LEGAL DIVISION
404•894•4812

Georgia Institute of Technology
Office of Contract Administration
Atlanta, Georgia 30332-0420 USA

Telex: 542507 GTRC OCA ATL
Fax: 404•894•3120

March 8, 1993

BY CERTIFIED MAIL

Frequency Liaison Branch
Federal Communications Commission
Room 7326
2025 M Street, N.W.
Washington, D.C. 20554

Re: Experimental Radio Station Licenses KK2XBA and KK2XBB
Six Month Progress Report

Dear Sir/Madam:

Enclosed for your files is the six month progress report required under Special Condition #2 of each of the above-referenced licenses. If you have any technical questions relating to this report, you may contact Eric Barnhart at (404) 894-8248. Please give me a call at (404) 894-4812 for any administrative questions.

Sincerely,

Gail Gunnells

E. Gail Gunnells
Attorney

EGG/vc
Enclosure
cc: Eric Barnhart

INTERIM TECHNICAL REPORT
NUMBER 2
EXPERIMENTAL LICENSE:
KK2XBA and KK2XBB

By
Michael L. Witten
Leslie W. Pickering
Eric N. Barnhart

January 26, 1993

Communications Laboratory
GEORGIA TECH RESEARCH INSTITUTE
Georgia Institute of Technology

TABLE OF CONTENTS

LIST OF FIGURES

1.0 INTRODUCTION

On January 3, 1992 the Federal Communications Commission granted experimental licenses KK2XBA and KK2XBB to the Georgia Tech Research Instate (GTRI). The license was requested for the purpose of taking measurements to characterize the in-building propagation channel to support development of indoor wireless communications technology. Specifically, the objectives of the program are as follows:

(1) Advancing the body of knowledge in indoor propagation as applied to wireless, digital communications;

(2) To establish a technology basis for development of indoor wireless communications technology and services;

To meet these objectives, GTRI conducted an 8-month effort to collect, assess and document data related to indoor propagation for indoor wireless applications. This report documents the following key sub tasks of the effort:

(1) Definition of the methodology and measurement procedures including frequencies, modulations, and locations to be included in the data collection;

(2) Design of the measurement apparatus and definition of required instrumentation and recording equipment to support data collection;

(3) Determination of data reduction procedures and formats for correlation and presentation of data;

(4) Construction of the measurement apparatus and instrumentation including software development as required for instrumentation control and data collection;

(5) Collection of the propagation data;

(6) Normalization and preliminary assessment of the data collected.

1.1 Overview

The GTRI approach to channel characterization of the indoor wireless propagation path was to make a direct measurement of the channel transfer function in the frequency domain by transmitting thousands of discrete frequency tones over the channel and recording the amplitudes and phases of these tones at the receiver. The time-domain multipath profile was then developed by obtaining the Discrete Fourier Transform (DFT) of the frequency-domain data.

In an earlier program, an analysis had been done to determine the frequency spacing of the tones used to probe the channel. This parameter selection has been validated by all subsequent measurements. It should be pointed out that data collected to date (as can be seen in later sections of this report) indicates strongly that the frequency domain is the domain in which continuity can be observed. Probing signal bandwidths are not yet large enough (and probably would have to be considerably larger) to generate an observable continuity in the time domain.

Measurement results presented in this report are valuable and unique by virtue of three facts: (1) There is a serious dearth of channel transfer function measurements on the indoor channel; (2) There are no channel transfer measurements in the important 1850 to 1990 MHz passband (except those reported by Georgia Tech); (3) There are no channel transfer function measurements covering a bandwidth as large as the 1850 to 2200 MHz band used for some of the measurements in this report.

The need for channel transfer function measurements is unarguable. Important and popular communication system simulation models, for example, require the definition of a channel transfer function. In those cases where distortion is not important, the transfer function may be as simple as a single complex number (one amplitude and delay that applies to all frequency components).

In the most complex multipath fading environments, exemplified by the indoor radio channel, complicated statistical models that reflect the strong frequency dependence of amplitude and phase must be used. To validate such models, they must be compared with benchmark measurements of the type presented in this report, i.e. with direct measurements of indoor channel transfer functions across the band of interest. In the same vein, benchmark communication simulations, in their reflection of true performance, can do no better than using actual measured channel transfer function data.

The collected data described in this report and the statistical data that will result from the extensive processing efforts will lead to a channel model. The individual series of measurements, the uses they will be put to, and the degree to which preliminary examination of the data validate their original promise are discussed below.

The goal of the *Coarse Grain Track* measurements, as in the case of the earlier coarse grain grid measurements, was to develop channel statistics for statistical channel modeling. As in the earlier series, the measurements were spaced far enough apart to provide rough statistical independence. For this series, however, the measurements were made along a track to approximate typical paths followed by pedestrians carrying telephones. Such measurements, in addition to characterizing the pedestrian situation, also provide insights into the distance dependence of the statistics. The measurements in this series were made along the track in such a way that, within each cluster, there were a statistically sufficient number of independent channel samples. An examination of the actual data has revealed that to be the case. Within clusters, the samples evidence the required degree of rough independence from sample to sample. Between clusters, there are observable trends reflecting the differences in the distances between the (fixed) receiver and transmitter locations in the different clusters. These data, of course, are essential for statistical modeling of the indoor channel.

A series of measurements (*Extra Fine Grain Vertical Diversity*) was made to characterize spatial variation in the vertical direction, a variability that *must* be characterized in order to evaluate or model spatial diversity. The primary statistical quantity of interest, here, is the spatial correlation function (in the vertical direction). The degree of decorrelation characterizing the fading experienced by the same transmitted signal at two different receiving diversity antennas is the primary performance indicator of spatial diversity systems. Without knowing, or being able to estimate this correlation, there is no way to model the potential of spatial diversity as a technique for combating multipath fading. An examination of collected data show the required continuity from sample to sample. This continuity is sufficient to calculate the spatial correlation function in the vertical direction, and thus, after statistical processing, will be used to determine the degree of decorrelation.

A series of *Cross Polarization Effects* measurements were made to investigate these effects in a multipath fading environment. The measurements are intended to enhance understanding of RF signal propagation in the indoor environment. In a specific application of interest, such effects have a direct influence on the performance of frequency re-use schemes that make use of orthogonal polarization channels. The potential of such system approaches should always be explored when the maximization of channel capacity is critical. The main mechanism of degradation in such systems is cross-polarization, which results in the information data in each channel interfering with the information data in the other. These measurements show a very interesting trend that is discussed in Section 4.7.

Penetration measurements were also made. For modeling purposes, characterizations of walls will be a primary input to analytical models. In fact, the concatenation of losses through structural elements will be of fundamental importance in modeling to determine the outer reaches of the cell.

The measurements described above all relate to distortion on the indoor wireless communication channel. Such distortion can be enormous. The means by which any communication scheme deals with that distortion must be considered in any viable comparison of candidates. In this regard, there are three major functions to which the data described in this report can be applied: (1) Provide channel transfer data that can be directly used in simulations; (2) On the basis of a statistical breakdown of the data, develop *statistical* channel models for use in communication evaluation tools; (3) Based on a firm foundation of measurements and physical principles, develop a *physical* model of the propagation channel. The basic thrust of (2) is to develop a mathematical model of the channel that, in similar specified environments, has the same statistics as the real channel. The approach in (3) is to develop a model that draws on environment descriptions and calculates the parameters of the ray paths (and hence the transfer function) from fundamental electromagnetic principles.

Models that will be developed will derive from a foundation based on a blend of (2) and (3) above. This joint modeling approach will be taken to give the tool a broader utility, and move it away from a dependence on specific files of raw channel data. Important measures of multipath, such as multipath spread and correlation bandwidth, in conjunction with the spatial, spectral, and temporal dependence of same, will be related to the local geometries and structural elements of buildings, to provide a powerful tool in which these later quantities can be provided as inputs.

1.2 Organization of This Report

Section 2 of this report addresses the measurement test plan, the instrumentation and software developed to conduct and process the in-building propagation measurements. Details of the measurements locations appear in Section 3. In Section 4 of this report, the results of the tests are reviewed and key elements of the data are summarized. The data discussed include both frequency and time domain representations (transfer functions and impulse response) of the multipath channel. Also treated are penetration measurements which characterize the absorption of building interior features such as walls and doors. Trends in the data are identified, leading to the presentation of conclusions and recommendations in Section 5.

Additional detail beyond the scope of this report in the areas of background and the basis for the measurements conducted in this program are provided in Reference [1], which is the interim report produced by GTRI under this program entitled "Test Plan for Hitachi In-Building Communications Channel Characterization Design and Measurement Plan for Propagation Characterization."

2.0 INSTRUMENTATION AND DATA COLLECTION SYSTEM

2.1 System Hardware

To directly measure the path and multipath losses of the office environment in the frequency domain, an approach based on a Network Analyzer (NWA) was used. The transmit and receive antenna were placed at various locations in the building. The NWA treated the path between the two antennas as a network, and generated the system transfer function directly by sweeping through a set of frequencies and comparing the received signal to the transmitted one. Both amplitude and phase data were directly measured and recorded.

Details of the hardware implementation of the measurement system appear in Figure 2-1. The major components of the measurement system were as follows:

HP8510C	Network Analyzer
HP8360	Synthesizer/Sweeper
HP8511	4 port Test Set
HP37204	GPIB Bus Extender (2 ea.)
ZHL-4240	MiniCircuits Broad band Amplifier, 40dB gain (as needed)
ANAREN 40710	RF Splitter
ORTEL3510B	Fiber Optic Transmitter (6GHz bw)
ORTEL4510B	Fiber Optic Receiver
PC Clone/486	Personal Computer
Kreko: D300-A	(Modified) Broad Band Discone Antenna (2 each)
EMCO 3115	Double Ridged Guide Antennas (2 each, as needed)

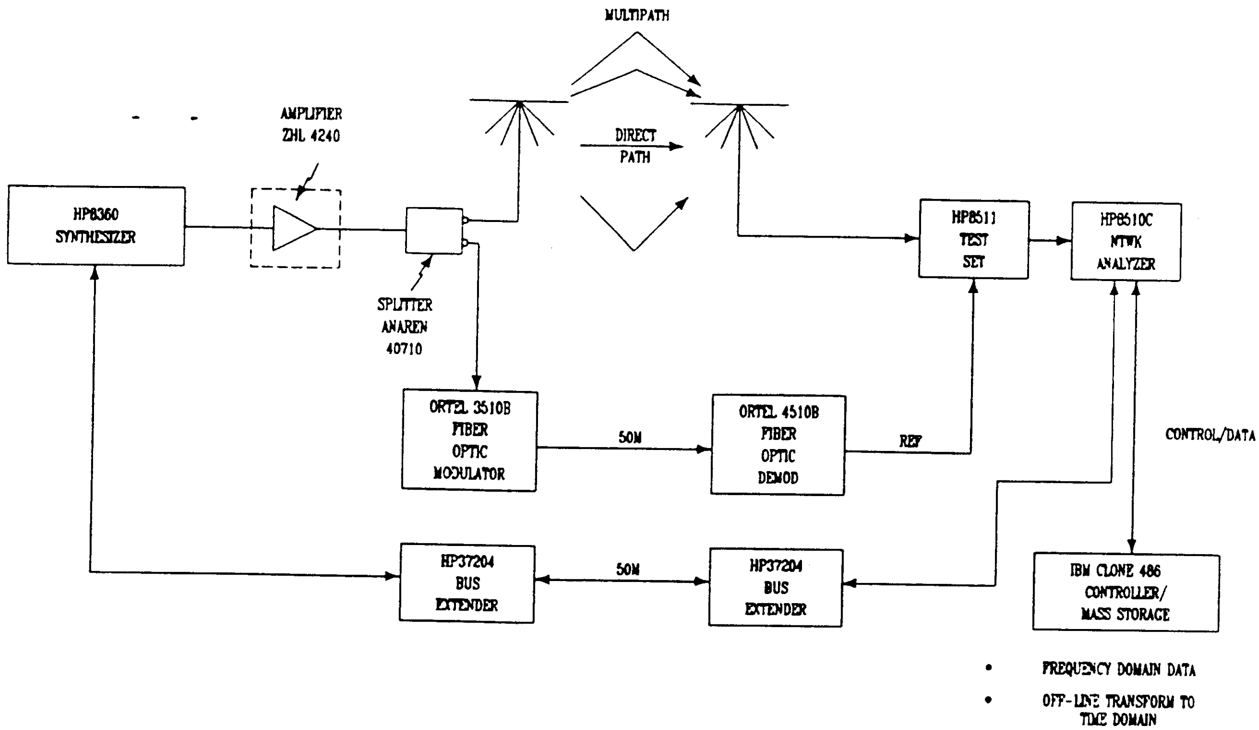

Figure 2-1 Measurement System Hardware Configuration.

To protect against RF leakage that could corrupt the measurements, double shielded coax was used for all RF cable runs greater than 4 feet in length. Shorter interconnects were made with semirigid cable whenever possible. When the goal of the measurement was to characterize multipath, the two discones were used. When the goal was to measure only path loss and to minimize the multipath effects, the EMCO ridged horns were used. The ridged horn antenna provides gain and directionality, both of which are desirable in this case. RF Absorber was used liberally on the antenna poles and on the carts containing measurement equipment to minimize reflections from these surfaces.

To take a measurement, the control computer commands the NWA to take a sweep of 801 points. The NWA in turn commands the synthesized source to step through the frequencies of interest. Commands to the synthesizer are passed through the GPIB bus extender. The synthesizer output was amplified and split with part of the signal being sent to a discone antenna, and part being sent to the reference port of the HP8511 test set through either a highly shielded cable or a broad band Fiber Optic transmitter/receiver pair. The fiber optics are used for the multipath measurements, and the cable was used in the penetration measurements. The NWA locks on this reference signal and compares the received signal to that of the reference. The magnitude and phase of this difference are stored for each point. Once the measurement is complete, the NWA dumps the data set, provided as real/imaginary complex pairs, to the control computer. The control computer then initiates the next sweep at a new set of frequencies. This process repeats until the desired band was measured.

The configuration used here was designed to minimize errors caused by RF cable leakage and by measurement system nonlinearities. The signal source was placed close to the transmit antenna to minimize the effects of cable leakage on the connecting cable. Since the NWA must (in this configuration) be near the test set and therefore the receive antenna, a bus extender was required to pass control information between the units.

This configuration also constrains the network Analyzer to be in "Step" mode for the sweeps, forcing the system to step through and lock on discrete frequencies one at a time. This was actually the more desirable mode (as opposed to "ramp" mode), as it provides greater precision in the measurements. All measurements were subject to at least 128 point averaging for each frequency measured.

To minimize the effects of nonlinearities in the system, the reference signal should ideally be taken from the last active component in the system. In this case, that would be the output of the amplifier, if any, or the synthesizer if no amplifier is present. This signal must then be connected back to the test set. This was the approach used by GTRI. To minimize cable leakage, a broad band fiber optic system was used to return the reference to the test set. This system provided a high quality reference for the network Analyzer, with minimal leakage and the ability to track minor variations in synthesizer or amplifier output.

2.2 System Calibration and Data Processing

Since the RF power to the amplifier and therefore the fiber optic system are constant from sweep to sweep, system nonlinearities, connector and cable losses (except for antenna effects) are accounted for by making regular calibration sweeps. These sweeps are performed with the antennas removed from the system, and the antenna cables connected directly through a coupler as shown in Figure 2-2. An attenuator was also placed in line to prevent overload of the test set inputs. With the antennas removed, a sweep was then made and stored to be used as a reference for that specific hardware configuration. The attenuators are assumed to be linear, and their effects are removed directly during processing. These calibration sweeps are taken any time system components are changed, as well as on a daily basis.

Raw data collected during the measurement process was corrected for variations in configurations and other major day-to-day system differences by correction with these through calibration sweeps. During data processing, each sweep was divided by the appropriate calibration sweep (in the frequency domain) to yield a data set that contains only the effects of path/multipath losses (the channel) and antenna effects.

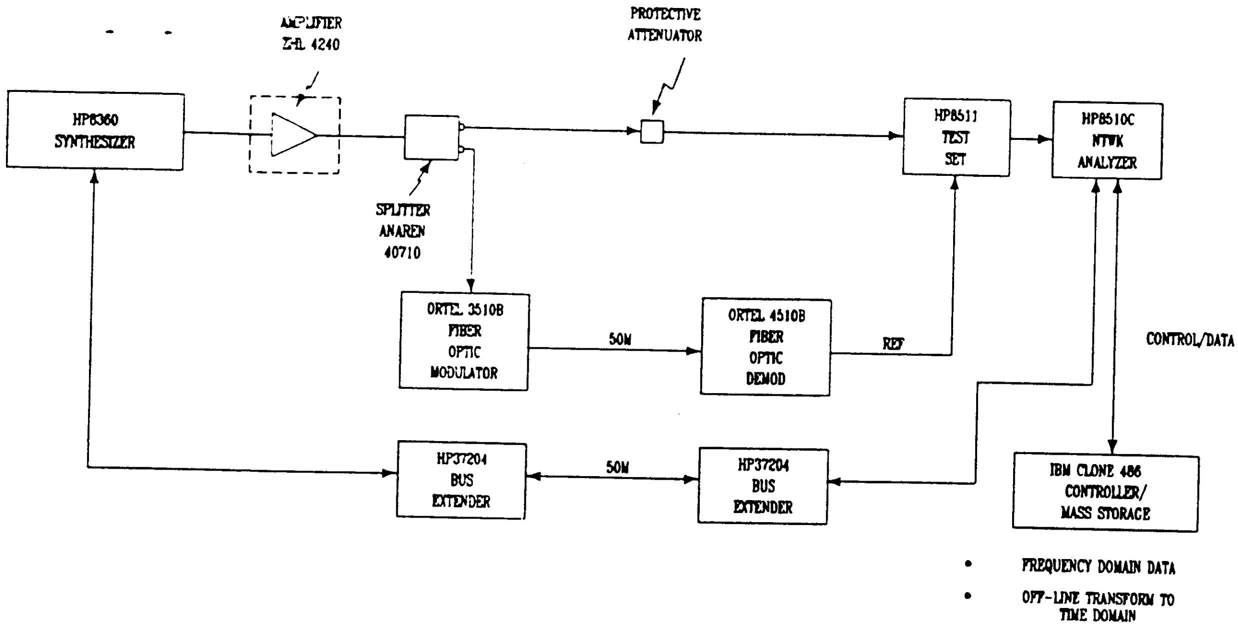

Figure 2-2 Measurement System Through Calibration Configuration

After the data has been corrected with the through calibration, the data is normalized to account for antenna effects such as gain and VSWR. To do this, a sweep was made with the antennas in an anechoic chamber at a fixed distance of 2 meters. This measurement, being in the far field of the antennas, was used as the absolute reference for all other measurements. This data, with its own "through" calibration information removed, was then divided into the corrected raw data to normalize for the antenna effects. The resulting data is the system transfer function with respect to a pair of isotropic antennas separated by 2 meters.

A somewhat simplified mathematical representation of the whole calibration/ normalization process appears below. The following definitions apply:

H_m	=	Transfer function of the data measurement.
H_r	=	Transfer function of the reference path.
H_{c1}, H_{c2}	=	Transfer functions of receive/transmit cabling.
H_{a1}, H_{a2}	=	Transfer functions of the antennas.
H_s	=	Transfer function of the environment (what we want)
H_{sc}	=	Transfer function of the ideal chamber environment with the antennas spaced 2 meters apart.
H_{tcal}	=	Measured through (no antenna) calibration.

H_{ccal} = Measured and corrected chamber calibration. For the removal of the cable and reference path effects, the measured data point (H_m) was divided by the measured through calibration (H_{tcal}):

$$H_m = H_r H_{cl} H_{a1} H_s H_{a2} H_{c2}$$

$$H_{tcal} = H_r H_{cl} H_{c2}$$

$$\frac{H_m}{H_{tcal}} = \frac{H_r H_{cl} H_{a1} H_s H_{a2} H_{c2}}{H_r H_{cl} H_{c2}}$$

To remove antenna effects, $H_{a1} H_s H_{a2}$ was divided by a calibration factor which includes the effects of the antennas and a 2 meter path in an echoic chamber (H_{ccal}). H_{ccal} (after processing as in the step above) = $H_{a1} H_{sc} H_{a2}$.

$$\frac{H_{a1} H_s H_{a2}}{H_{a1} H_{sc} H_{a2}} = \frac{H_s}{H_{sc}}$$

H_s/H_{sc} was the final result, which was the channel transfer function referenced to a pair of isotropic antenna with a 2 meter free space path distance. Additional information on how this processing was implemented is discussed in Section 2.3 below.

2.3 Software

The data acquisition and processing software are written in the "C" programming language. Standard subroutine packages were used to perform the inverse Fourier transform (IFFT), data conversion and plotting functions. The GPIB was programmed with subroutines provided by the GPIB interface manufacturer (National Instruments).

All processing and data storage was performed in the control computer. The results were stored both as raw data (as provided by the NWA) and as fully corrected data. All data is stored in the frequency domain.

Data processing consisted of correcting with the calibration files as described above, plotting magnitudes and phases of the frequency data, and converting the sweeps to the time domain. As received from the Network Analyzer, the data was in byte reversed, 32 bit IEEE standard floating point Cartesian point pairs (real, imaginary). Immediately after the data was received and the next portion of the Network Analyzer sweep (if any) was started, the data was byte swapped to make it usable. Once all the data for a given frequency sweep was collected, the data was viewed and stored.

Each raw file, as stored, contains a header with software revision level ID, a character array containing a one line description of the file, run power levels and other information needed for later processing. The description was provided by the operator at the time the data was taken. The other information was taken directly from the stored setup used by the computer to run the measurement. This information was then followed by the real/imaginary complex pairs of data.

Processing of the data involves a number of steps. First, a point-by-point complex division with the regular or "through" calibration run data was performed. Second, the data was divided again by the appropriate chamber measurement run (already corrected for its through calibration) to yield the "fully corrected" file. Detailed discussion of this calibration process is covered in Section 2.2 above. The corrected complex data was converted to Log Magnitude data (20log(data), Phase) and both magnitude and phase are plotted as desired.

2.4 General Measurement Procedures

Most measurements were taken in the Hitachi Telecom Norcross facility. Multipath and wall penetration measurements were taken in a variety of locations throughout the building. The remainder of the measurements were taken in the Hemphill warehouse facility on the Georgia Tech Campus. License constraints in effect at the beginning of the measurement period necessitated the inclusion of the Georgia Tech site. Nevertheless, this site represented a typical warehouse structure similar to that at the Hitachi Norcross facility.

2.4.1 Multipath Measurements

The frequencies measured were those allowed by the FCC license in effect, 1850-1990 MHz for the first few weeks, and 1850-2200 MHz for the remainder of the period. The narrower 140 MHz bandwidth provided a time domain resolution of 7.14 ns. Two 800 point sweeps were used to cover the band, yielding 1600 data points per measurement. Each sweep took approximately 54 seconds, yielding a measurement time of about 2 minutes per data set. With the acquisition, display and header entry process, each measurement took on the order of 2-3 minutes.

The 1850-2200 MHz sweeps represent the bulk of the measurements. This 350 MHz bandwidth provided a time domain resolution of 2.86 ns. Five 800 point sweeps were used to cover the band. Acquisition time, including header entry, storage and display averaged approximately 5 minutes per sweep.

Since the license allowed transmission on a non-interfering basis only and a number of local businesses had receivers within "range", maximum output power was adjusted to the minimum required for a given measurement location. Power output levels ranged from approximately 0 dBm up to +20 dBm. The different levels, accounted for in the various calibration measurements and in the reference path, only serve to move the noise floor up or down.

The noise floor was measured at least once for each receive antenna position. These ambient measurements are made by terminating the transmit antenna cable into a load and performing a run as usual. This data was used to verify that measurements were well above the average level of the noise floor.

Measurement system accuracy depended somewhat on the particular measurement. In general, the following tolerances apply:

MEASUREMENT ACCURACY

Antenna Position (absolute)	+/- 2. cm
Antenna Position (relative, base moved)	+/- .5 cm
Antenna Position (relative, base not moved)	+/- .1 cm
Antenna Position (high resolution)	+/- 2. mm
Frequency	10. Hz
Power	+/- 1.5 dB

The base of the transmit antenna was constructed with loaded bearing slide rails that could be very accurately positioned. The rail length was 50 cm. For this reason, if two measurements were made without moving the base, just by sliding the table, the much higher relative precision figure shown above could be achieved.

The anechoic chamber antenna-antenna calibration run used to correct the multipath measurements was made at a range of 2 meters. For this reason, all multipath results and plots in this report are presented with respect to ideal isotropic antennas separated by 2 meters.

To verify system accuracies, periodic re-runs of calibrations and measurements were performed. These measurements demonstrated repeatability consistent with the accuracies listed above.

A typical measurement was conducted as follows:

(1) The receive antenna was placed in the desired position, usually a pre-determined standard location used for most of the measurements. Absorber was placed on the receive cart as necessary.

(2) A transmit antenna location was selected, generally one of a series of locations pre-marked on the floor. Absorber was used to cover the antenna-facing side of the cart if necessary. The cart location was also selected to minimize its effect on the measurement.

(3) The computer initiated a run, setting the start and stop frequencies over which the 801 points were to be taken and starting the sweep. The typical first sweep covered the range 1850-1920 MHz.

(4) When the NWA signaled completion of data acquisition, the computer read the sweep from the NWA, set the next set of frequencies (1920-1990 MHz) and triggered the sweep. The computer then performed the byte-swap on the first set of data. This process was repeated until the full band had been measured.

(5) The NWA again signaled completion, and the last sweep of data was collected from the computer, byte-swapped and stored.

(6) A copy of this data was converted to log magnitude format and displayed. This gave the operator a chance to verify that no major glitches occurred during the run.

(7) The operator was queried for one line of header information. The file name was a three character series ID, an a, b or c depending on the frequency band being measured (1850-2200, 866-869, 902-928) and month and day of the run, followed by a three character extension representing the number in sequence that the file was for that day. For example: HIBA0205.006 was the 6th file taken on February 5, was a 1850-2200 MHz sweep, and was a measurement of the HIB series. The file was stored to disk. Pertinent run information was recorded in the written run log.

(8) At a later time, off site, the data was corrected and normalized to the daily through calibration run and antenna-to-antenna chamber calibration using the procedure described in the preceding section.

(9) If desired, the results were plotted in log magnitude and phase plots in the frequency domain, and (after the IFFT) with a magnitude stick plot in the time domain. Samples of these plots appear in Section 4.

2.4.2 Penetration Measurements

Some measurements were made with the intention of yielding a path-loss only figure. These measurements were made in basically the same way as were the multipath measurements, except that the EMCO ridged horn antennas were used in place of the discones. For through-wall measurements, absorber was placed on the floor between the two antennas (where possible) to minimize multipath. For penetration measurements, three series of sweeps were made, with one over the standard 1850-2200 MHz range, and the other two at 866-869 MHz and 902-928 MHz respectively.

Processing of this data was somewhat different from that of the multipath sweeps. First, a separate set of antenna-to-antenna chamber calibration files was created for each antenna-antenna distance used in the actual measurements. This value was used in the final data correction, yielding a final processed file that represents the difference between the transmitted power through the wall (or other object) and the power transmitted through the same amount of free space. Overall penetration measurement system accuracy is +/-.5 dB or better

Another difference in processing was the generation of a single loss value for each run. Since, for these measurements, the actual system transfer function was not the goal and multipath effects are not of interest, an RMS value for the loss was calculated. This value was formed using the fully processed data files to develop the RMS value of loss across the entire band measured.

3.0 DETAILED MEASUREMENT DESCRIPTIONS

In the actual measurement period of January 6 through March 4, 1992 in excess of 1000 multipath, penetration and calibration measurements were performed in and around the Hitachi Telecom facility in Norcross (FCC License KK2XBA), Georgia as well as the Georgia Tech Central Receiving warehouse on Hemphill road, Georgia Tech Main Campus (FCC License KK2XBB). A detailed rational for the physical layout of the measurements appears in [1]. Detailed descriptions of the measurement topologies appear below.

Any statistical processing of data referred to in the text of this section is for reference only. Such processing will be the focus of ongoing indoor channel model development work.

The measurements have been divided into 8 groups based on their topologies. Unless otherwise noted, all measurements were made with the receive antenna in a fixed location and the pattern (grid, linear series) formed by moving the transmit antenna.

All measurements in figures are metric. The figures are provided to give relative feature placement only and are not to scale. The origin of grid and high resolution track measurements are marked with an enlarged dot.

3.1 Coarse Grain Track Measurements

The goal here is to develop channel statistics for statistical channel modeling. As in the earlier series, the measurements are spaced far apart enough to provide rough statistical independence. This time, however, the measurements are made along a track to approximate typical paths followed by pedestrians carrying telephones.

Two series of measurements were made on coarse tracks, each made down a hall and around a corner. The first series was taken on 25 cm spacings, and can be seen in Figure 3-1. This series represents a typical hall construct, with both direct and reflected direct paths available.

The second series was made at 50 cm spacings down a hall and around a corner. In addition to being used for normal track analysis, this series was made with both a co-polar and cross-polar antenna orientation. Details of this series, including figures, are provided in Section 3.3.

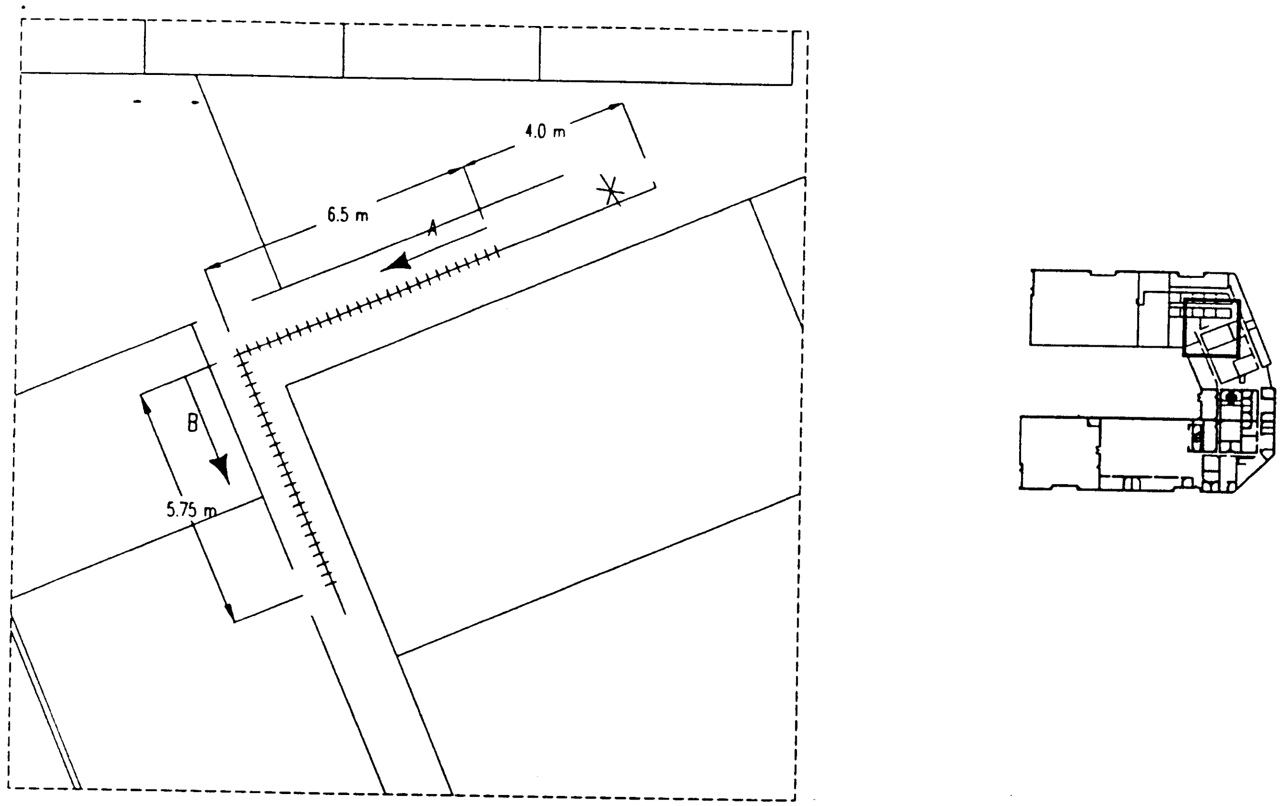

Figure 3-1 Hitachi Building 25 cm Linear Series.

3.2 Vertical Diversity Measurements

This series of measurements was made to directly characterize spatial variation in the vertical direction, a variability that *must* be characterized in order to do any spatial diversity evaluation or modeling. In all probability, base station spatial diversity antennas, if they are to be deployed at all, will be separated vertically. This is due primarily to the fact that, in a vertical deployment, each antenna is less likely to interfere with the pattern of the other. The primary statistical quantity of interest is the spatial correlation function (in the vertical direction). Without knowing, or being able to estimate this correlation, there is no way to model and evaluate the potential of spatial diversity as a technique for combating multipath fading without actually deploying candidate radios and antennas and measuring their performance.

The general approach to these measurements was to place the two antennas in different locations, and then take measurements with one of the antennas fixed and the other being raised for each new sweep. The antenna mounts for these series were only able to step in multiples of .75 inches (1.905 cm). Because of this odd increment, the descriptions that follow generally use a starting height and a step increment in place of individual heights for each measurement. Two series were measured.

3.2.1 Conference Room

This first set was made in the conference room described in Section 3.1.3 of [2]. The conference room measurements feature no direct or reflected direct path for RF between the antennas. This set consisted of measurements made in this room with the transmit antenna at two floor locations 1.5 meters apart, and the receive antenna in the hall as marked in Figure 3-2. At the first location, the transmit antenna started out located 148 cm from the floor, and was stepped in single increments for 16 more sweeps. At this point, the steps were increased to 10 increments (19.05 cm) each, and the sweeps were continued for 5 more (10 increment) steps.

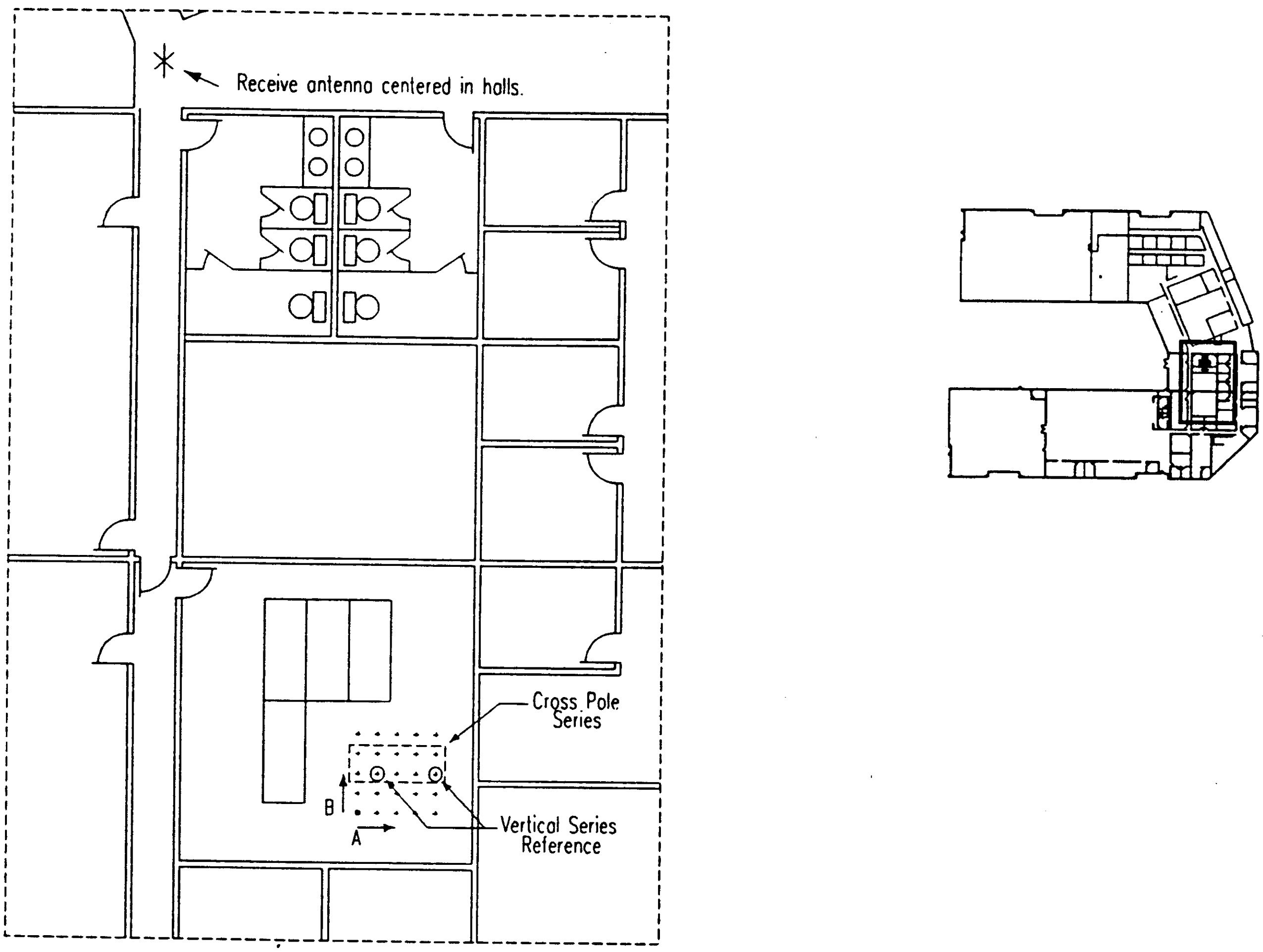

Figure 3-2 Conference Room Vertical Diversity Antenna Locations.

The transmit antenna base was then moved to a location 1.5 meters away to assure reasonable measurement independence from the first set while being within the same general multipath area. At this location, measurements were made at 10 increment spacing from 178.5 cm and continued for 5 (10 increment) steps.

3.2.2 Hall Locations

The second major series of vertical diversity measurements consisted of three subsets. With the receive antenna in three different locations, one for each series, the transmitter antenna was stepped in 10 increment steps from 150 cm above the floor to eight (10 increment) steps. The measurements were then resumed at height of 237 cm and continued for five additional (10 increment) steps. The break in the series was also an artifact of the antenna mount. The antenna locations, both of the three used for the receive antenna and the one used for the transmit antenna appear in figure 3-3.

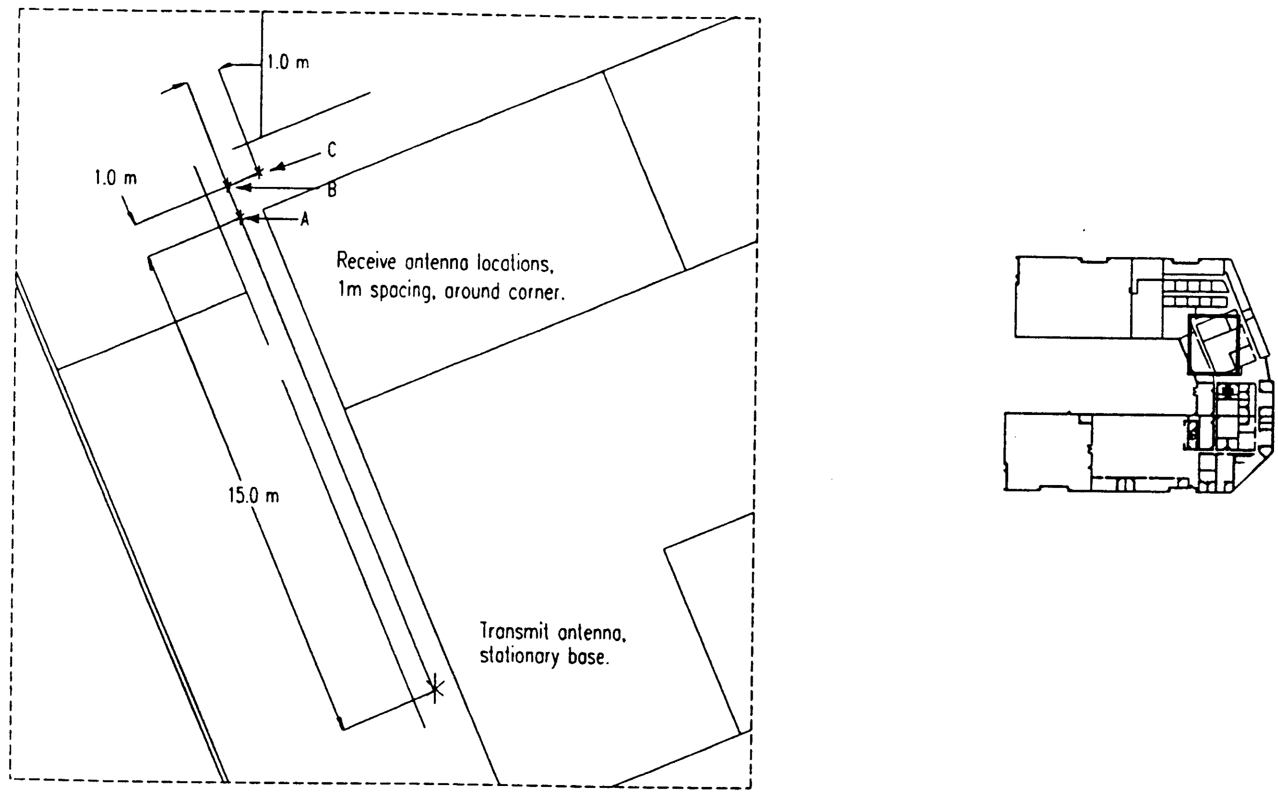

Figure 3-3 Hall Vertical Diversity Measurement Locations.

3.3 Cross-Polarization Measurements

This series of measurements was made to investigate cross-polarization effects in a multipath fading environment. Generally, it is important to have some insight into such effects in order to develop a full understanding of the way in which RF signals propagate in the indoor environment. Specifically, such effects have a direct influence on the performance of frequency re-use schemes that make use of orthogonal polarization channels. (These systems operate by transmitting two different information streams on the orthogonal polarizations.) Although the demand may not *now* be that great, the potential of such system approaches should always be explored when the maximization of channel capacity is critical. The main mechanism of degradation in such systems is cross-polarization which results in the information data of each channel interfering with the information data of the other.

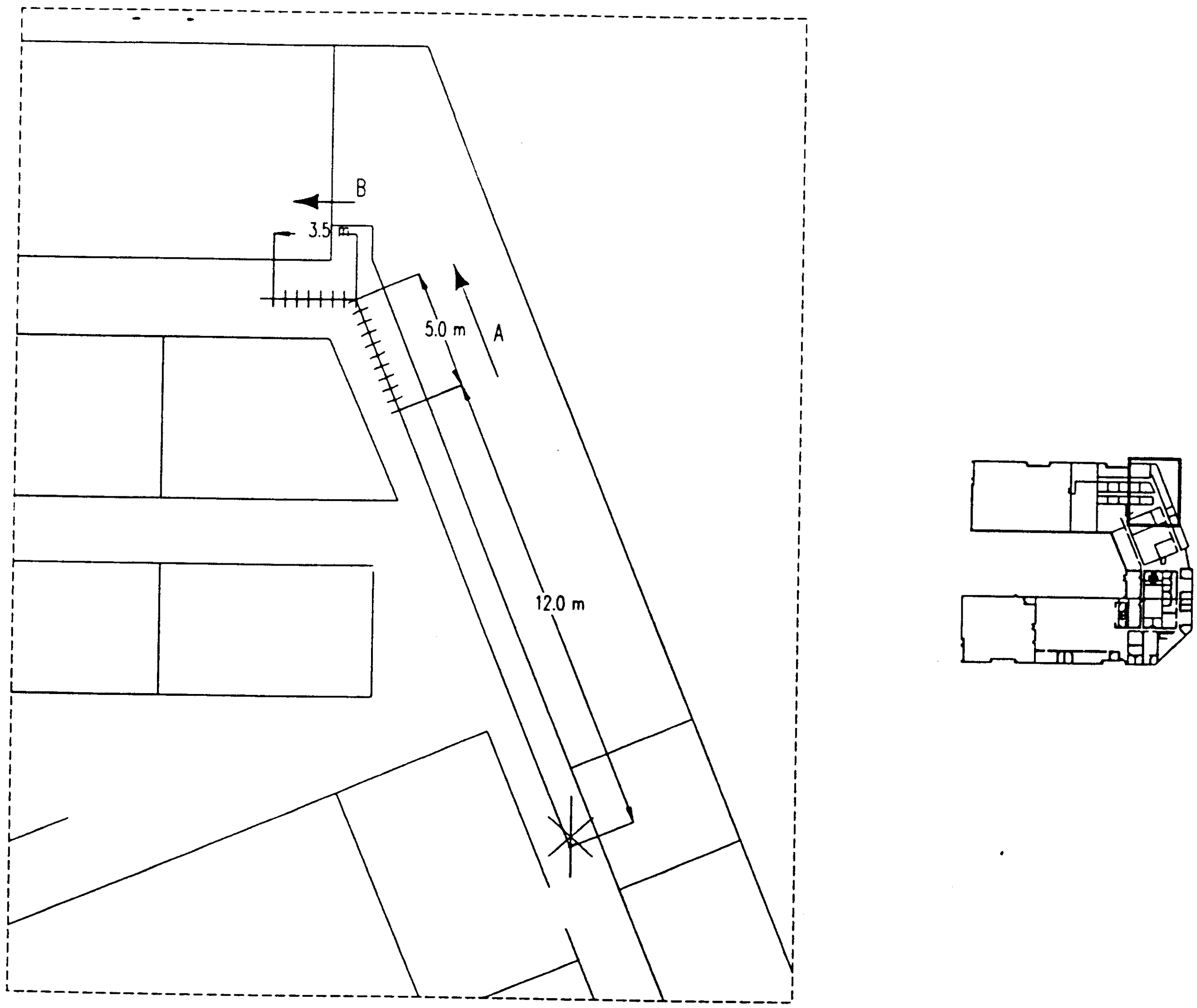

Figure 3-4 Cross Polarization Linear Series.

Two sets of measurements were made in this series. The first was a linear track down a hall and around a corner. Sample spacing was 50 cm, with a total of 19 samples in each polarization for the series. See Figure 3-4 above for details. The track itself was also mentioned in Section 3.1 above, and represents a moderately independent series with line-of-sight or direct-reflected paths available.

This track was first used to perform 19 measurements in the co-polar (vertical-vertical) configuration at each location. Once measurements on the track were complete, the receive antenna was adapted and re-positioned for 19 measurements of the cross-polar configuration (vertical-horizontal). To measure this orientation, the receive antenna was mounted at a right angle to its original position, and adjusted to match the original phase center as closely as possible. Once the antenna was re-mounted, the track set was repeated. The first two measurements of the repeat track were made without having to reposition the transmit mount base, so they represent a precision pair of samples for comparing the two polar orientations.

The second series consists of ten measurements made in two rows on the grid used previously [2]. These measurements represent a grid of moderately independent samples, with no direct or reflected-direct line-of-sight paths available.

These ten measurements were made with the transmit antenna rotated to provide cross-polarization. No attempt was made in this case to rotate about the phase center of the antenna. The new phase center was displaced approximately 46 cm from those performed previously [2].

3.4 Penetration Measurements

Penetration measurements differ significantly from the straight line measurements in that their primary goal was to measure path loss, not multipath effects. Any model must use as a primary element the losses incurred passing through walls and doors. Measurements were made with two EMCO directional ridged horn antennas. The antennas were placed a sufficient distance from the walls under test to eliminate potential near field effects. Measurements were taken at a number of locations for each material. The measurements were made on site for the following construction materials:

1) Concrete block wall. This is the standard structural support and exterior wall.

2) Fire wall. This is a two layer gypsum wall with a metal fire barrier in the air space.

3) Tenant separation wall. Similar to a standard office wall, it has a somewhat larger airspace, and contains insulation for temperature and thermal separation of different tenants. While the Hitachi building is occupied by a single tenant, it was designed to hold more than one if desired.

4) Standard gypsum wall. This is the standard interior construction wall. It is constructed of two sheets of gypsum wallboard separated by an empty airspace, primarily meant to provide partitioning. Structural support is provided by metal studs.

5) Standard Office Door. The lightweight doors used on all offices in this facility.

6) Window. On the street-facing sides of the building, the walls are primarily made up of large windows. The measurements were made with no blinds.

4.0 PRESENTATION AND DISCUSSION OF RESULTS

This section presents a summary of the data collected for each series outlined in Section 3 above. The data was first reviewed , series by series, with sample plots provided as appropriate to illustrate obvious trends and unique features in the data. Discussion of the results is provided, including problems or limitations on the data. This document is intended as a presentation of the results of the data collection process, not a thorough analysis. A brief discussion of how the data will be processed and applied to modeling efforts is also included with each section.

Three types of plots are used in this document. Log magnitude and phase are used to represent the channel transfer function in the frequency domain, while stick plots are used for the time domain impulse response. All frequency domain magnitude plots have been normalized to the RMS for the file (displayed in the upper right corner of the plot) and are plotted on a fixed scale of -30 to +20 dB. Phase plots are plotted on a +/- 180 degree scale. Time domain plots display unnormalized data directly. Only the first 119 samples of the time domain data are plotted, representing approximately 100 meters of path length in free space. Time domain plots are scaled to the highest value plotted.

For each series, the data was corrected with the daily through calibration and normalized with the appropriate antenna-antenna chamber calibration measurement. All plots were generated from this data, with no additional filtering or correction.

4.1 Coarse Grain Track Measurements

Measurements on tracks, meant to typify walking patterns, in addition to characterizing such situations, also provide insights into the distance dependence of statistics. On the basis of a preliminary examination of the data, it is clear that the goal of obtaining clusters along the track, in such a way that within each cluster there are a statistically sufficient number of independent channel samples, has been obtained. Within clusters, the samples evidence the required degree of rough independence from sample to sample. Between clusters, there are observable trends reflecting the differences in the distances between the (fixed) receiver and transmitter locations in the different clusters. These data, of course, are essential for statistical modeling of the indoor channel.

Transfer function (log magnitude and phase) plots and the first 100 meters of the impulse response plot for the closest and farthest (around a corner) points on the track shown in Figure 3-3 are provided in Figures 4-1 and 4-2. These plots demonstrate a number of features of this track and the measurements in general. The magnitude plots show the overall signal attenuation (approximated in the RMS figure) as well as the fading. The phase plots demonstrate two features: major fades cause rapid local

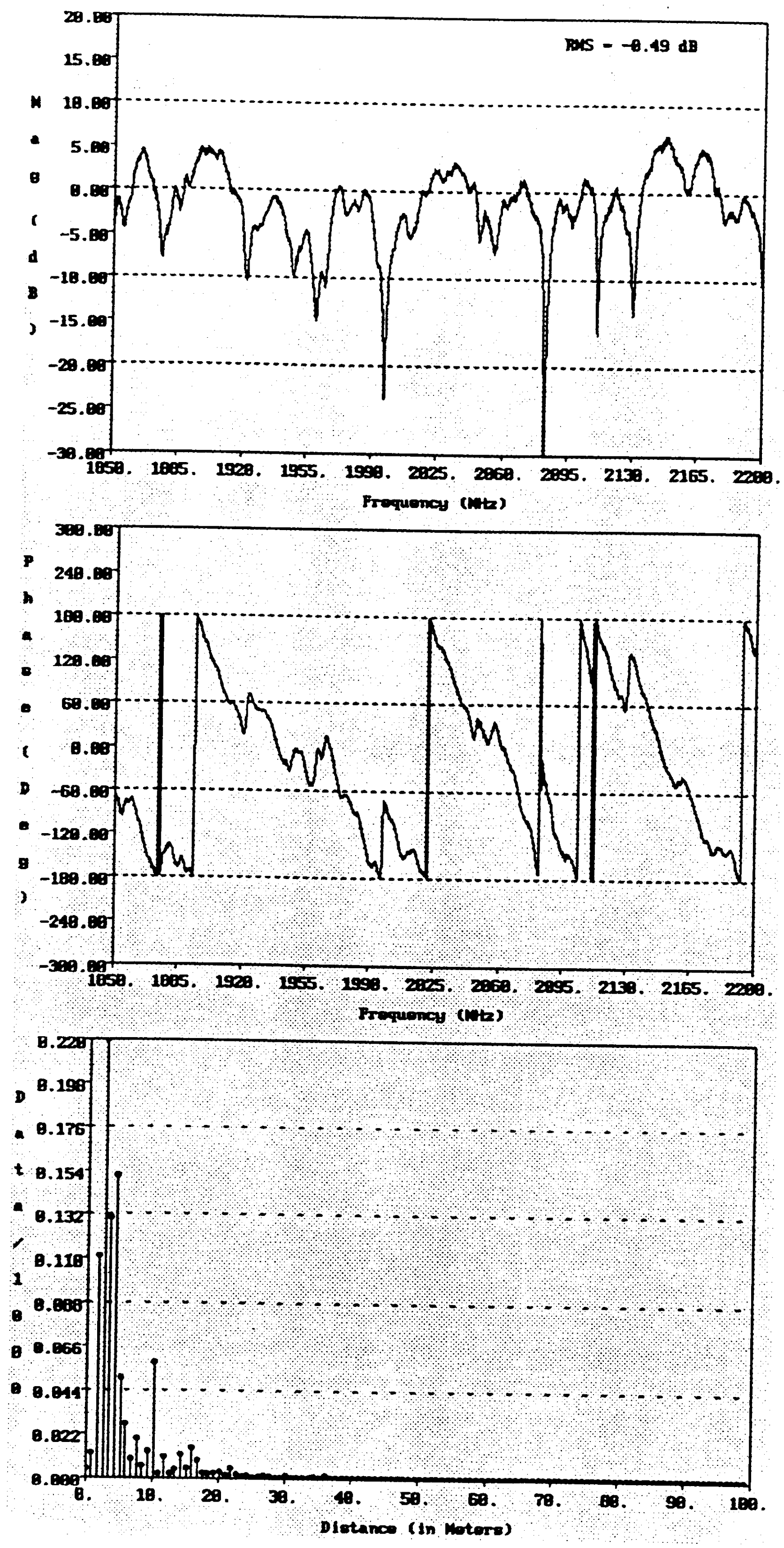

Figure 4-1 Sample Track Measurement: Shortest Antenna-Antenna Distance.

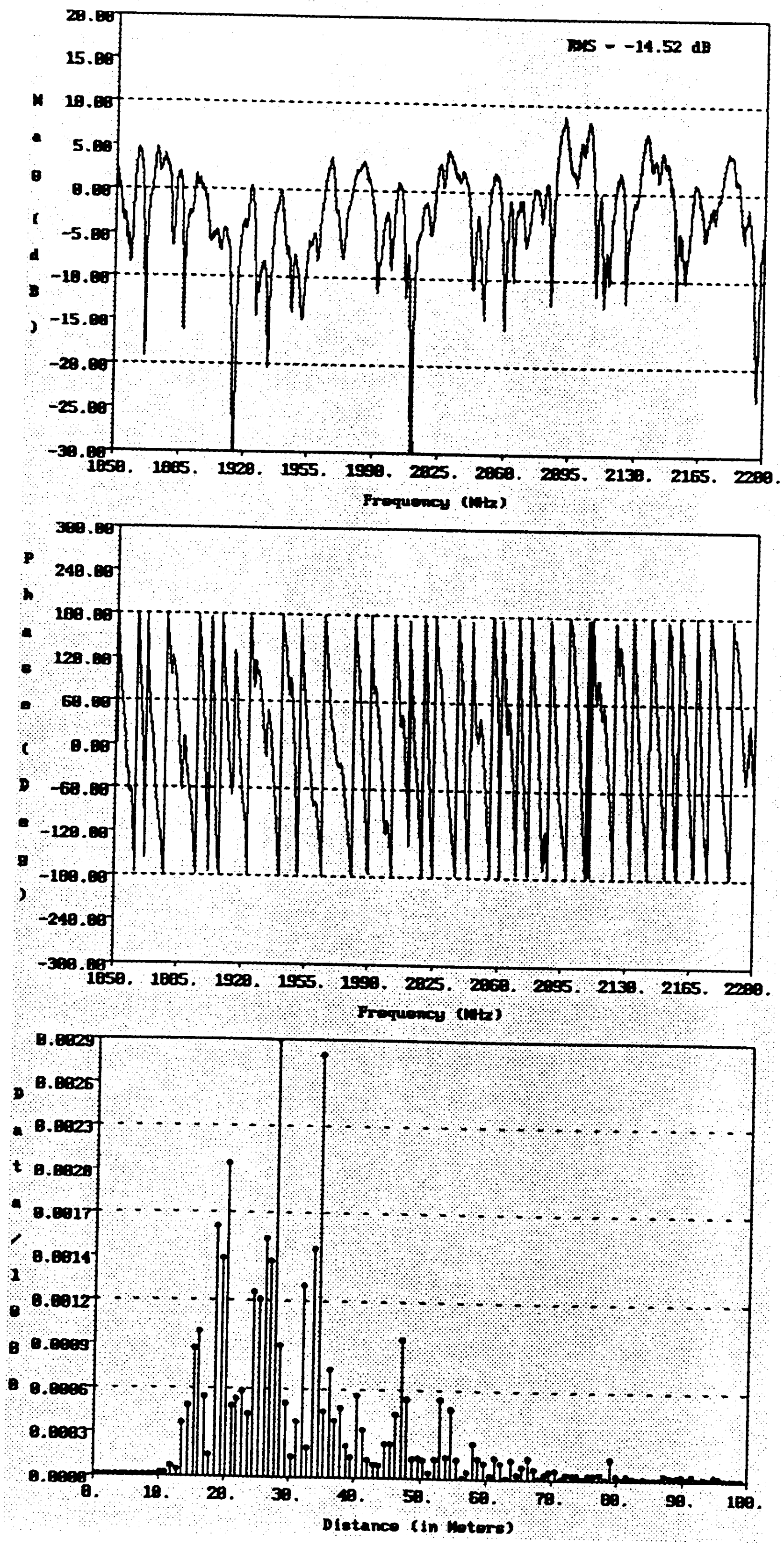

Figure 4-2 Sample Track Measurement: Longest Antenna-Antenna Distance.

variations in the phase pattern, and the period of the phase rotation with frequency increases with the distance between the antennas. The impulse response (time domain) plots show how the various paths contrast at the two distances. Closer antennas have a dominant primary path, while other, reflective paths tend to become more important once distance and direct path blockage take effect.

4.2 Vertical Diversity Measurements

The measurements in this series, required for the modeling of a likely configuration of spatial diversity antennas (as described in Section 3.2), must be processed to show the required (and expected) continuity from sample to sample. This continuity, should be sufficient to calculate the spatial correlation function in the vertical direction, and thus, after statistical processing, will be used to determine the degree of decorrelation (as a function of vertical antenna separation) that can be expected at different antenna placements. This degree of decorrelation, of course, is the primary performance indicator of spatial diversity systems.

4.3 Cross Polarization Measurements

These measurements, important in the evaluation of frequency re-use schemes, as described in Section 3.2, show some very interesting trends. The track measurements in particular illustrate the fact that as one "walks" one antenna away from the other, that cross-polarization increases dramatically when a corner is rounded. Relative RMS values for files taken at the same location are quite close, -17.7 dB compared to -17.6 dB for the cross pole location at the distant end of the series around the corner. At the closer locations, differences are much greater: -4.3 and -11.1 dB respectively for a shorter distances. This does not clash with intuition, of course, since for the around corner measurement, the direct path no longer exists. However, it does highlight the fact that multipath reflections from ceilings and floors may reach an approximate equality with multipath reflections from walls as one antenna recedes from the other along a path for which there is no line of sight. This kind of insight into the physical nature of the channel has not been found to date in the literature searches that have been conducted by Georgia Tech.

The in-room cross pol series were meant to provide statistics for comparison. Final evaluation of these is the subject of ongoing analysis.

4.4 Penetration Measurements

The penetration measurements contain few suprises. The heavier building materials, such as concrete, give the most resistance to RF penetration. The lighter materials tend to have much lower losses. Data showing a net gain through a given material is the probable result of reflections. Metal stringers evenly spaced through the walls, for some locations, can "funnel" RF energy between the antennas. For this reason, a number of locations must be sampled at different horizontal locations along a gypsum wall to get an average received power. A sufficient number exist for most of the materials measured, but additional data may be needed for some series. GTRI has taken additional data to supplement the problem measurements in other locations, so this need not affect model development.

5.0 CONCLUSIONS AND RECOMMENDATIONS

Measurement results presented in this report are unique by virtue, among other things, of their comprehensiveness in an extremely important indoor communication passband for which no other channel transfer function measurements have been made. Even if the measurements covered a less important band, the general dearth of channel transfer measurements for the indoor channel (especially over wide passbands) would make them of considerable value. In those cases where distortion is not important, the transfer function may be as simple as a single complex number (one amplitude and delay that applies to all frequency components). In the most complex multipath fading environments, exemplified by the indoor radio channel, complicated statistical models that reflect the strong frequency dependence of amplitude and phase on the channel must be used. All of these, if such statistical models are to have any validity, must be compared with benchmark measurements of the type presented in this report, i.e. with direct measurements of indoor channel transfer functions across the band of interest. In the same vein, benchmark communication simulations, in their reflection of true performance, can do no better than using actual measured channel transfer function data.

The collected data described in this report and the statistical data that will result from the extensive processing efforts will lead to a channel model. The individual series of measurements, the uses they will be put to, and the degree to which preliminary examination of the data validate their original promise are discussed below.

Coarse Grain Track Measurements The goal here, as in the case of the earlier coarse grain grid measurements, was to develop channel statistics for statistical channel modeling. As in the earlier series, the measurements were spaced far apart enough to provide rough statistical independence. For this series, however, the measurements were made along a track to approximate typical paths followed by pedestrians carrying telephones.

Measurements on tracks, in addition to characterizing the pedestrian situation, also provide insights into the distance dependence of the statistics. The measurements in this series were made along the track in such a way that, within each cluster, there were a statistically sufficient number of independent channel samples. An examination of the data has revealed that to be the case. Within clusters, the samples evidence the required degree of rough independence from sample to sample. Between clusters, there are observable trends reflecting the differences in the distances between the (fixed) receiver and transmitter locations in the different clusters. These data, of course, are essential for statistical modeling of the indoor channel.

Vertical Diversity Measurements This series of measurements was made to characterize spatial variation in the vertical direction, a variability that *must* be characterized in order to do any spatial diversity evaluation or modeling. It is quite possible that base station spatial diversity antennas will be separated vertically. This is due primarily to the fact that, in a vertical deployment, each antenna is less likely to interfere with the pattern of the other. The primary statistical quantity of interest is the spatial correlation function (in the vertical direction). The degree of decorrelation characterizing the fading experienced by the same transmitted signal at two different receiving diversity antennas is the primary performance indicator of spatial diversity systems. Without knowing, or being able to estimate this correlation, there is no way to model the potential of spatial diversity as a technique for combating multipath fading.

The measurements were taken at fine enough sample intervals to show the required continuity from sample to sample. This continuity is sufficient to calculate the spatial correlation function in the vertical direction, and thus, after statistical processing, will be used to determine the degree of decorrelation.

Cross Polarization Measurements This series of measurements was made to investigate cross-polarization effects in a multipath fading environment in order to develop a full understanding of RF signal propagation in the indoor environment. Specifically, such effects have a direct influence on the performance of frequency re-use schemes that make use of orthogonal polarization channels. (These systems operate by transmitting two different information streams on orthogonal polarizations.) Although the demand may not *now* be that great, the potential of such system approaches should always be explored when the maximization of channel capacity is critical. The main mechanism of degradation in such systems is cross-polarization which results in the information data in each channel interfering with the information data in the other.

The measurements show a very interesting trend. As one "walks" one antenna away from the other, the cross-polarization increases dramatically when a corner is rounded. This does not clash with intuition, of course, since the direct path no longer exists. However, it does highlight the fact that multipath reflections from ceilings and floors may reach an approximate equality with multipath reflections from walls as one antenna recedes from the other along a path for which there is no line of sight. This kind of insight into the physical nature of the channel has not been found to date in the literature searches that have been conducted by Georgia Tech.

Penetration Measurements For modeling purposes, characterizations of walls will be a primary input to analytical models. In fact, the concatenation of losses through structural elements will be of fundamental importance in modeling.

The measurements described above all relate to distortion on the indoor wireless communication channel. Such distortion can be enormous. The means by which any communication scheme deals with that distortion must be considered in any viable comparison of candidates. In this regard, there are three major functions to which the data described in this report can be applied: (1) Provide channel transfer data that can be directly used in simulations; (2) On the basis of a statistical breakdown of the data, develop *statistical* channel models for use in communication evaluation tools; (3) Based on a firm foundation of measurements and physical principles, develop a *physical* model of the propagation channel. The basic thrust of (2) is to develop a mathematical model of the channel that, in similar specified environments, has the same statistics as the real channel. The approach in (3) is to develop a model that draws on environment descriptions and calculates the parameters of the ray paths (and hence the transfer function) from fundamental electromagnetic principles.

Models under development will derive from a foundation based on a blend of (2) and (3) above. This joint modeling approach will be taken to give the tool a broader utility, and move it away from a dependence on specific files of raw channel data. Important measures of multipath, such as multipath spread and correlation bandwidth, in conjunction with the spatial, spectral, and temporal dependence of same, will be related to the local geometries and structural elements of buildings, to provide a powerful tool in which these later quantities can be provided as inputs.

6.0 REFERENCE

[1] Witten, M.L., Pickering, L.W., and Barnhart, E.N., "Test Plan for Hitachi In-Building Communications Channel Characterization," Georgia Tech Research Institute/Communications Laboratory, August 1991.

[2] Witten, M.L., Pickering, L.W., and Barnhart, E.N., "Interim Technical Report Number 1, Experimental License: KK2XBA and KK2XBB," Georgia Tech Research Institute/Communications Laboratory, August 1992.