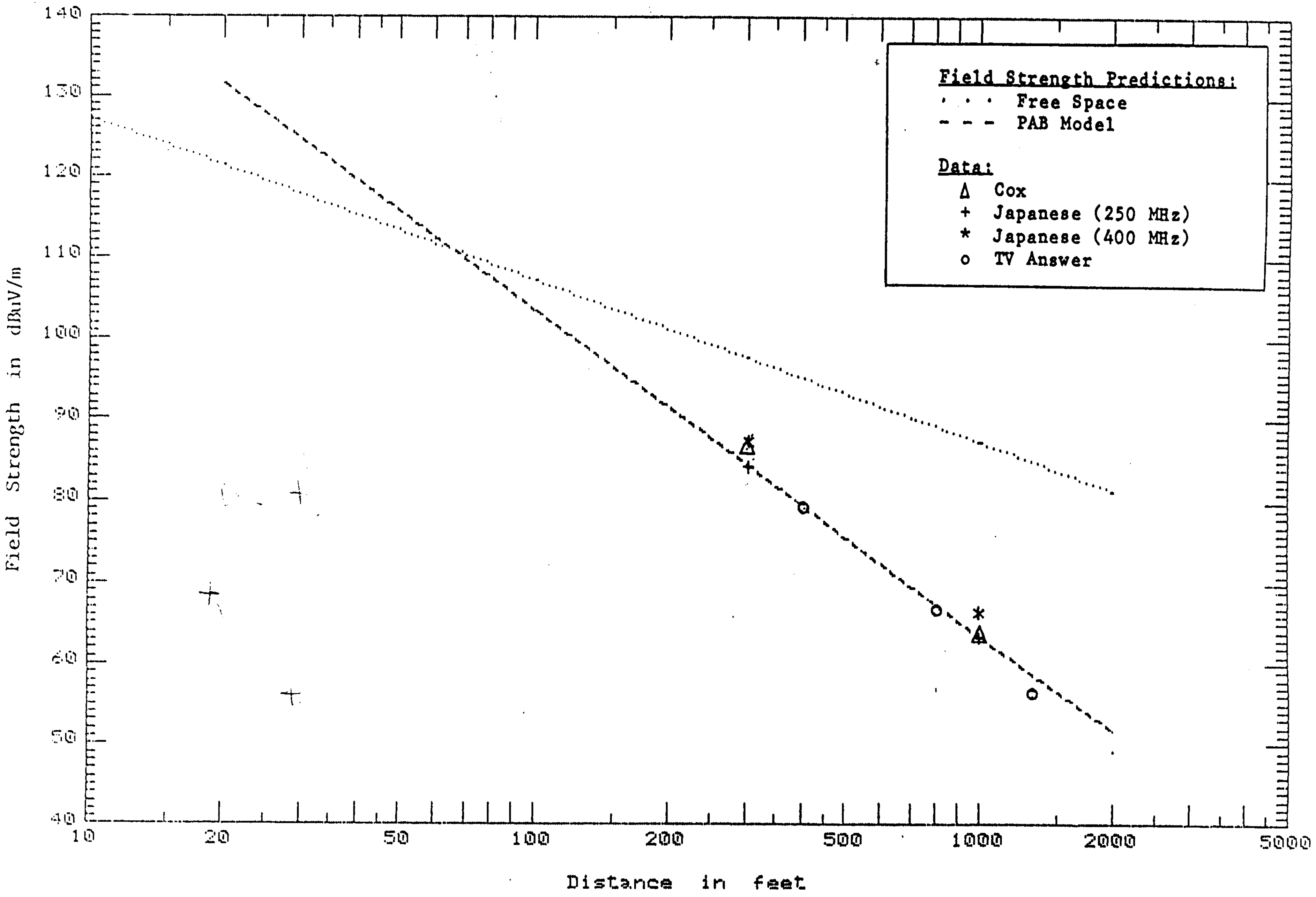

Figure 3: Building Penetration Loss