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CHANNEL MEASUREMENTS FOR AUTOMATIC VEHICLE MONITORING SYSTEMS

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MARCH 1974
FINAL REPORT

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16. Abstract

Co-channel and adjacent channel electromagnetic interference measurements were conducted on the Sierra Research Corp. and the Chicago Transit Authority automatic vehicle monitoring systems. These measurements were made to determine if the automatic vehicle monitoring systems could operate in the land mobile communication channels without affecting the performance of existing channel users.

Evaluation measurements were also performed on the Chicago Transit Authority AVM system to determine the cause of failures between the base control station and the mobile vehicles.

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PREFACE

The co-channel and adjacent channel electromagnetic interference measurements on the Sierra Research Corp. and Chicago Transit Authority automatic vehicle monitoring systems described in this report were performed as part of the Ground Vehicle Communication and Control program. This program was sponsored by the Department of Transportation Office of Telecommunications and the Urban Mass Transportation Administration for the purpose of determining if automatic vehicle monitoring systems could be compatible with existing radio channel users in the land mobile communication channels.

The assistance from Robert Gagnon and Eugene Leonard in the preparation, calibration and operation of the mobile laboratory, the helpful advice from Dr. Sherman Karp, and the assistance from the Motorola Communication Division and Sierra Research Corporation is greatfully acknowledged.

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1. INTRODUCTION

In 1968 the Department of Housing and Urban Development (HUD) initiated a program to improve public transportation. The goal of this program was to achieve reliable location and status data from a large fleet of vehicles in an urban area. As part of this program HUD gave a grant to the Chicago Transit Authority (CTA) to perform a preliminary feasibility study of automatically monitoring a transit bus fleet from a central location. This program was transferred to the jurisdiction of the Department of Transportation, Urban Mass Transportation Administration (UMTA) and was continued by a follow-on grant to the CTA. The UMTA grant was for the implementation and testing of an automatic monitoring system for a bus fleet which would supply information to supervisory and management personnel for improving service, providing up-date statistical data and increasing personnel efficiency.

In addition to the CTA-Automatic Vehicle Monitoring (AVM) system, UMTA initiated a program to demonstrate the feasibility of different AVM techniques. The demonstrations culminated in experiments in Philadelphia to assess the performance capabilities of each AVM technique. Four companies participated in these experiments demonstrating the performance of proximity, trilateration and Loran C type AVM systems.

Because of the progress in the development of AVM systems, the Federal Communication Commission is assessing the requirements for permanent assignment of radio spectrum space for these vehicle location services. This assessment is essentially on the performance comparisons of AVM systems with respect to accuracy, bandwidth, up-date rates, data transmission capabilities and compatabilities with present land mobile channels.

DOT/TSC conducted measurements on two AVM systems to assist in making this assessment, the CTA-AVM system and the Sierra Research Corp AVM system. The measurements conducted were primarily to determine the compatibility of the two AVM systems with respect to the present UHF land mobile channels and to determine the reliability of the CTA-AVM system.

2. SIERRA RESEARCH CORP. AVM SYSTEM

2.1 SUMMARY

Co-channel and adjacent channel interference measurements were conducted in Philadelphia by DOT/TSC from July 5 to July 7, 1972 during the UMTA evaluation tests of the Sierra Research Corp. AVM system. In addition, some man-made noise measurements were also conducted.

The results of the measurements were that the Sierra Research AVM system caused no adjacent interference. It is probable that if the complete AVM system had been deployed the adjacent channel interference would still be satisfactory.

The co-channel interference tests generally conformed to the predicted man-made noise levels in urban areas except in a few locations. The peak co-channel level of interference observed was -81 dBm referred to a ground plane dipole.

2.2 SIERRA RESEARCH CORP. AVM SYSTEM DESCRIPTION

The Sierra AVM system uses phase multilateration from a number of sensor stations to determine vehicle location. Specifically location of vehicles is accomplished from measurements of the difference of the time of arrival of a signal at the sensor stations. The vehicle to be located transmits an audio 1.5KHz tone which frequency modulates the carrier of an appropriate transceiver for 10 milliseconds. The signal is received by the receiving sensor stations where it is demodulated and the audio signal is transmitted to the base station via dedicated telephone lines. The base station contains the logic circuitry which performs the computations of the vehicle location based on the phase differences of the demodulated tones. The system operates in a time-division mode with a period of 1 minute. Each vehicle is alloted a time of 15 milliseconds, i.e., 10 milliseconds for the tone and a 5 millisecond guard time. Although not used in the UMTA evaluation tests, the sytem has the capability of transmitting 10 bits of digital information in appropriate time slots, also 15 milliseconds long. The modulation system for the transmission of data would be ASK/FM which is essentially FSK with respect to the carrier. The system is designed to accomodate 1360 fixed route vehicles or 680 random route vehicles on two 25KHz bandwidth channels. In the UMTA evaluation tests, only one vehicle and a fixed calibration station were used. The vehicle transmitted a range tone signal four times per minute at either 35 or 70 millisecond pulse duration.

2.3 ADJACENT CHANNEL INTERFERENCE

Two different adjacent channel interference measurements were conducted. The first measurement was to display and record the spectrum of the 1.5KHz modulated 450 MHz carrier of the automatic vehicle monitoring (AVM) location tone transmission and to determine if the Sierra Research Corp. AVM system transmission was confined within the 25KHz bandwidth channel assigned by the FCC for the tests.

The interference measurement system consisted of a 460 MHz ground plane dipole mounted on the roof of the DOT/TSC mobile laboratory. The signal recieved from the antenna was coupled directly into a HP 8551B spectrum analyzer. Photographic records shown in Figure 1, were made of the AVM data transmission displayed on the analyzers cathode-ray tube. These records were made during data transmission when the spectral width of the transmitted signal was at a maximum. The results of the measurement were as follows:

Spectrum Width	Measured Attenuation
8 KHz	-3 dB
12.5 KHz	-16 dB
16 KHz	-20 dB
21 KHz	-30 dB
25 KHz	-37 dB

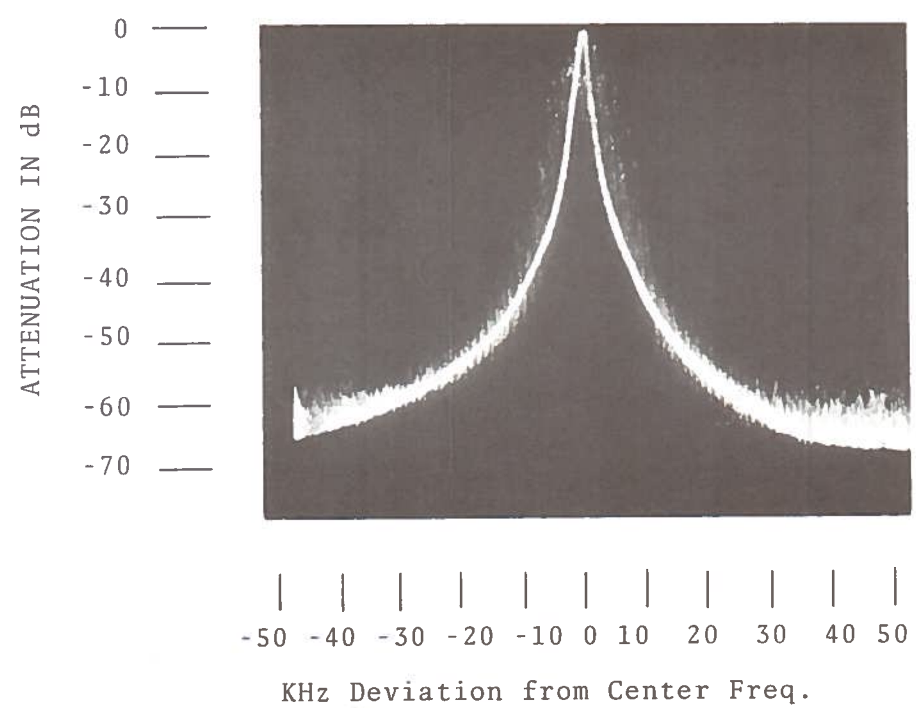

Figure 1. Sierra Research Corp. AVM Base Station Transmission Spectrum

The FCC specifications on the bandwidth limitations on land mobile channels are as follows:

"(c) The mean power of emissions shall be attenuated below the mean output power of the transmitter in accordance with the following schedule:
(1) On any frequency removed from the assigned frequency by more than 50 percent up to and including 100 percent of the authorized bandwidth: At least 25 decibels;
(2) On any frequency removed from the assigned frequency by more than 100 percent up to and including 250 percent of the authorized bandwidth: At least 35 decibels;
(3) On any frequency removed from the assigned frequency by more than 250 percent of the authorized bandwidth: At least 43 plus 10 Log_{10} (mean output power in watts) decibels or 80 decibels, whichever is the lesser attenuation.
(d) When an unauthorized emission results in harmful interference the Commission may, in its discretion, require appropriate technical changes in equipment to alleviate the interference."*

In correlating the recorded spectrum to the FCC standards, the Sierra Research Corp. AVM system transmissions do not quite meet the 25 dB attenuation below mean output power at the 50% point of the assigned frequency but slightly exceeds the requirement of 35 dB attenuation below the mean output power at the 100% bandwidth point of the assigned frequency, Figure 2. Because of insufficient dynamic range of the instrumentation, measurements for part (31) of the FCC specifications Article 21,106 could not be conducted.

Probably the most important FCC bandwidth limitation specification is in part (3d), namely, emission outside of the authorized bandwidth shall not cause harmful interference.

The second adjacent channel interference measurement was conducted to determine if the Sierra AVM system met the requirement of part (3d) of the FCC specifications. For this test a general purpose DEI GPR-20 communication receiver was used to

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*Code of Federal Regulations, Title 47: Chapter I-Federal Communications Commission (Continued) page 3, Part 93 Land transportation radio services. Section 93.104 Emission limitations.

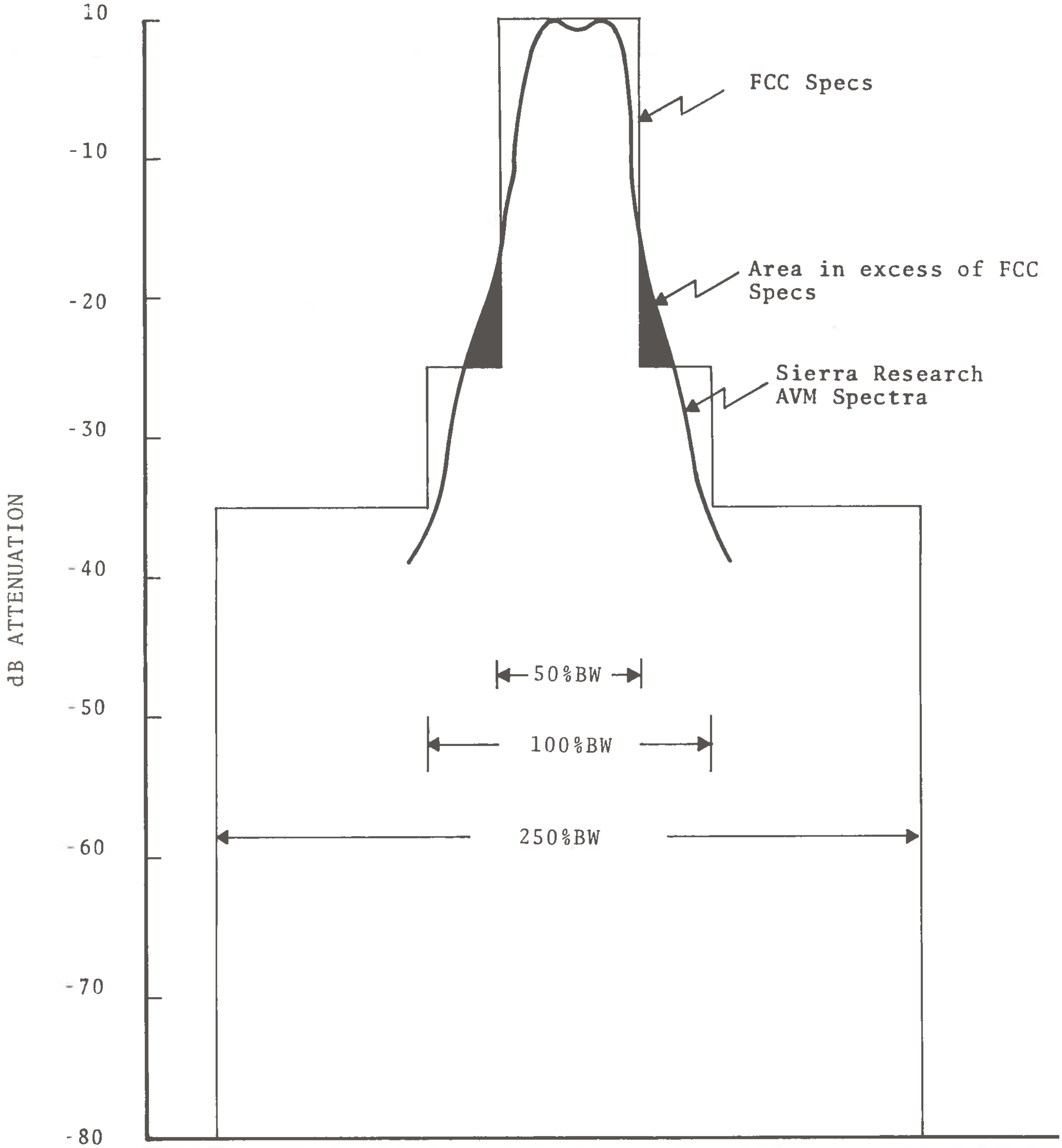

Figure 2. Comparison of FCC Specifications and Sierra Research Corp. AVM Spectrum

subjectively listen to the adjacent channels for interference from the AVM system. Because the land mobile communication channels are presently using voice communication, this test was considered more than adequate to determine if the AVM system produced "harmful interference". Two hours of subjective listening tests were conducted in the area around the State Building where the AVM calibration transmitter was located. This area was chosen to enhance the possibility of detecting adjacent channel interference by operating in a maximum AVM system field strength region. The result of the measurement was that no detectable AVM interference was heard on the adjacent channels.

One should note though, that the Sierra Research AVM system tested at Philadelphia was operating at 15 watts output power instead of the proposed 20 watts and was not transmitting any digital data or interrogation codes. If the complete AVM system which transmits data and codes is tested at a later date with an output of 20 watts, then adjacent channel interference could possibly be present and the adjacent interference measurements should be repeated.

No adjacent channel interference from the Sierra Research Corp. AVM system was found. It is believed that the results of the measurements would not change if the system was operating at full capacity, monitoring 1000 vehicles instead of only one vehicle and a fixed calibration station.

2.4 CO-CHANNEL INTERFERENCE

Co-channel interference measurements were conducted over a large area of Philadelphia. The measurement system consisted of an antenna, receiver and strip chart recorder. The antenna was a 460MHz ground plane dipole mounted on the roof of the mobile laboratory. The antenna was connected to the input of a 10 KHz bandwidth receiver tuned to the center frequency of the Sierra Research Corp. AVM system. The receiver's 60 dB dynamic range, log video output was recorded on a strip chart recorder. Due to the response time of the strip chart recorder, impulsive man-made noise was averaged over an integration time of approximately 0.01 seconds.

The results of the measurements were that the man-made noise was generally below -104 dBm with the exception of a few noisy locations. The measurements at these noisy locations are shown in Figures 3 to 8. The periodic spikes in the figures are the Sierra Research Corp. AVM transmissions. The output in the spacing between the spikes is caused by man-made noise levels.

The average noise power in the figures falls between the levels of -104 to -94 dBm. These levels are within the man-made noise levels reported by Skomal* in urban areas (Figure 9). The few areas that exceeded Skomal's predicted noise levels are City Hall, Arch and 11th Streets, Chestnut and 10th Streets, Walnut and 11th Streets, Locus and 10th Streets and Locus and 11th Streets. Some of these levels were as high as -81 dBm, approximately 13dB above Skomal's reported urban noise levels. These high levels of co-channel interference could be either exceptionally high electromagnetic man-made noise interference or co-channel radio transmissions. Because of the form of the recorded data, it is not possible to determine which source of interference it is.

2.5 WIDEBAND NOISE MEASUREMENTS

The requirements for the characterization of man-made noise are much more stringent for digital communication than for voice communication. The reason for this is that impulsive noise generated by man-made sources such as automobile engines, industrial equipment etc., can cause bit errors to appear in the digital communications, while in voice communications impulsive noise usually causes only minor static and not the loss of information transfer. The man-made noise characteristics required to analyze the performance of digital communications are:

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*Skomal, E.N. (1965), Distribution and frequency dependance of unintentionally generated man-made VHF/UHF noise in metropolitan areas, IEEE Trans. on Electromagnetic Compatibility, Vol. EMC-7, pp. 263-278, September 1965.

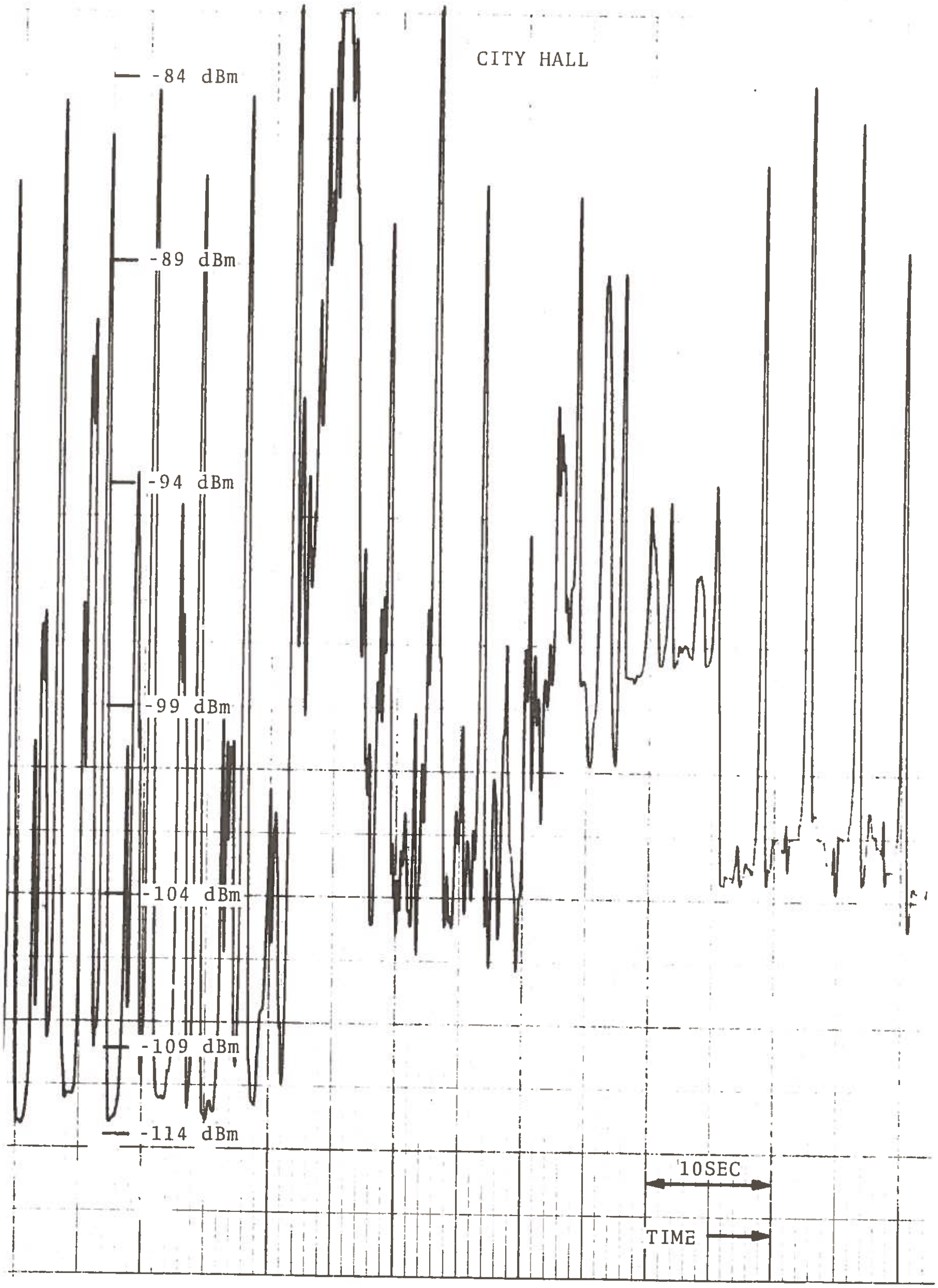

Figure 3. Co-channel Interference-City Hall

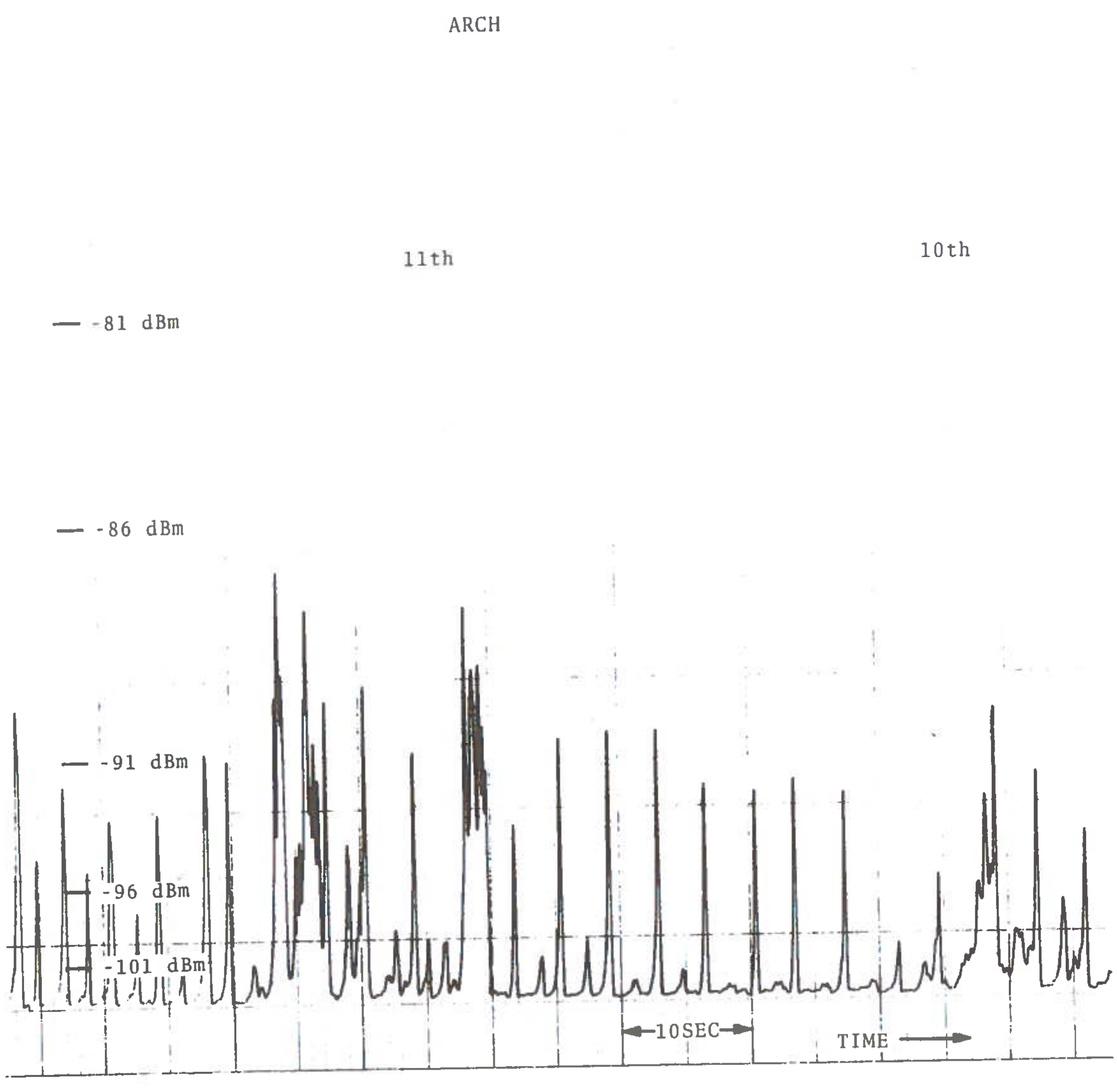

Figure 4. Co-channel Interference-Arch and 11th

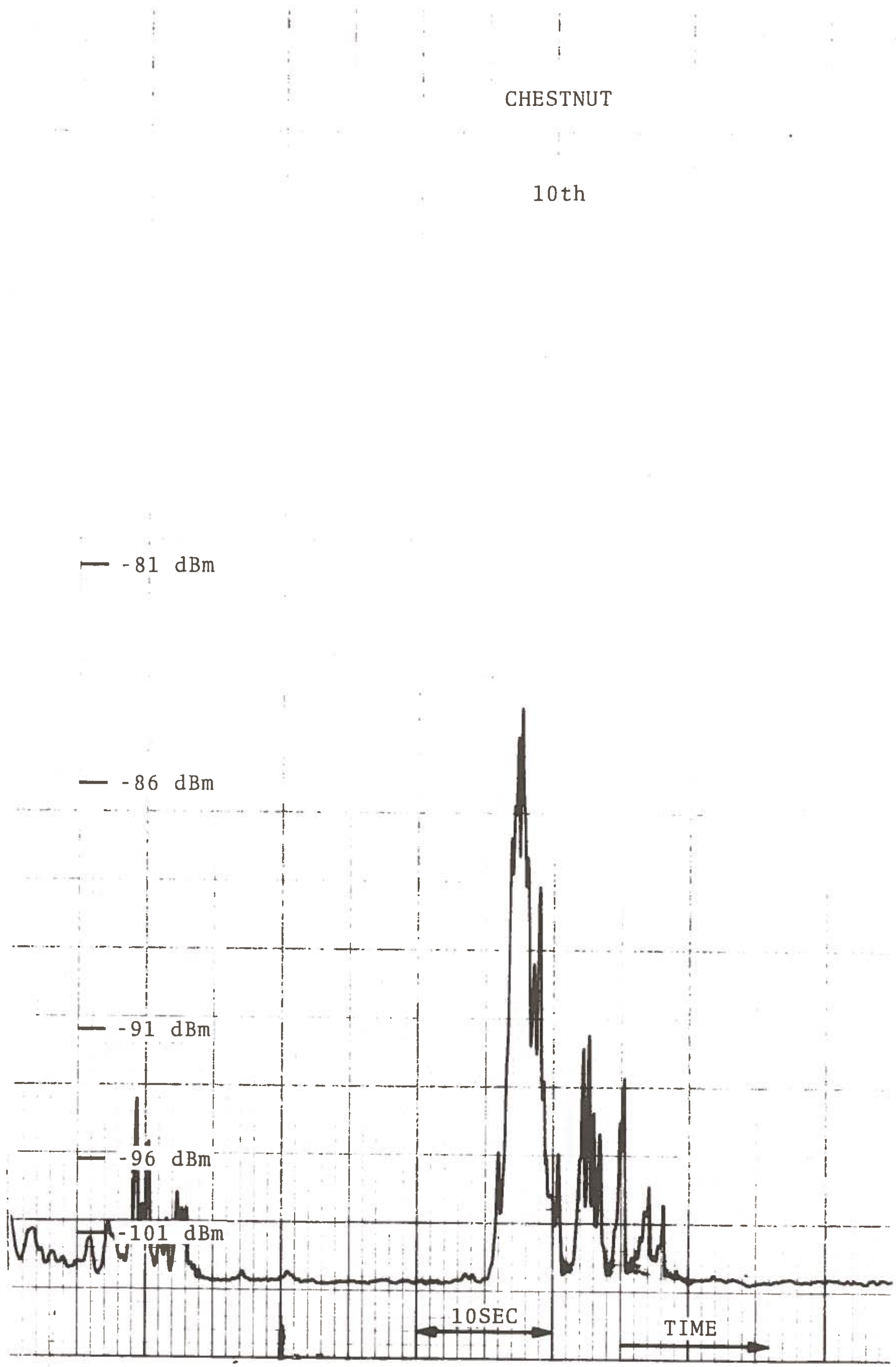

Figure 5. Co-channel Interference-Chestnut and 10th

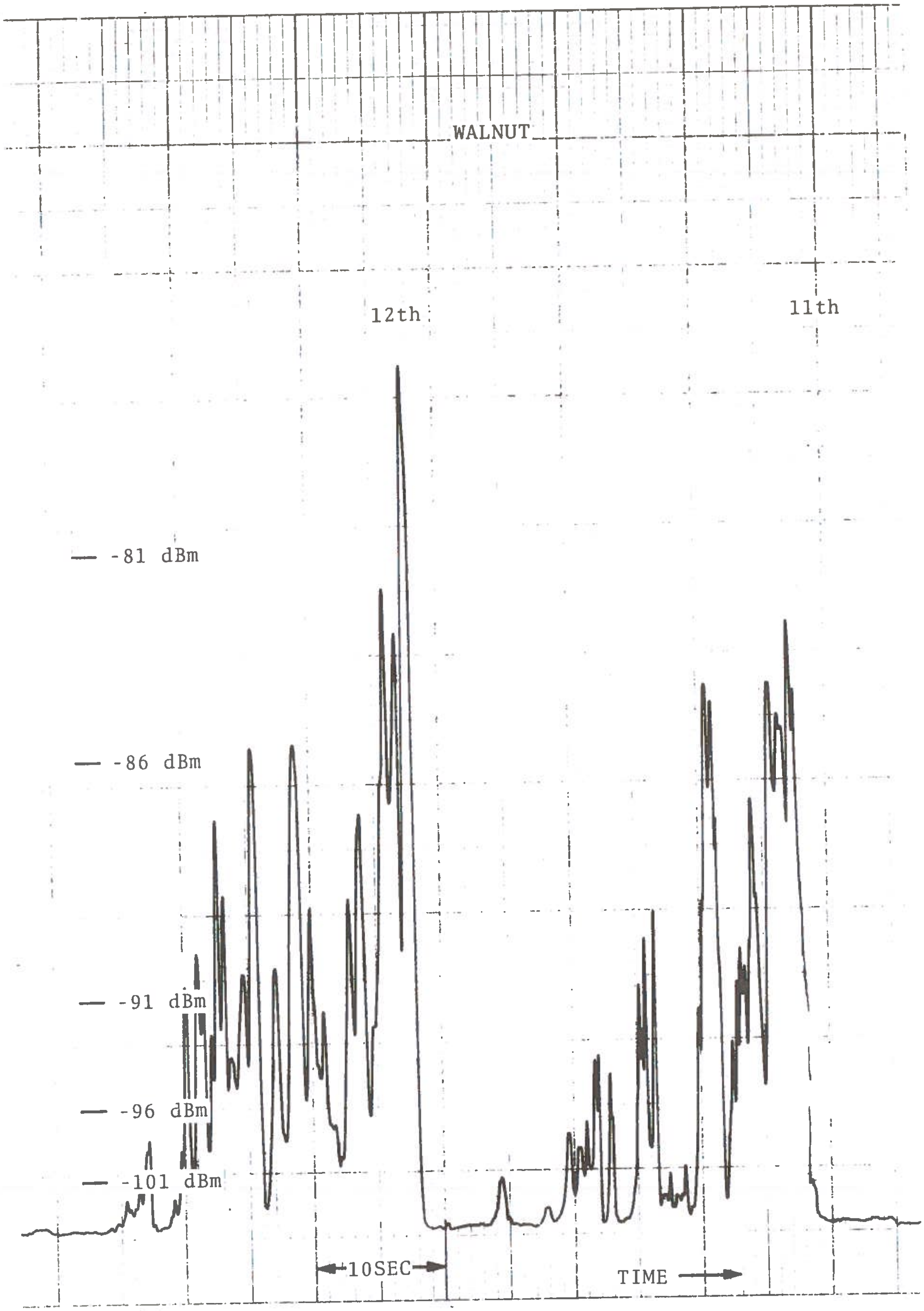

Figure 6. Co-channel Interference-Walnut and 12th

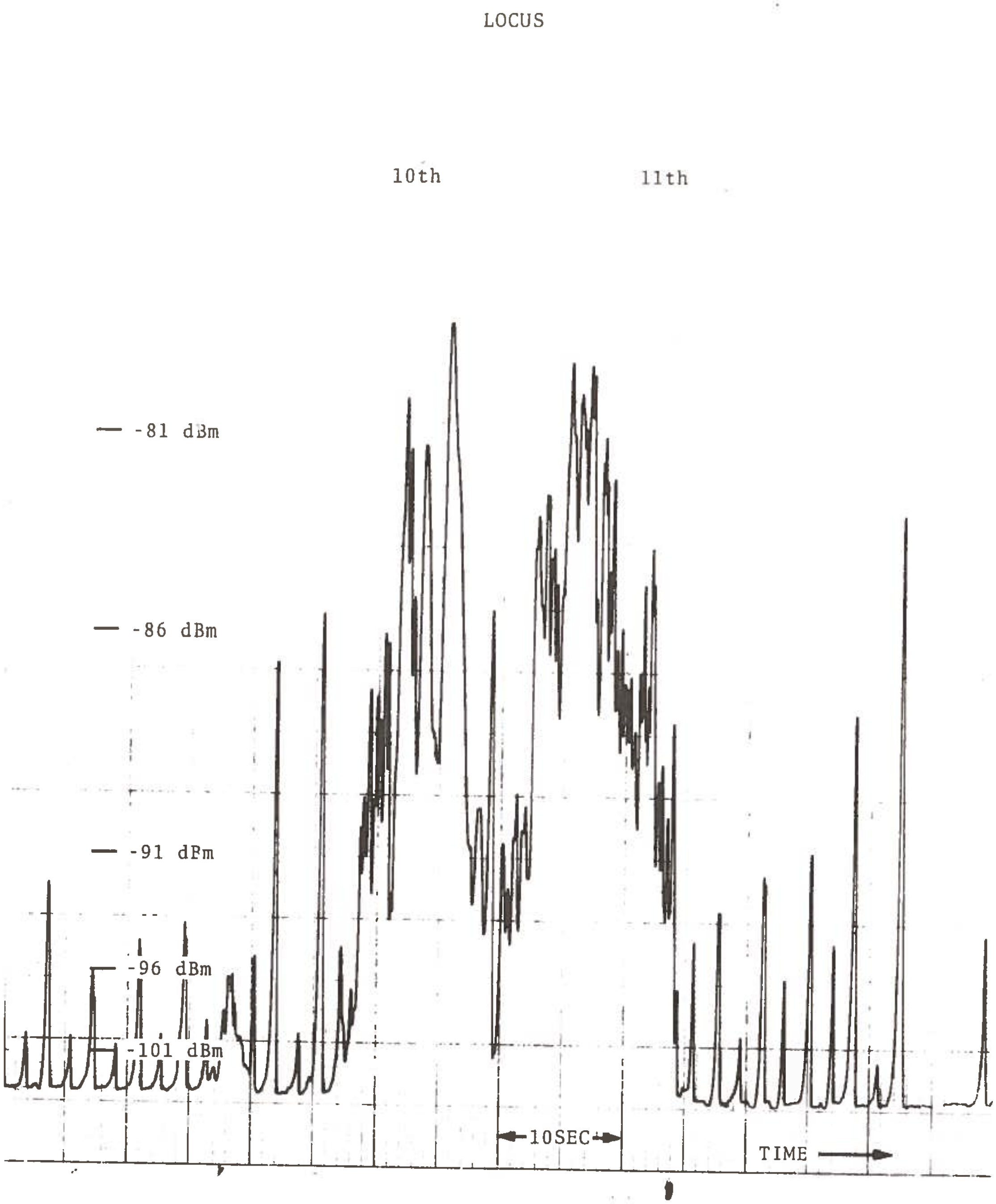

Figure 7. Co-channel Interference-Locus and 10th -11th

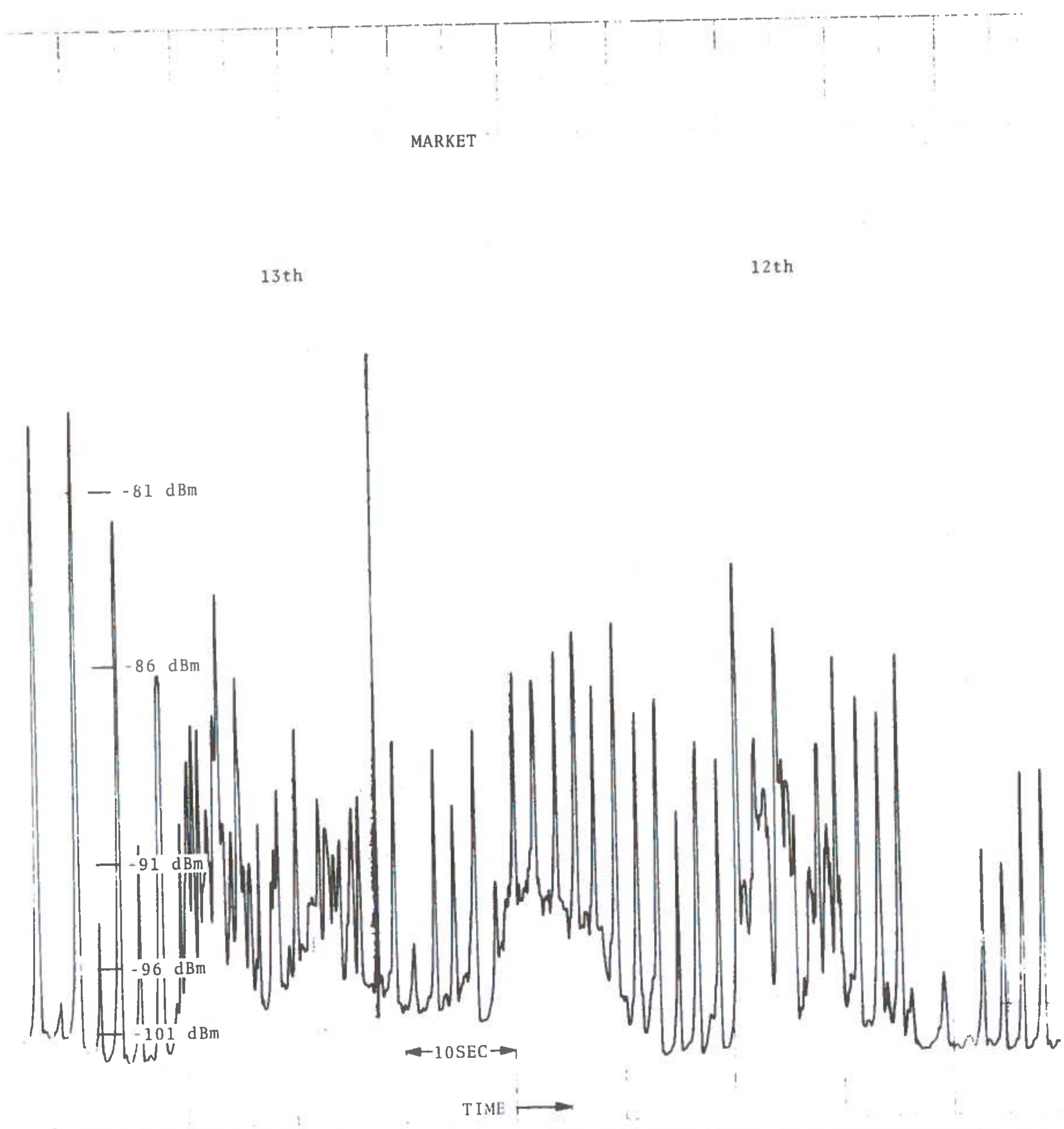

Figure 8. Co-channel Interference-Market and 12th -13th

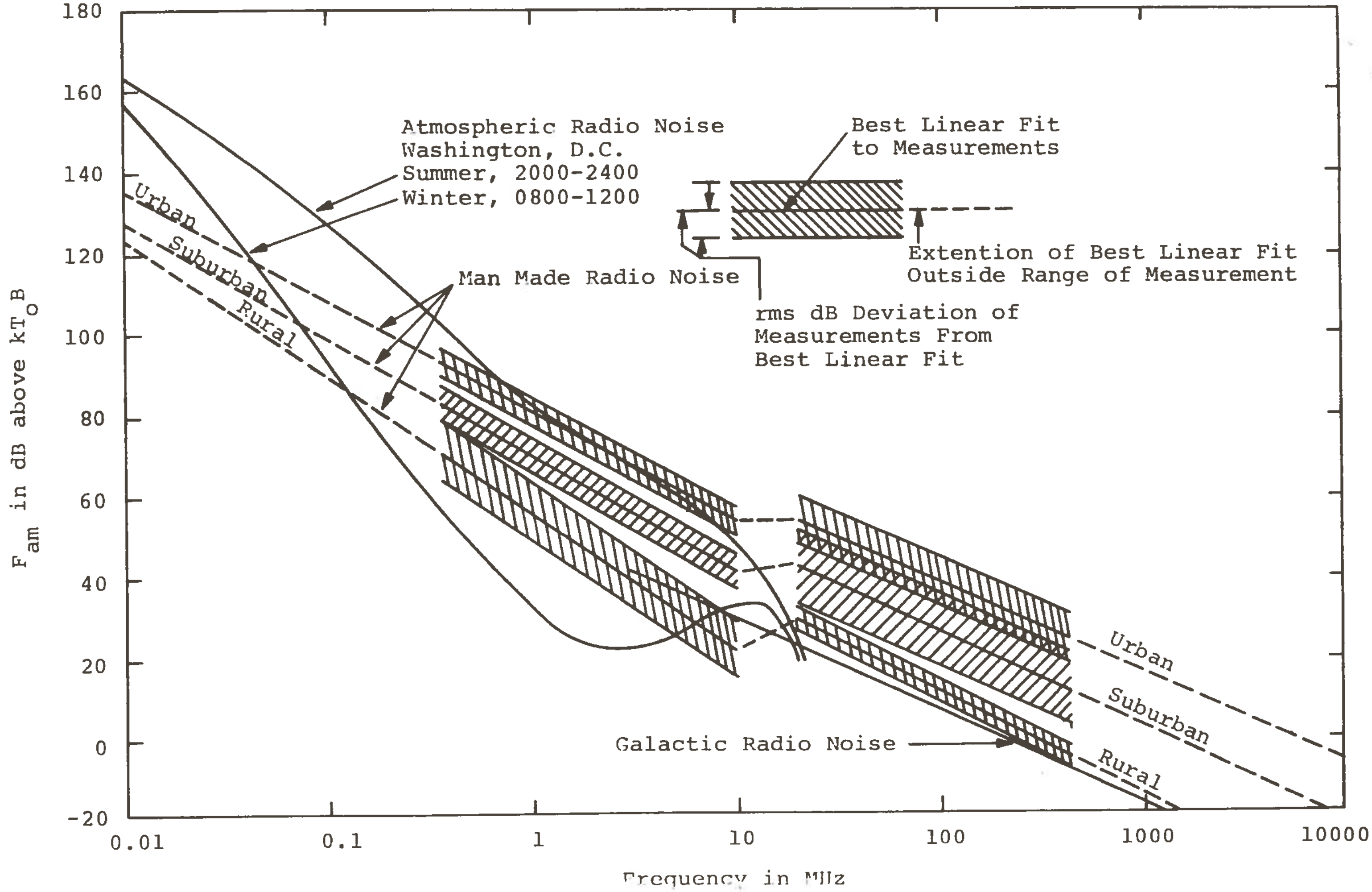

Figure 9. Median Values of Radio Noise Power (Omindirectional Antenna Near Surface).

Ref: Skomal, E.M., "Comparative Radio Noise Levels of Transmission Lines, Automotive Traffic, and RF Stabilized Arc Welders", IEEE Transactions on Electromagnetic Compatibility. pp. 73-77, (1967).

1. average power
2. amplitude probability distribution
3. pulse spacing probability distribution
4. pulse width probability distribution.

These parameters must be measured at a bandwidth equal to or greater than that used for the digital communiction system. Although these characteristics were not measured directly in Philadelphia, the man-made noise was recorded in a bandwidth, 80KHz, greater than the standard 25KHz mobile communication channels. The recordings were brought back to DOT/TSC, for later analysis in the laboratory.

Prior to the wideband noise measurements, a frequency surveillance was conducted to find a portion of the spectrum near 460 MHz that was free of intelligible transmissions from radio stations. In such a region only man-made noise should be detected. The surveillance measurement system consisted of 460 MHz center frequency ground plane dipole mounted on the roof of the mobile laboratory. The antenna output was coupled to the input of a spectrum analyzer. The log video output of the specturm analyzer was recorded on an X-Y chart recorder. The spectrum was scanned and recorded continuously over a period of approximately 1/2 hour. Thus, reasonable assurance is obtained that intermittent radio broadcasts will not be omitted in the spectrum surveillance.

In Philadelphia only a 100KHz bandwidth at approximately 470 MHz could be found free of intelligible transmissions so that only man-made noise could be measured. The lack of intelligible radio broadcasts at approximately 470 MHz can be seen in the frequency surveillance measurement data shown in Figure 10.

Several magnetic tapes were made of wideband man-made noise. The measurement system used consisted of an antenna, receiver and tape recorder. The antenna used was a 460 MHz ground plane dipole mounted to the top of the mobile laboratory. The antenna output was coupled to a 100KHz bandwidth, 60 dB dynamic range receiver. The log video output of the receiver was recorded on a 80 KHz bandwidth magnetic tape recorder operating in the FM record mode.

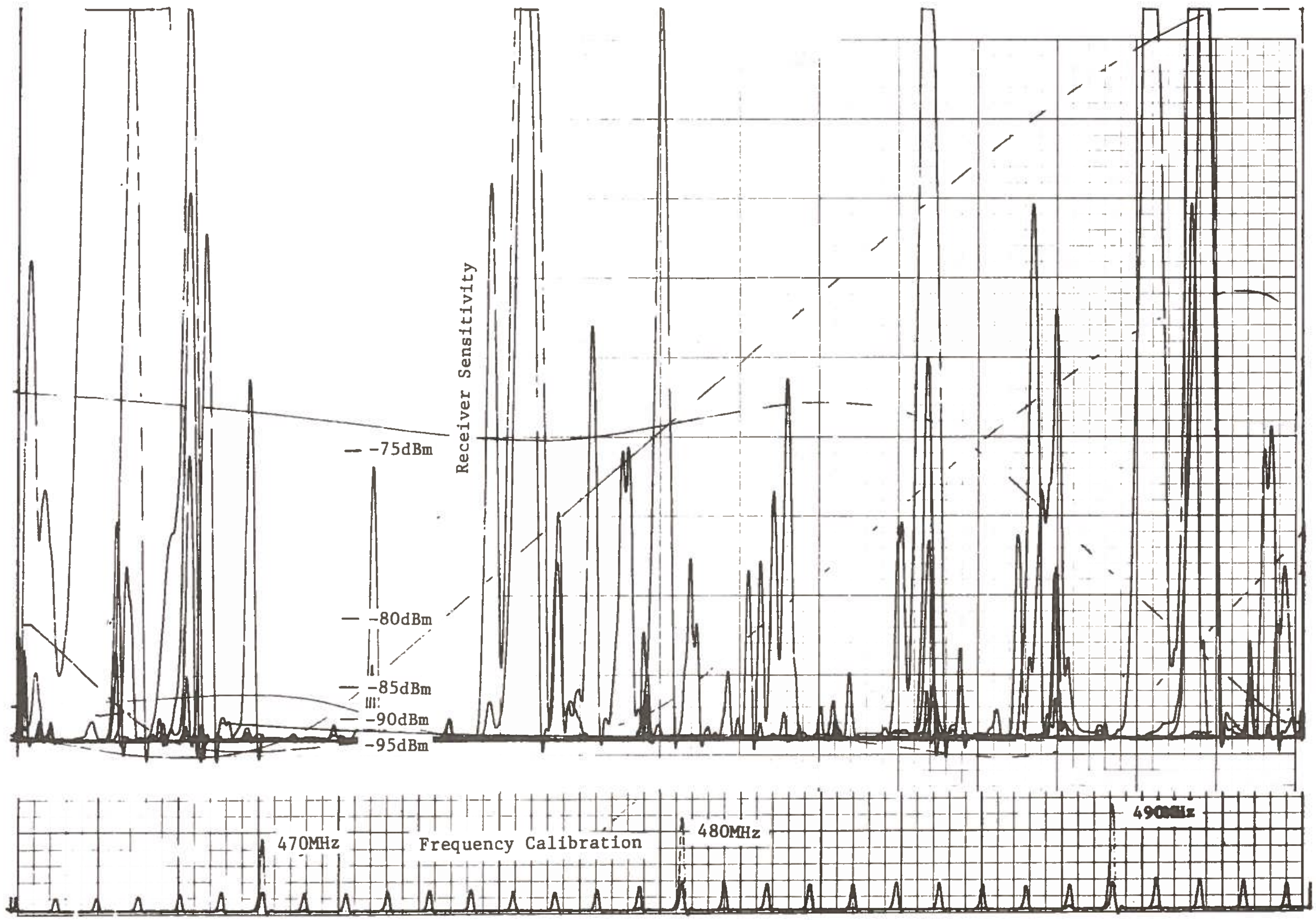

Figure 10. Spectrum Surveillance of Philadelphia

Operating in this mode the tape recorder has a 35 dB signal to noise ratio. This signal to noise ratio allows an approximately 1 dB resolution of the 60 dB dynamic range log video output of the receiver.

It should be pointed out that the noise detected in the mobile laboratory has little meaning in regard to the performance of the Sierra Research Corp. AVM system. The reason for this is that the signal used in the trilateration calculations for vehicle location is transmitted from the vehicle to nine different satellite stations. It is the signal to noise ratio at these nine satellite stations that determines the system performance. Therefore, man-made noise measurements should be made at the satellite receiver sites.

Originally plans* were made to reduce the noise data into the form of pulse amplitude and pulse spacing histograms, but since the measurements were conducted in the mobile laboratory and not at the satellite receiver sites, the results would not be meaningful in the analysis of the Sierra Research Corp. AVM system tested in Philadelphia. The tapes were saved for possible later analysis of digital communications from the AVM base station to the mobile vehicle.

2.6 CONCLUSION

Sierra Research Corp. tested a partial AVM system in Philadelphia for UMTA for the purpose of determining the system's ability to accurately locate mobile vehicles. The system tested operated at 15 watts output power instead of the proposed 20 watts, had no digital radio communication, and monitored only one vehicle and a fixed calibration station instead of the proposed 1000 vehicles. This system tested was compatible with the present UHF 25 KHz bandwidth land mobile channels.

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*See, R. Esposito and R. Buck, "A Mobile Wide-Band Measurement System for Urban Man-Made Noise", IEEE Transactions on Communications, Vol. Com-21 No. 11, pp. 1224-1232. Nov. 1973.

Although there appears to be no reason why the complete AVM system proposed by Sierra Research Corp would not also be compatible with the existing land mobile channels, it is recommended that the measurements be repeated on the complete system.

3. CHICAGO TRANSIT AUTHORITY AVM SYSTEM

3.1 SUMMARY

A series of measurements were conducted in Chicago in August 1972 for the purpose of evaluating the Chicago Transit Authority Automatic Vehicle Monitoring (CTA-AVM) system. This system is officially designated "Monitor-CTA" by the Department of Transportation. These evaluation measurements were to determine if the CTA-AVM system was compatible with existing radio channel users in the land mobile communication channel and to determine why the CTA-AVM system was only obtaining approximately 50% replies from the buses when interrogated from the base control station.

The results of the measurements were:

1. The CTA-AVM system caused no adjacent channel interference.
2. The CTA-AVM system was compatible with the existing land mobile communication channels
3. The telephone line communication system between the satellite receiver stations and the base control station was acceptable (approximately 99.5% correctly decoded reply rates).
4. Average signal strengths in the vicinity of the four measured sign posts varied over a range of 18 dB.
5. The multipath fading combined with reduced median signal level in some areas could cause the observed degradation in the CTA-AVM reply rates and that diversity antenna implementation is considered the most cost effective means of improving the CTA-AVM bus reply rates.

3.2 CHICAGO TRANSIT AUTHORITY AVM SYSTEM DESCRIPTION

The CTA uses a hybrid proximity and dead reckoning system to locate its buses. In this system, a 10 bit digital code is transmitted from fixed location "sign posts". This transmission has a center frequency of 150 MHz (nominal), a 12.5 KHz bandwidth and a 100 milliwatts output power. The digital code, which represents the sign post's location, is detected by the receivers installed in the passing buses. The most recent received code is stored memory. Once the bus is outside the detection range of the sign post, an interval timer starts. The number of 12 second increments that have accrued since the bus last passed a sign post is also stored in memory. When the bus arrives within range of the next sign post, the interval timer is automatically reset to zero and the previous sign post's digital location code is replaced in memory by the new sign post's code.

The buses are interrogated from the base station on a 25 KHz bandwidth channel operating at 450 MHz (nominal). A bus identity message totaling 41 digits is used to interrogate the buses. The buses respond on another 25 KHz bandwidth channel operating within approximately 1.8 MHz of the bus interrogation channel. The message from each bus is 45 bits long and contains the sign post's location code and interval timer information. In addition, alarm messages can be transmitted on the bus-to-base station channel.

The three satellite stations detect the buses' transmission and relay this information to the base station via a standard data telephone line.

This system, for each full duplex data channel, has a capacity of 1,650 buses with an update rate of 2.5 minutes. In addition to the two 25 KHz bandwidth data channels and the 12.5 KHz sign post channel, there is a duplex voice channel to allow simultaneous voice communication between the buses and the base station. The total bandwidth is therefore, 112.5 KHz.

It should be noted that because CTA had the bandwidth available, the AVM system manufacturer, Motorola, made no effort to conserve bandwidth. The CTA-AVM system could readily be reduced to 62.5 KHz without affecting the system.

3.3 ADJACENT CHANNEL INTERFERENCE MEASUREMENTS

To determine if the CTA-AVM system caused an adjacent channel interference, three separate measurements were conducted. These measurements consisted of subjective listening to the demodulated adjacent channels, surveillance of the CTA-AVM spectrum, and wide band tape recordings containing the CTA-AVM channel and its adjacent radio channels.

The subjective listening measurement equipment consisted of a commercial FM radio transceiver with a 460 MHz ground plane dipole antenna mounted on the roof of the mobile laboratory. The transceiver, loaned to DOT/TSC for the duration of the Chicago field tests courtesy of Motorola Communication Div., Schaumburg, Illinois, was a Motorola Mocom 70. This transceiver was equipped with the appropriate crystals to allow selection of the CTA-AVM base station to bus interrogation channel and its adjacent channels. The Mocom 70 FM transceiver has a 25 KHz bandwidth and a approximately 4 microvolt sensitivity at 20 dB quieting. Initially the transceiver was set on the CTA-AVM channel to become familiar with the audio sound of the demodulated digital interrogation signal emitted from the transceiver speaker. The purpose of this was to enhance the possible detection or recognition of the CTA-AVM digital signal when listening later to the adjacent channels. The subjective listening measurement of the adjacent channels was conducted in several different areas of Chicago. Measurements were carried out close to the CTA-AVM base station transmitter site at Lake Point Towers where there was a maximum field strength of the digital transmission of the CTA-AVM channel and a maximum adjacent channel interference would be expected to occur. During these measurements the Mocom 70 transceiver squelch was disabled to obtain the maximum transceiver sensitivity. The demodulated audio output of the transceiver was recorded on magentic tape during these measurements.

The results of the subjective listening measurements was that interference from the CTA-AVM transmissions was not detectable in the adjacent channels. It should also be noted that the Chicago Police Dept., which is located on the upper adjacent channel, did not detect any interference from the CTA-AVM system.

In the second adjacent channel measurement, spectral surveillance, photographic records were taken of the CTA-AVM base station to bus interrogation channel spectrum. The equipment used in this measurement consisted of a 460 MHz ground plane dipole mounted on the roof of the mobile laboratory connected to the input of a HP 8551B spectrum analyzer. The spectrum analyzer has a 1 KHz resolution and a 60 dB dynamic range.

The results of the CTA-AVM channel spectral measurements were as follows: (See Figure 11)

Bandwidth	Attenuation level
12.5KHz	-25dB
25KHz	-40dB
50KHz	-55dB

Comparing this measured CTA-AVM spectrum with the following FCC specifications of band width limitations for the land mobile communication channels shows that the CTA-AVM is well with in the FCC specifications.

FCC Emission Limitations

"(c) The mean power of emissions shall be attenuated below the mean output power of the transmitter in accordance with the following schedule:
(1) On any frequency removed from the assigned frequency by more than 50 percent up to and including 100 percent of the authorized bandwidth: At least 25 decibels;
(2) On any frequency removed from the assigned frequency by more than 100 percent up to and including 250 percent of the authorized bandwidth: At least 35 decibels;
(3) On any frequency removed from the assigned frequency by more than 250 percent of the authorized bandwidth: At least 43 Plus 10 $\log_{10}$ (mean output power in watts) decibels or 80 decibels, whichever is the lesser attenuation.
(d) When an unauthorized emission results in harmful interference the Commission may, in its discretion, require appropriate technical changes in equipment to alleviate the interference."*

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*Code of Federal Regulations, Title 47: Chapter I-Federal Communications Commission (Continued) page 3, Part 93 Land transportation radio services. Section 93.104 Emission limitations.

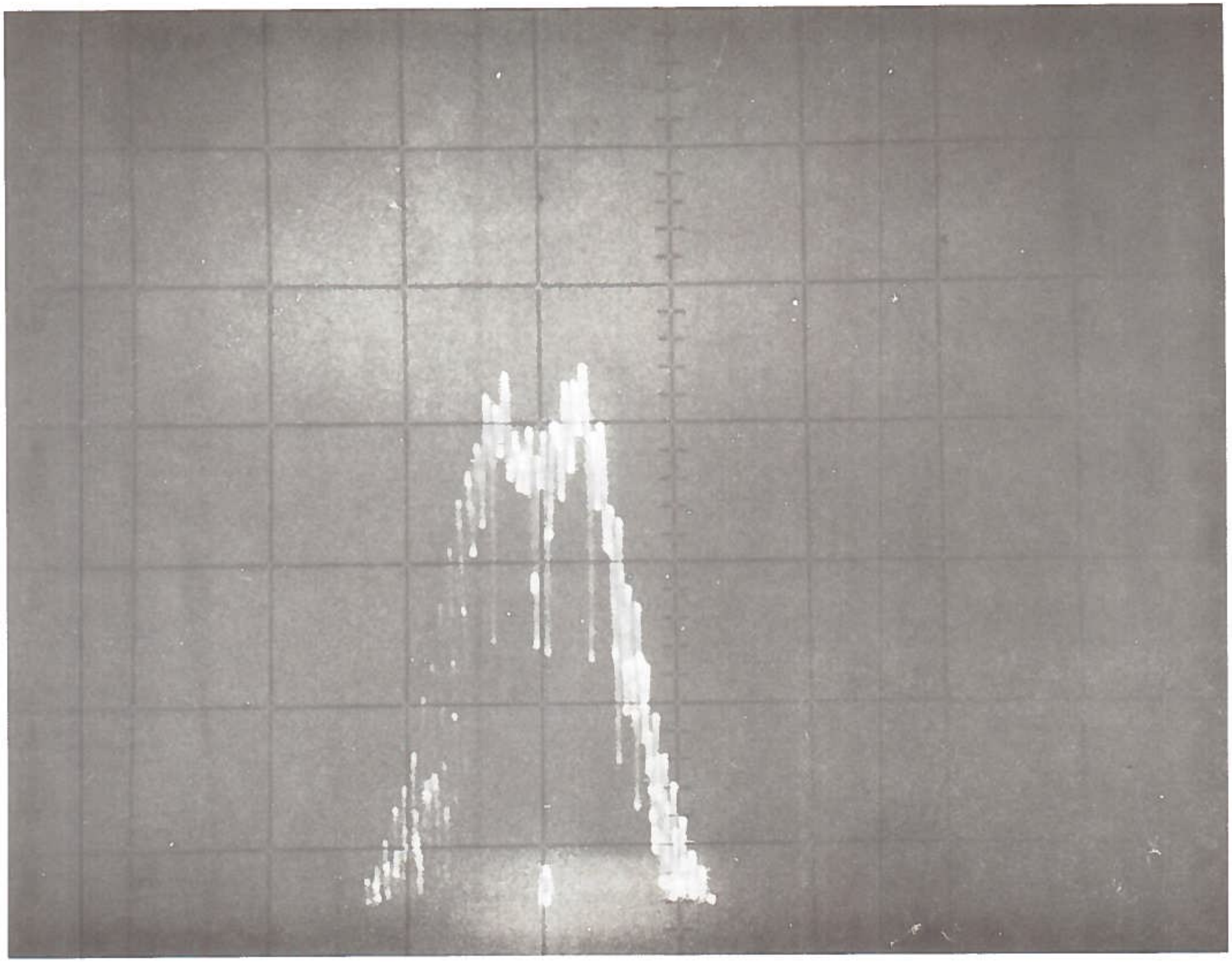


Figure 11. Chicago Transit Authority AVM Base Station Spectrum

The third set of adjacent channel interference measurements was carried out to record data for later analysis at DOT/TSC. In this measurement, the 453.325 MHz CTA-AVM base station to bus interrogation signal was converted down to 50 KHz and passed through a 100 KHz low pass filter. The output of the filter was recorded on a 80 KHz bandwidth FM tape recorder. The down converted spectrum of the CTA-AVM transmission was also observed in real-time using a low frequency spectrum analyzer.

Based on the real-time observation, the CTA-AVM spectrum appears to be well contained in the FCC allocated channel.

In conclusion, the subjective listening to adjacent channels, the spectral surveillance of the CTA-AVM channel, the real-time observation of the CTA-AVM spectrum, and the non-interference of the CTA-AVM system with the Chicago Police Dept. all confirm that the CTA-AVM system is compatible with existing UHF land mobile communication channels. Therefore, the recorded data from the third set of measurements was not analyzed to conserve available funds.

3.4 TELEPHONE LINE QUALITY MEASUREMENTS

The telephone lines used to transfer CTA-AVM system data between the three satellite receiver stations and the control room are a combination of 19H88 and 22H88 lines having DC continuity. Both CTA and Bell Telephone lines are included in the system. The modems used for data transmission and reception were designed and built by Motorola Company specifically for the CTA-AVM system. Since Bell Telephone Co. only conducts quality tests on their own equipment. They would not test the CTA-AVM telephone data transmission system. Because telephone line quality measurements were necessary for a complete CTA-AVM system evaluation, a meeting was held with L Bogan, J. Johnson and W. Nitschke of the Motorola Communication Division in Schaumberg, Illinois, to determine what could be done that would test the telephone data system qualitatively. As a result of this meeting a test system was devised by which a bus transceiver was installed at the satellite stations and directly connected to the input of the satellite transceiver. The 31 bit bus reply, containing a preset sign post location and interval timer information was repeatedly transmitted from the satellite station to the CTA control room via the telephone lines. The number of bus reply messages transmitted and the number of correct bus reply messages decoded at the control room were recorded. With this approach not only were the telephone line modems tested, but also the satellite transceivers and the control room receiver. The tests were conducted for approximately two hours at both the South Side satellite station and the Lake Point Tower satellite station.

The results of these tests were that, of the 30,000 bus messages sent from the South Side station, 29,843 were correctly decoded for a reply rate of 99.5 or a error rate of 0.5%. Similarly, the 20,000 bus messages sent from the Lake Point Tower station 19,938 messages were correctly decoded for a reply rate of 99.7% or an error rate of 0.3%.

Although long term variations occur in telephone line quality, these variations would not appreciably change the measured error rates and since these error rates are well below the acceptable CTA-AVM system bus non-reply rates, further measurements on the telephone line quality were not required.

3.5 SIGN POST FIELD STRENGTH MEASUREMENTS

Field strength measurements were conducted on four CTA-AVM sign posts. The sign posts transmit on a splintered channel having a 12.5 KHz bandwidth and at a center frequency of 153.740 MHz. The measurements were made in the moving DOT/TSC mobile test laboratory. The test equipment used for these measurements includes a 150 MHz ground plane dipole antenna mounted on the roof of the mobile laboratory. The signal from the antenna was detected by a 10 KHz bandwidth receiver tuned to the sign post center frequency. The output of the receiver was recorded on a strip chart. Distance from the sign post was estimated visually and manually marked on the strip chart. The distance estimates are accurate to approximately 50 ft. The sign posts measured were all located at or near the intersections of two or more streets.

The field strength measurements were conducted on each of the intersecting streets and on each side of each street. The four sign posts measured were located at:

Location	Sign Post Transmitter No.
Halsted and Harrison	3
Halsted, Grand and Milwaukee	7
Western and Blue Island	71
Western and Harrison	77

The results of the measurements were as follows:

1. Variation of mobile van position in the vicinity of a sign post caused roughly 10 dB variations in observed signal strength.
2. Average signal strength in the vicinity of a sign post varied over a range of roughly 18 dB for the 4 sign posts tested.
3. Sign posts signals were detected at some intersections (and on top of one bridge) where no sign posts were located. These signals were approximately equal to the signals detected from the Halsted, Grand, and Milwaukee sign post intersection, which emitted the lowest field strengths of the sign posts measured.
4. When the mobile lab stayed on the same side of the street while passing a sign post, that sign post detected field strength would remain with in approximately 5dB of the maximum recorded level for 100 ft.

Some of the sign post field strength measurements are shown in Figures 12-22.

From the few sign post field strength measurements which were carried out, it became apparent that each sign post output power must be adjusted independently. These adjustments should be made by measuring the field strengths at the various sides of the intersecting streets of a sign post intersection that the CTA buses would be scheduled to travel.

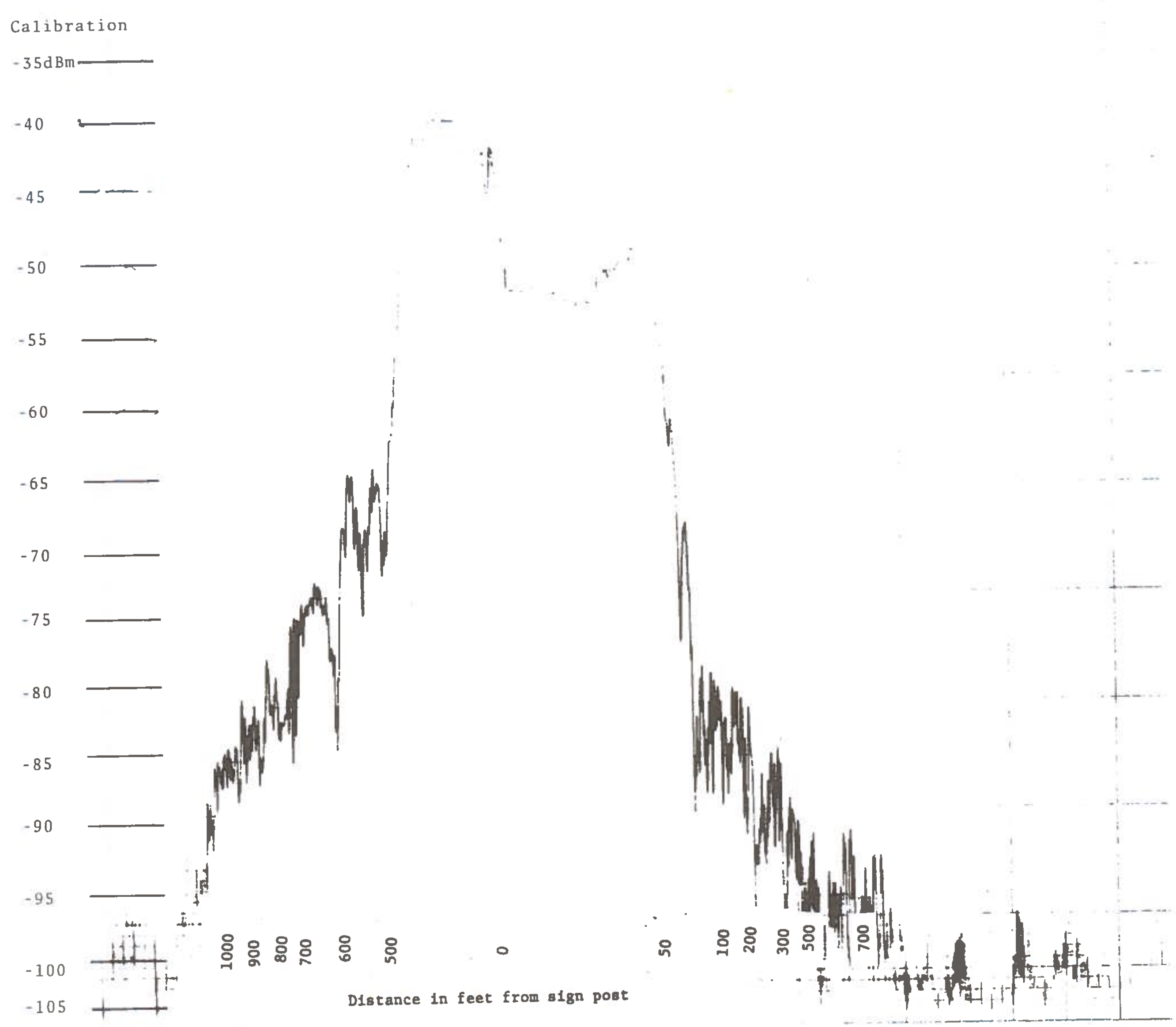


Figure 12. Sign Post Transmission-Halsted and Harrison

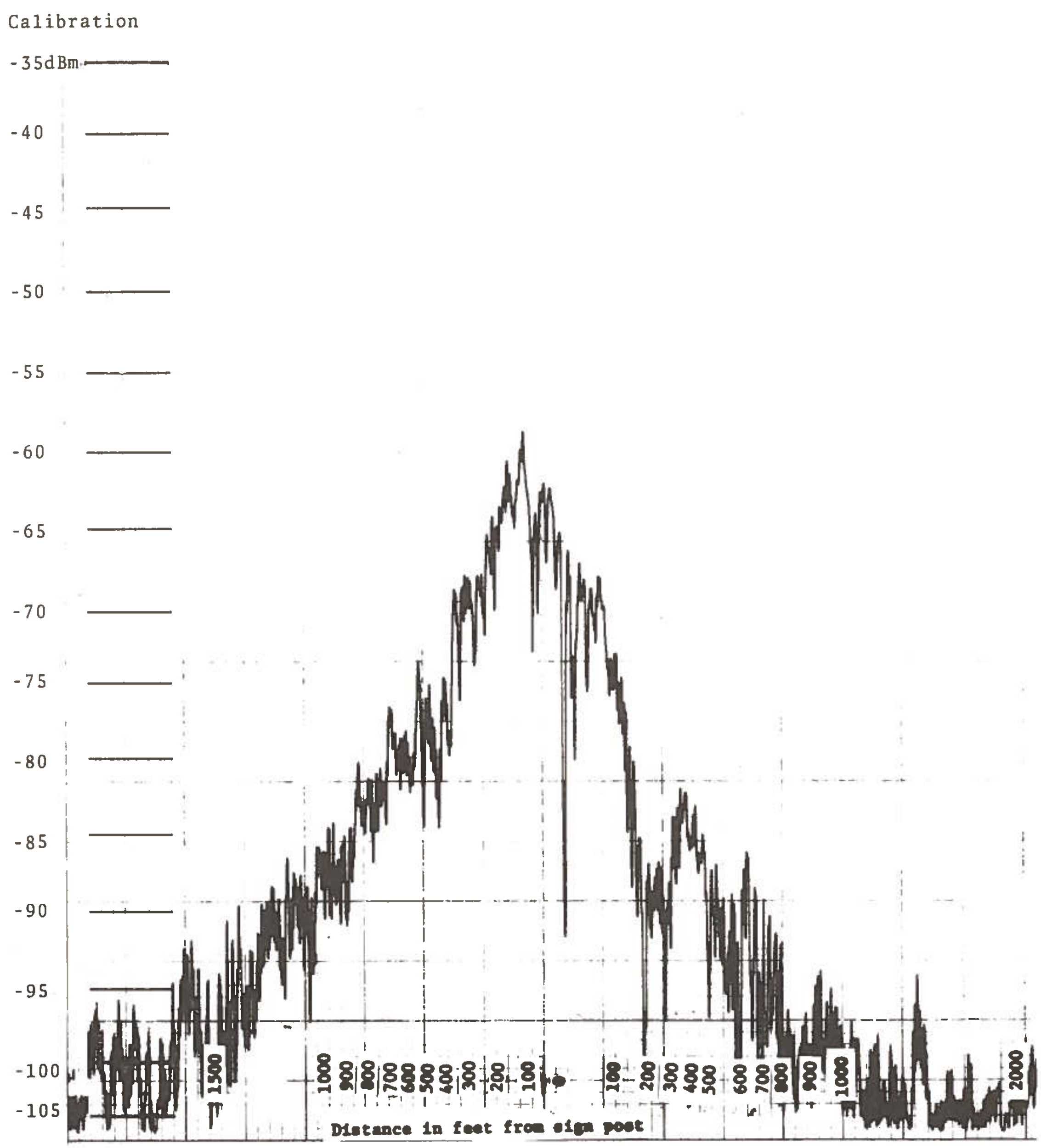


Figure 13. Sign Post Transmission-Halsted and Harrison

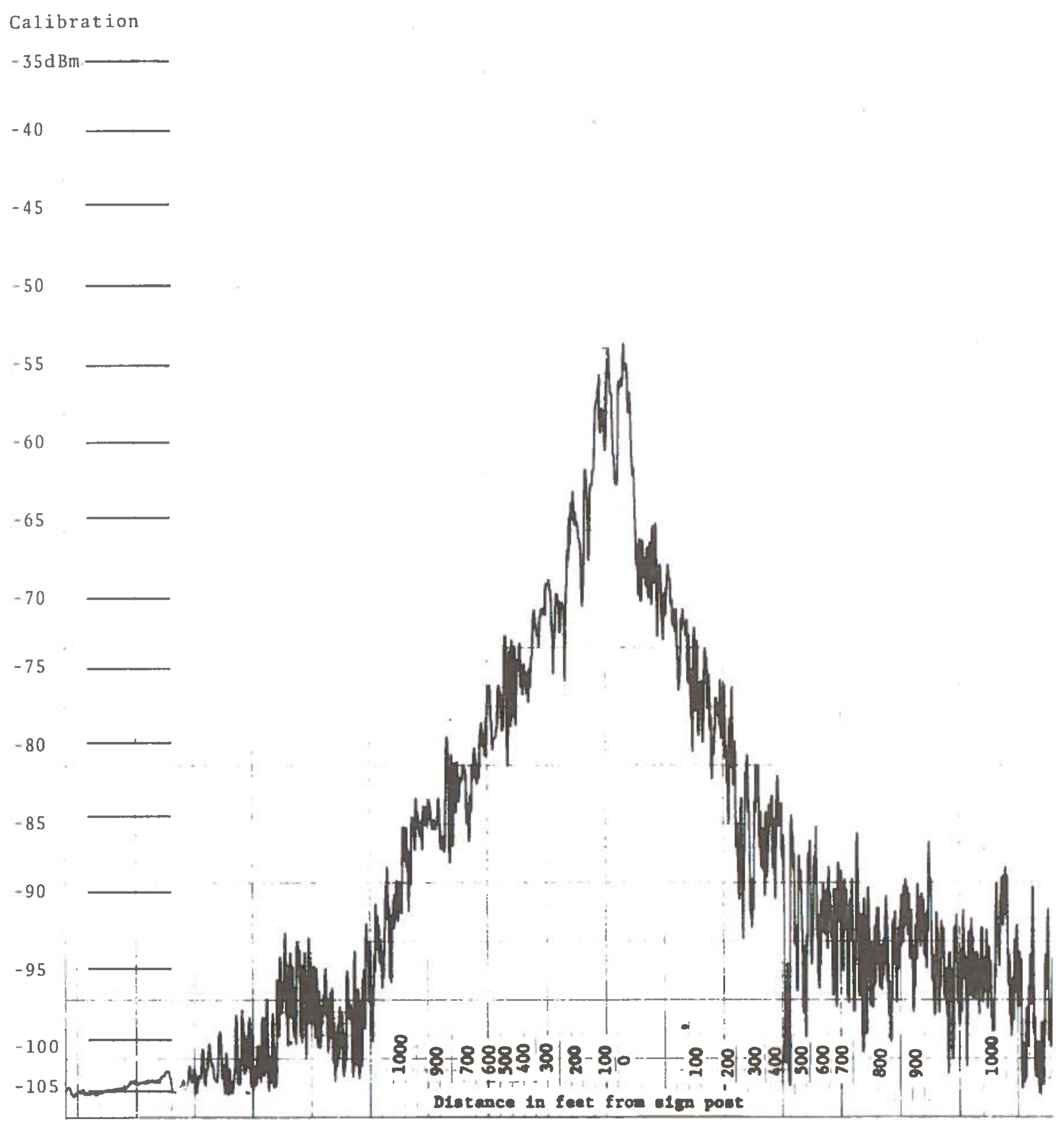


Figure 14. Sign Post Transmission-Halsted and Harrison

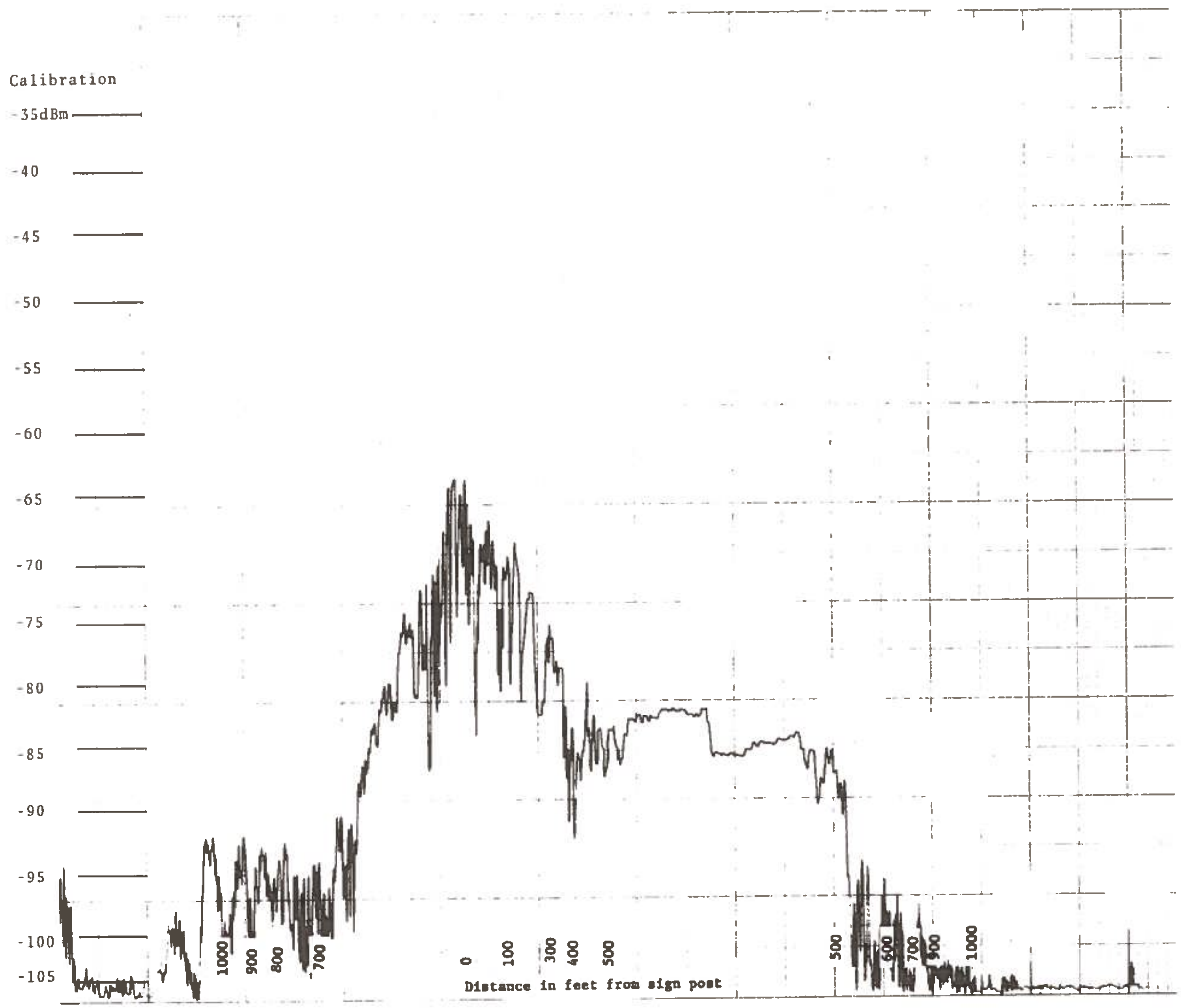


Figure 15. Sign Post Transmission-Western and Blue Island

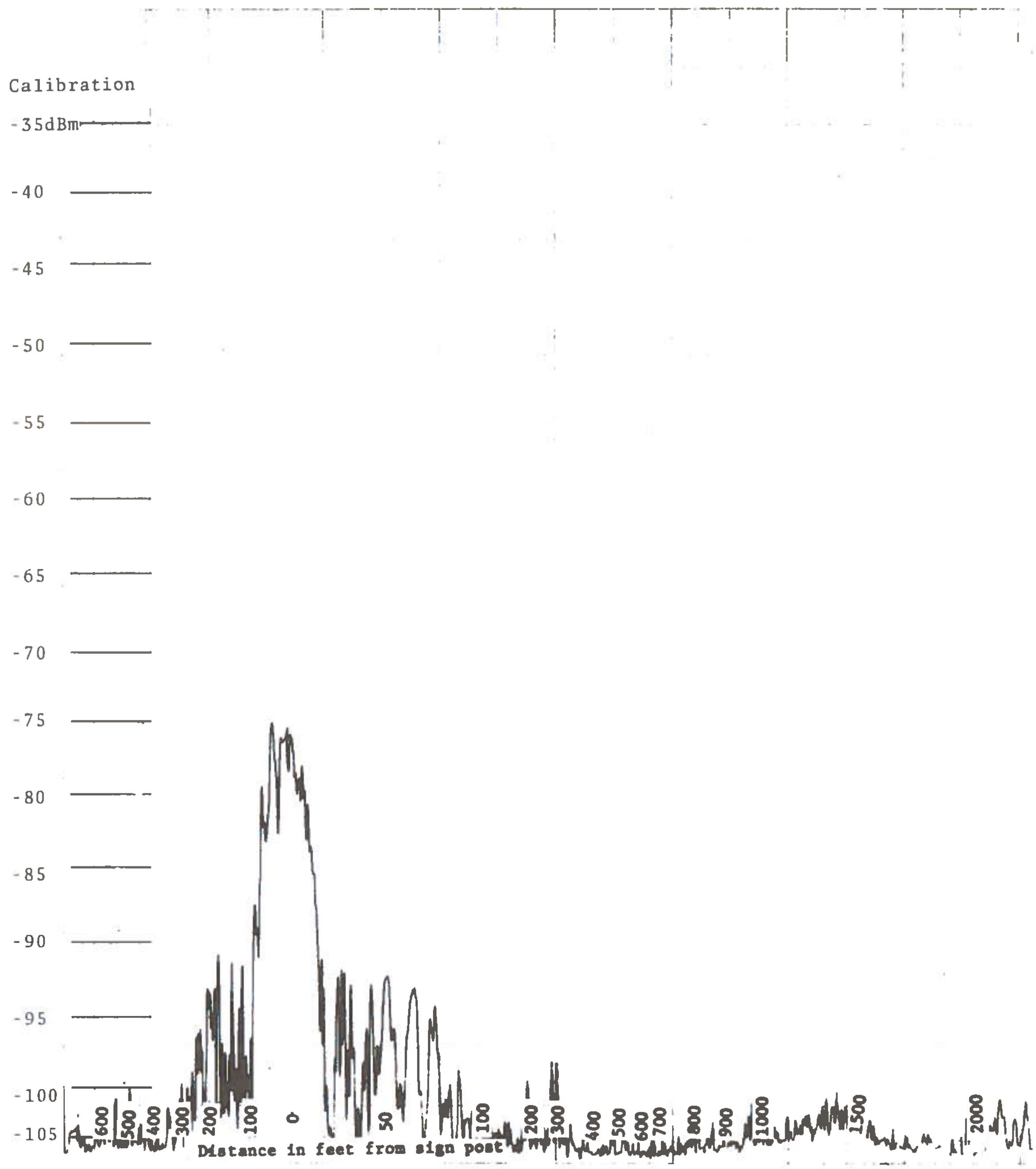


Figure 16. Sign Post Transmission-Grand and Milwaukee

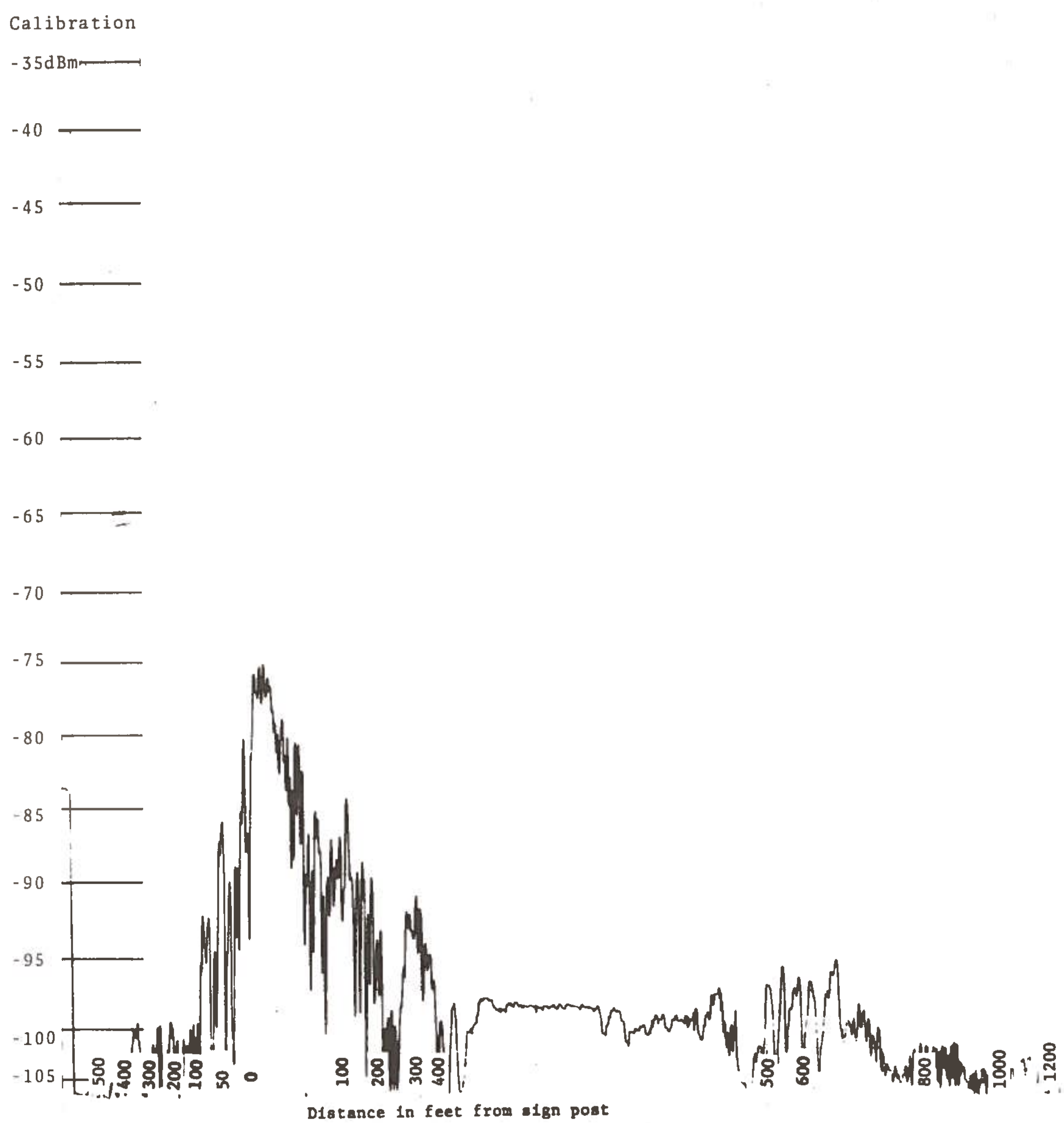


Figure 17. Sign Post Transmission-Grand and Milwaukee

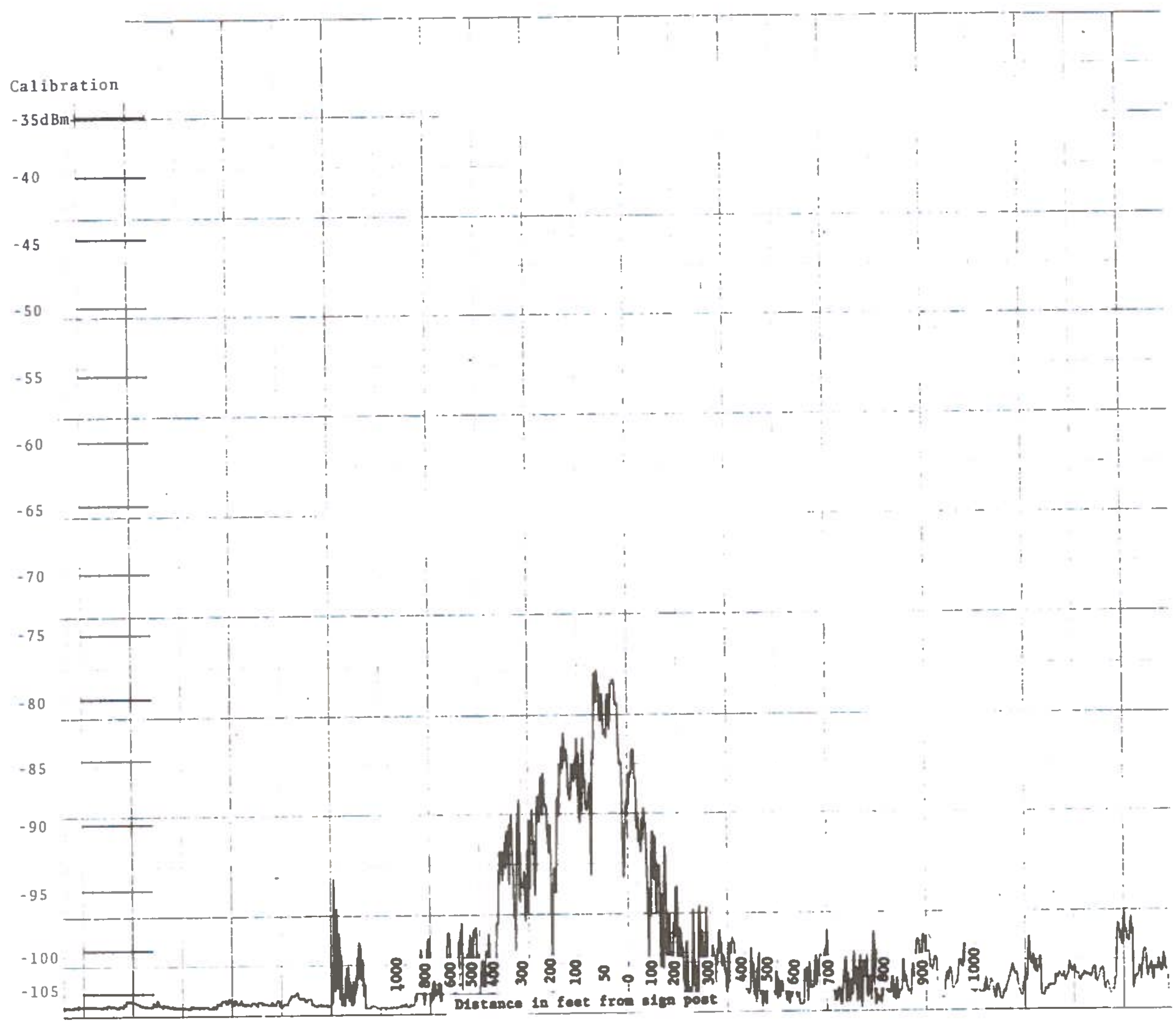


Figure 18. Sign Post Transmission-Grand and Milwaukee

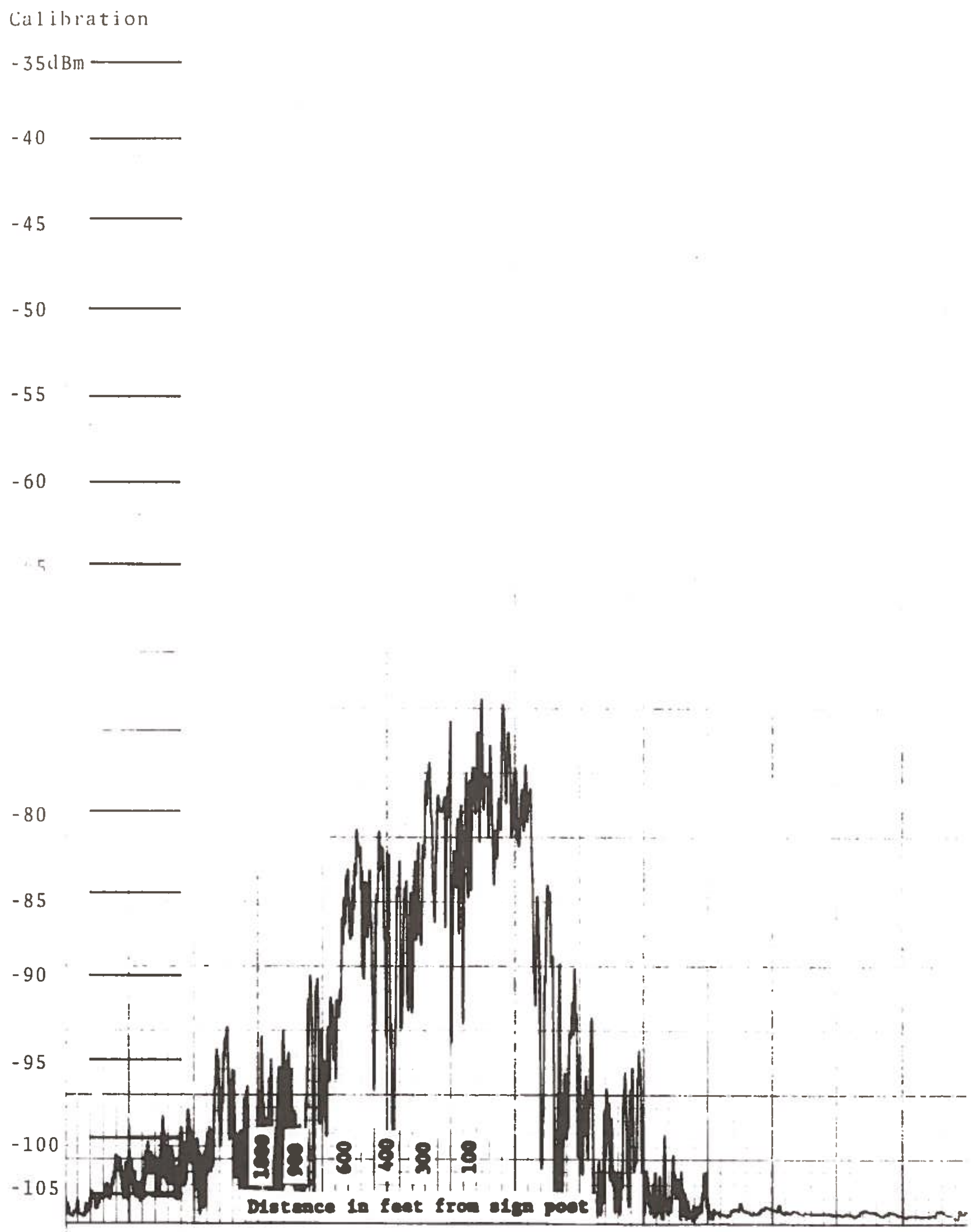


Figure 19. Sign Post Transmission-Western and Harrison

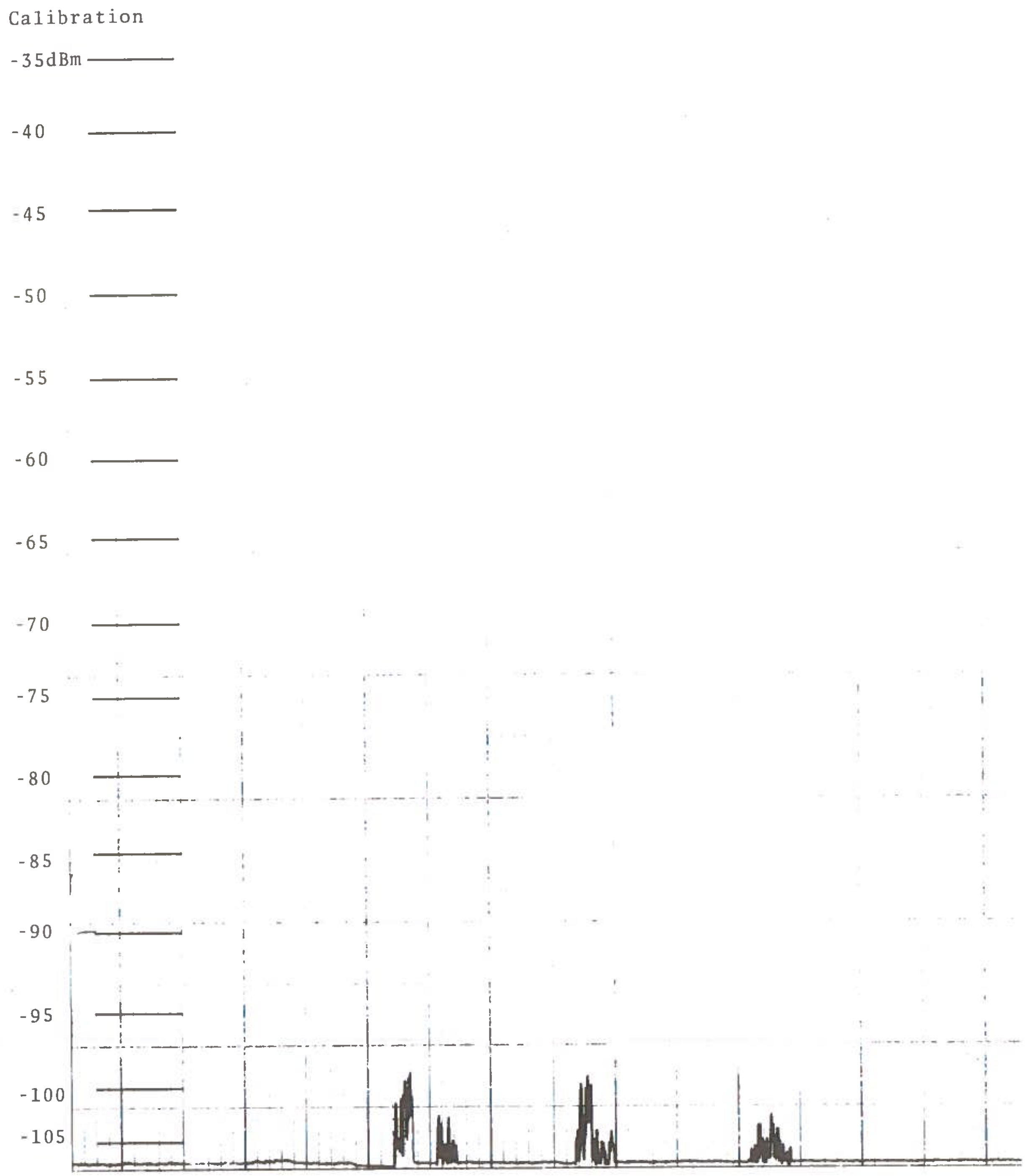


Figure 20. Sign Post Detection at Non-Sign Post Locations

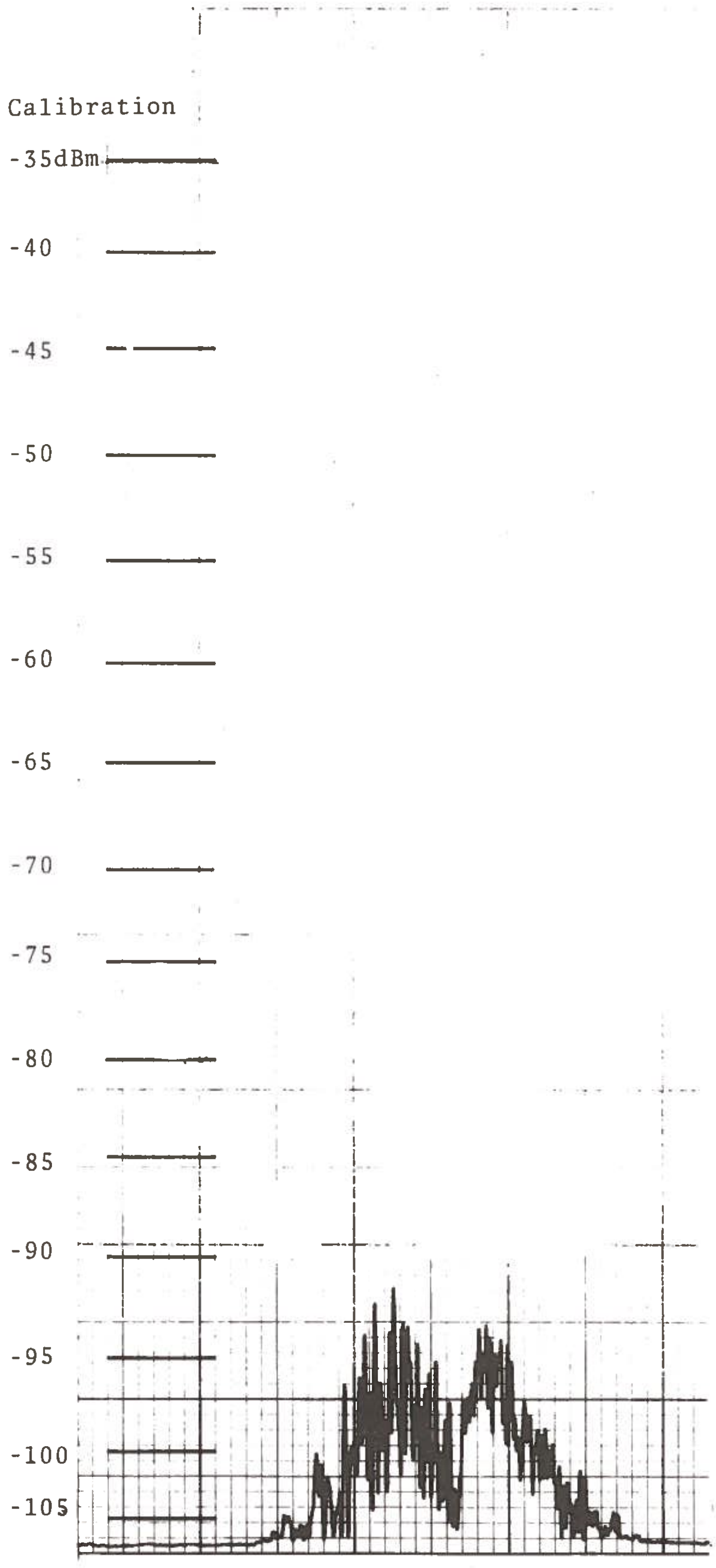


Figure 21. Sign Post Detection at Non-Sign Post Locations

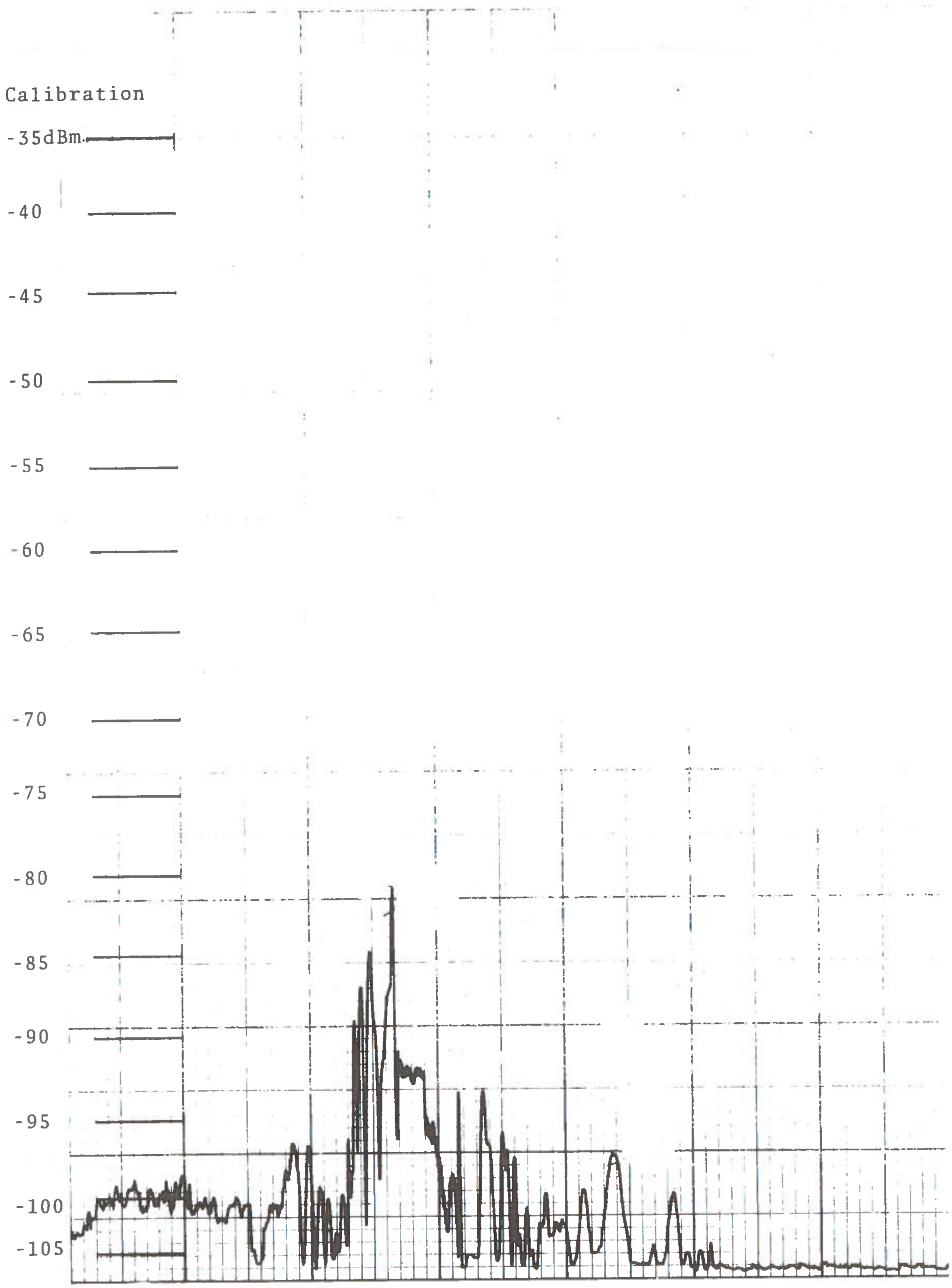


Figure 22. Sign Post Detection at Non-Sign Post Locations

The sign post output powers should be adjusted so that the field strengths observed at the sign post intersections along any CTA bus route do not fall below a specified minimum value. The CTA bus sign post receivers should have signal threshold level detectors set to eliminate any signals lower than the specified minimum value.

After the bus receivers and sign post adjustments have been made, tests should be run to determine if any sign post signals are detectable at improper locations where no sign posts exist. If such a signal is detected than the detected sign post must be moved to a new location and recalibrated.

Although these adjustments would initially take considerable time, once completed with proper documentation of each sign post output power level, maintainance should be no problem.

3.6 CHICAGO PROPAGATION TESTS

This section discusses a propagation test effort conducted in Chicago, Illinois in August 1972. The purpose of this measurement program was to determine the multipath propagation characteristics in the Chicago area. Multipath is a candidate cause of communication performance degradation which would account for the frequent "no-replies" observed in the CTA-AVM system operation.

The propagation test program consisted of three phases. First, the Chicago multipath environment was surveyed by monitoring the fading of the CTA-AVM bus interrogation signal at the mobile laboratory. In the second phase, detailed channel propagation characteristics were measured along CTA bus routes using a RAKE type channel analyzer which was mounted in the mobile laboratory. Finally, the channel propagation characteristic data were used to control the response of a channel simulator installed at DOT/TSC. The channel simulator was used to investigate typical data modem performance in the Chicago environment.

3.6.1 Summary of Results

No specific correlation between multipath characteristics and "no replies" was observed. However, it was noted that the bus interrogation signal was 10-15 dB weaker in high density "no reply" areas. The slightly weaker average signal coupled with the multipath fading probably accounts for the marginal system performance observed.

In general, the multipath characteristics well outside the Chicago Loop area do not exhibit appreciable multipath spread. However, deep fading was typically observed. Exceptions occurred on overpasses and other elevated areas where stong, reasonably steady signals were received. Fading rates varied from 0 to roughly 50 Hz depending on vehicle direction and velocity. In traffic the fading rate was typically less than 10 Hz (eyeball estimate).

The multipath spread in the downtown area was very large at times. It is estimated that the 10 dB width of the multipath spread can be as large as 25 usec. Maximum spreads were observed when the vehicle was positioned so that the signal had to propagate through the entire Loop.

Based upon the brief experimental effort and verbal undocumented system descriptions, some preliminary conclusions concerning the CTA system are suggested. It is emphasized that these conclusions are not firm because they are not backed up by any detailed analysis. They are presented only for the purpose of evaluating the utility of various courses of future action.

It appears that the weakest link in the CTA system is the interrogation link from the central site to the buses. The bus receivers use a rather unorthodox demodulation and decoding procedure which rejects all but perfectly received messages. The probability of receiving messages perfectly is significantly degraded by mulitpath fading.

Three possible approaches to this problem are suggested, 1) increase transmitted power by 10-15 dB, 2) modify interrogation transmission format and bus receiver structure, and 3) modify bus antenna structure to reduce the effects of fading.

Increasing the transmitter power is probably the least expensive fix. However, adjacent channel interference may become a problem given more power. Furthermore, increasing the power will not eliminate the problem. Note, for example, that "no replies" occur all over the city. Increasing the power will only reduce the frequency of "no replies" somewhat.

Modification of the interrogation format and receiver processing will probably be most expensive. Careful examining of the current system implementation is required to determine exact costs. The goal of such a modification is to convert from an asynchronous system to a synchronous system.

Implementation of a diversity antenna looks like the most desireable approach at the present time. It could produce the most benefit for the least cost.

3.6.2 Phase I - Propagation Characteristic Survey

The field strengths along various CTA bus routes were measured in a straight forward manner. Specifically, the CTA-AVM bus interrogation signal was monitored in the mobile laboratory using a half-wave dipole antenna and a fixed gain high dyanmic range receiver. The log output of the receiver was monitored and recorded on a strip chart recorder.

Figure 23 is a portion of the strip chart output which shows a number of interesting features of the signal level variation. In particular, note the sharp drop in signal level caused by going through an underpass between 69th and 70th St. the signal loss is roughly 25 dB. The character of the fading is easily discerned when the vehicle moves slowly between 70th and 71st streets. At 450 MHz maxima and minima can be traversed by moving only a few feet. Typically, the signal stays in a 15 dB range over short time intervals. It should be noted, however, that some of the interference minima are very deep, i.e., more than 25 dB. These are not clearly indicated in the strip chart because the dynamic

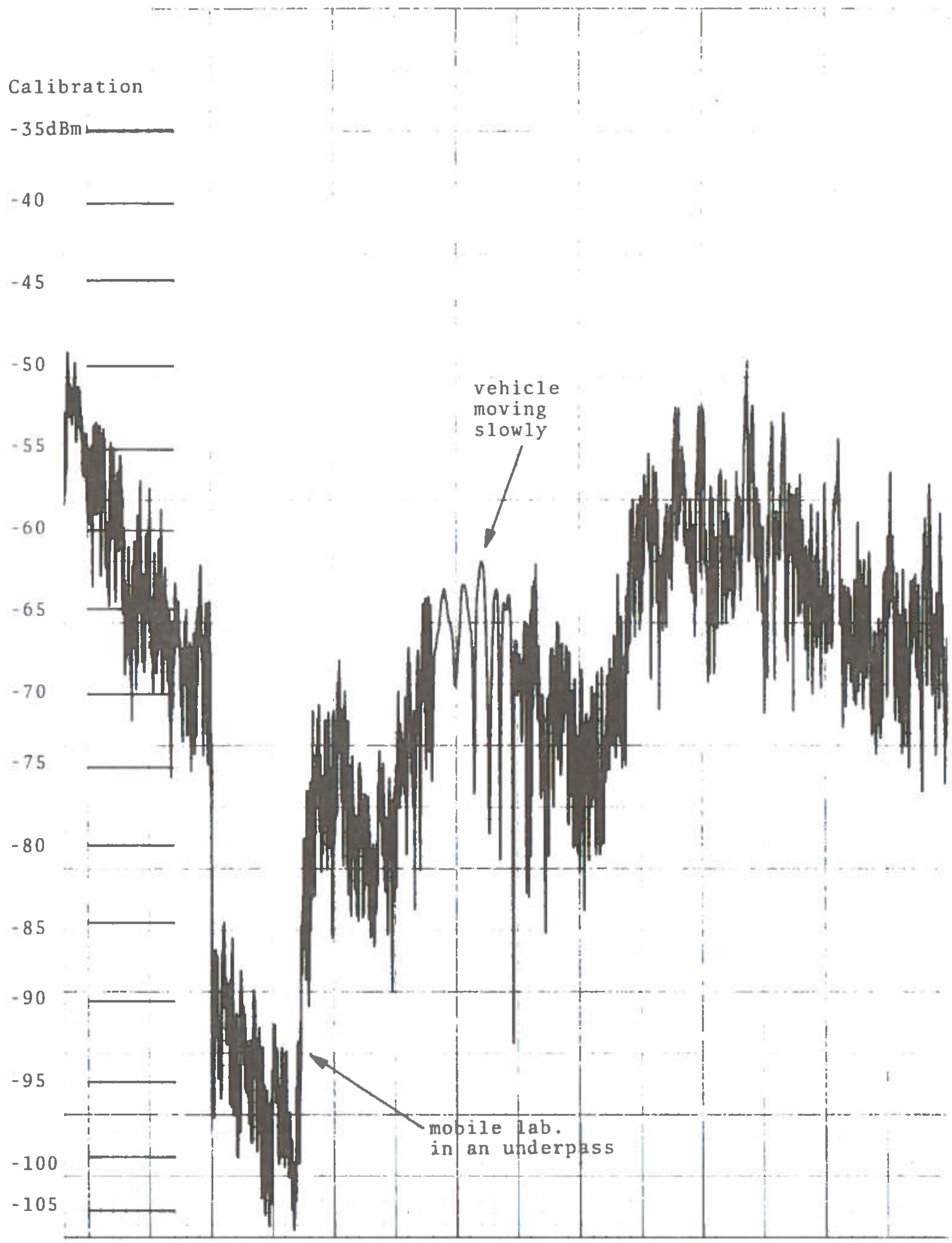


Figure 23. CW Channel Fading

capabilities of the pen drive were insufficient to follow these fast signal level changes. For this reason, deep nulls are not shown when the vehicle is moving rapidly in traffic. This is the case from 71st St, to 74th St. in Figure 23.

Figure 24 shows an extended run of typical signal level fluctuations. Figure 25 shows an unusually wide range of signal levels observed by first traversing a street which is radial from the transmitter followed by a street which sat right angles to the first. These fluctuations are caused by a combination of antenna pattern effects and multipath. Finally, Figure 26 was recorded with the mobile laboratory parked. The sharp 15 dB (nom) level changes are caused by reflections from passing trailer trucks and buses.

In general, the preliminary propagation survey indicated that 10-15 dB fading was observed everywhere in the CTA bus system. The median signal levels on routes which were relatively far from the transmitter site were roughly 10 dB lower than signal levels in the downtown Chicago area. However, the gross signal level variations and the fade depths were observed to be greater downtown, in most cases.

3.6.3 Phase II - Detailed Channel Measurement

Following the preliminary propagation survey, detailed data was collected using a RAKE type channel prober which is part of the DOT/TSC channel Playback Facility. Before discussing the results of these measurements, the channel measurement and playback simulator equipment are described.

3.6.4 Equipment Description

The channel playback facility includes two major subsystems: A channel measurement and recording system and a simulator system. Figure 27 shows the simulator portion of the system. The channel measurement equipment collects channel propagation data in the field. This data is recorded in a manner which is compatible with the channel simulator data input requirement. The recorded data

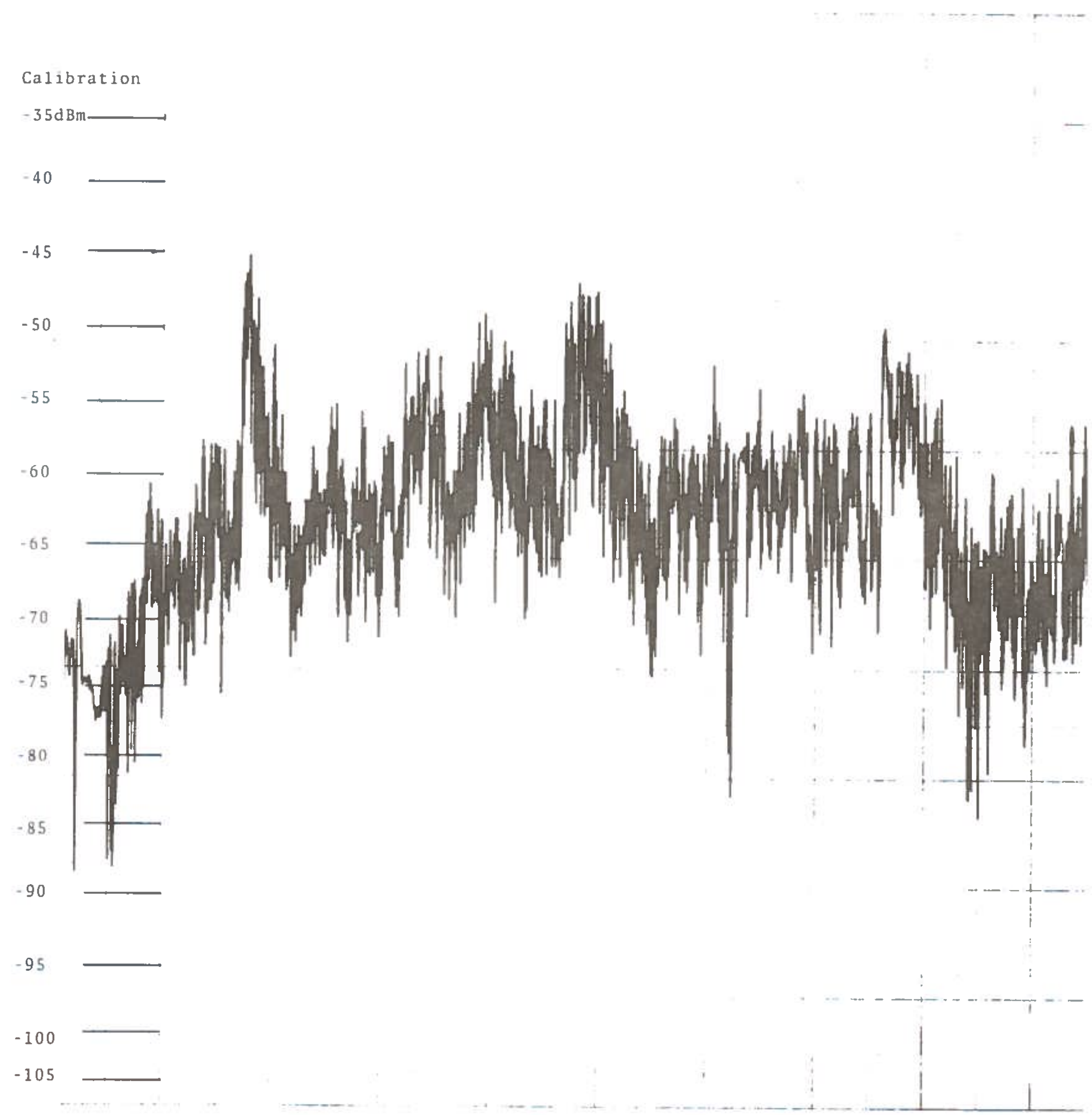


Figure 24. CW Channel Fading

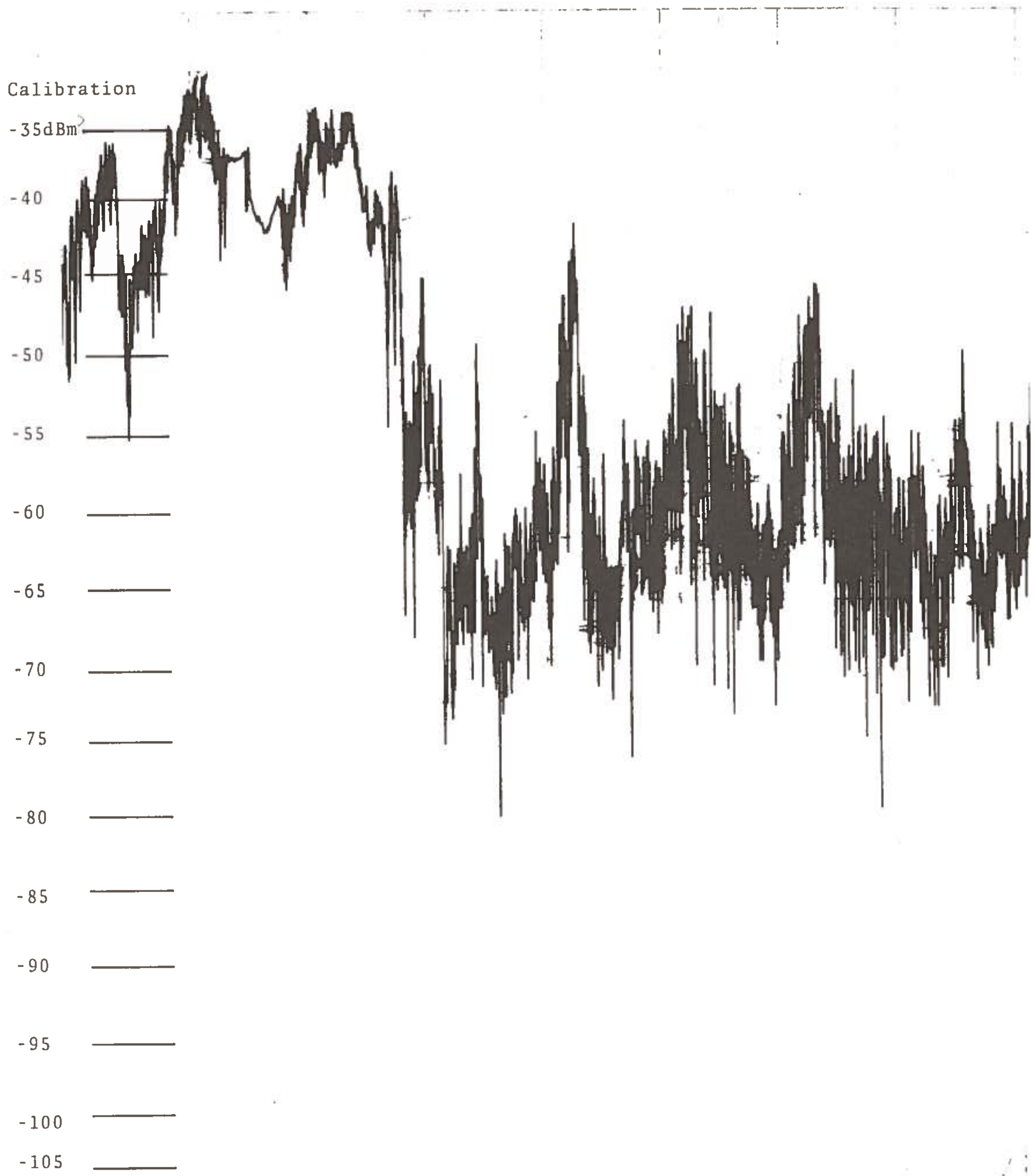


Figure 25. CW Channel Fading

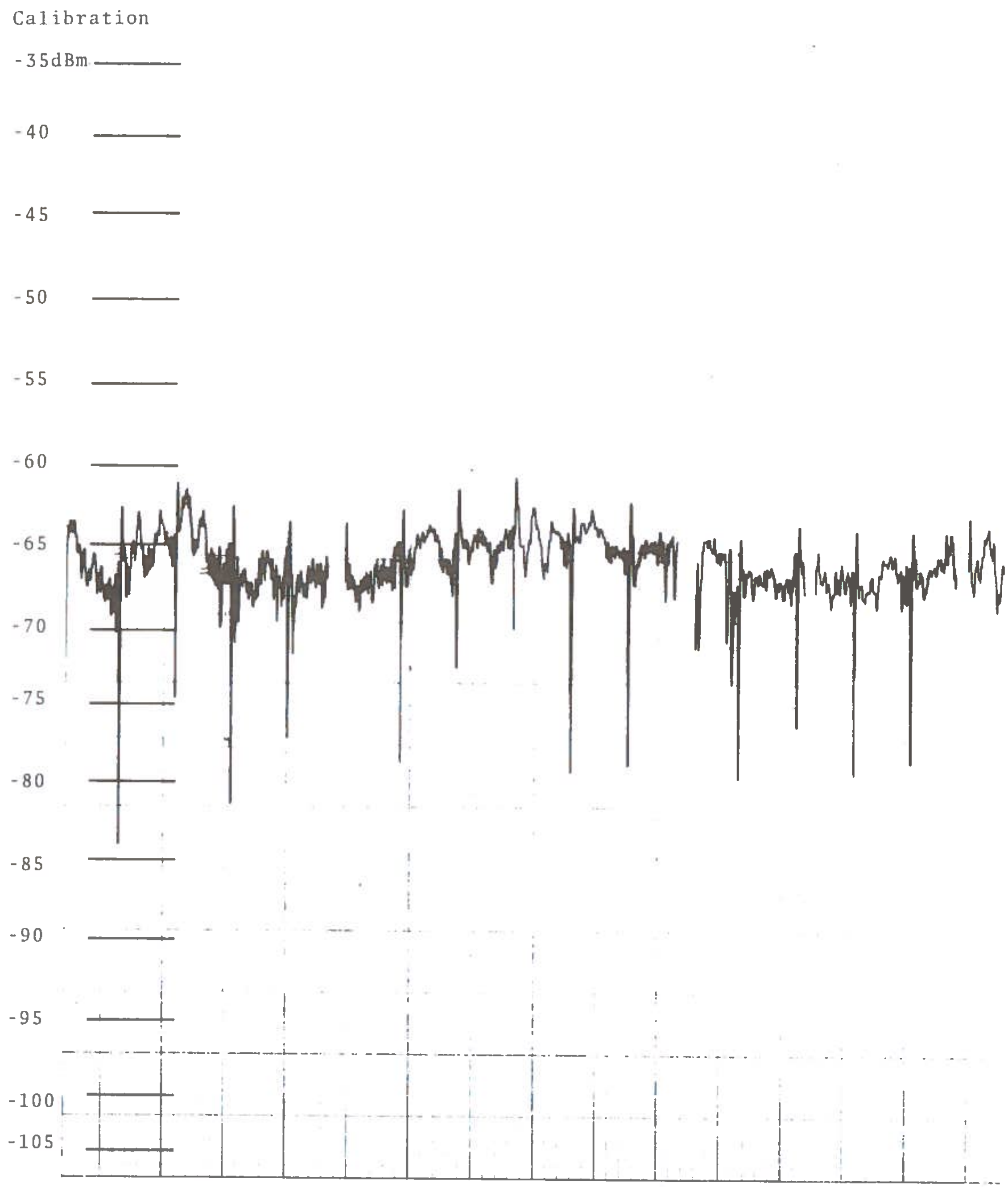


Figure 26. CW Channel Fading

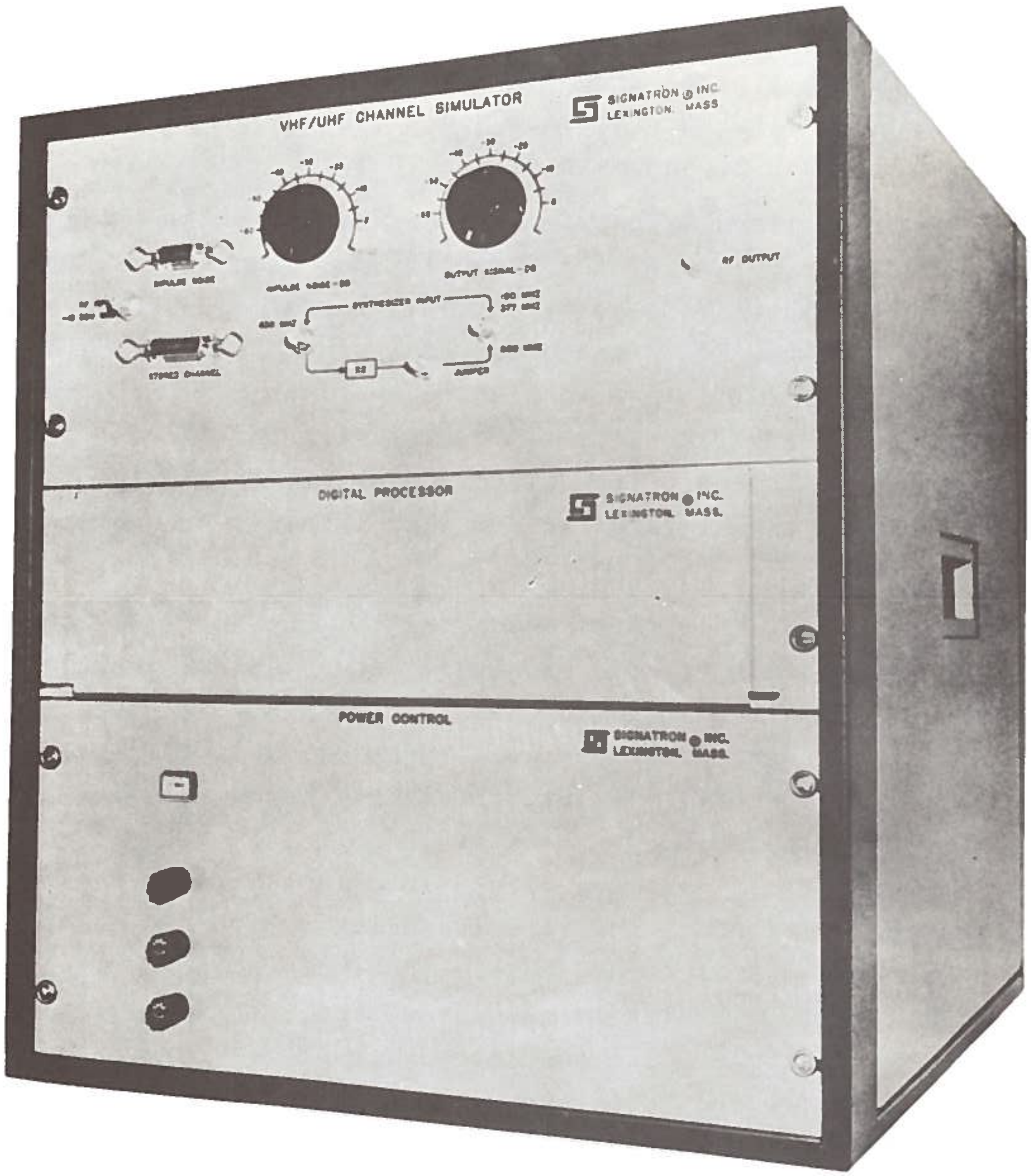


Figure 27. Channel Simulator

is later used to control simulator parameters. Thus, the simulator reproduces actual channel propagation characteristics in the laboratory.

3.6.5 Channel Measurement Subsystem

Channel propagation characteristics are measured by a RAKE type channel prober. Specifically a channel probing signal is radiated from a typical urban transmitter site. A receiver, multipath data analyzer, and recorder are installed in the interior of the mobile van as shown in Figure 28.

The transmitted signal is a pseudo-random phase shift keyed carrier. The bit rate of the pseudo-random sequence is 200 kb/s. Thus, the multipath time delay resolution achieved by the channel measurement system is on the order of 5 usec. Clearly, this capability is insufficient to resolve the physical paths which are present at any given time. However, the goal of the channel measurement equipment is to collect data for the simulator facility rather than to investigate the detailed physical properties of the channel.

The channel simulator is designed to provide valid reproduction of propagation effects on signals whose bandwidths are 50 KHz or less. For this purpose, a channel prober bit rate of 200 KHz is ample, i.e., the probing signal spectrum is almost flat in the bandwidth of interest. The prober signal energy received at the mobile van is analyzed by a bank of 10 correlation demodulators. Each demodulator is provided with a locally generated pseudo-random code reference. The relative delays of the 10 code references are staggered at 5 usec intervals. Thus, the outputs of each of the correlation demodulators are associated with specific 5 usec path delay intervals. The absolute delay of the reference sequences is controlled by frequency standards at the transmitter site and in the mobile van.

The analyzer outputs are the real and imaginary components of the complex, time varying impulse response of the channel. These are filtered at baseband in low pass filters with 120 Hz

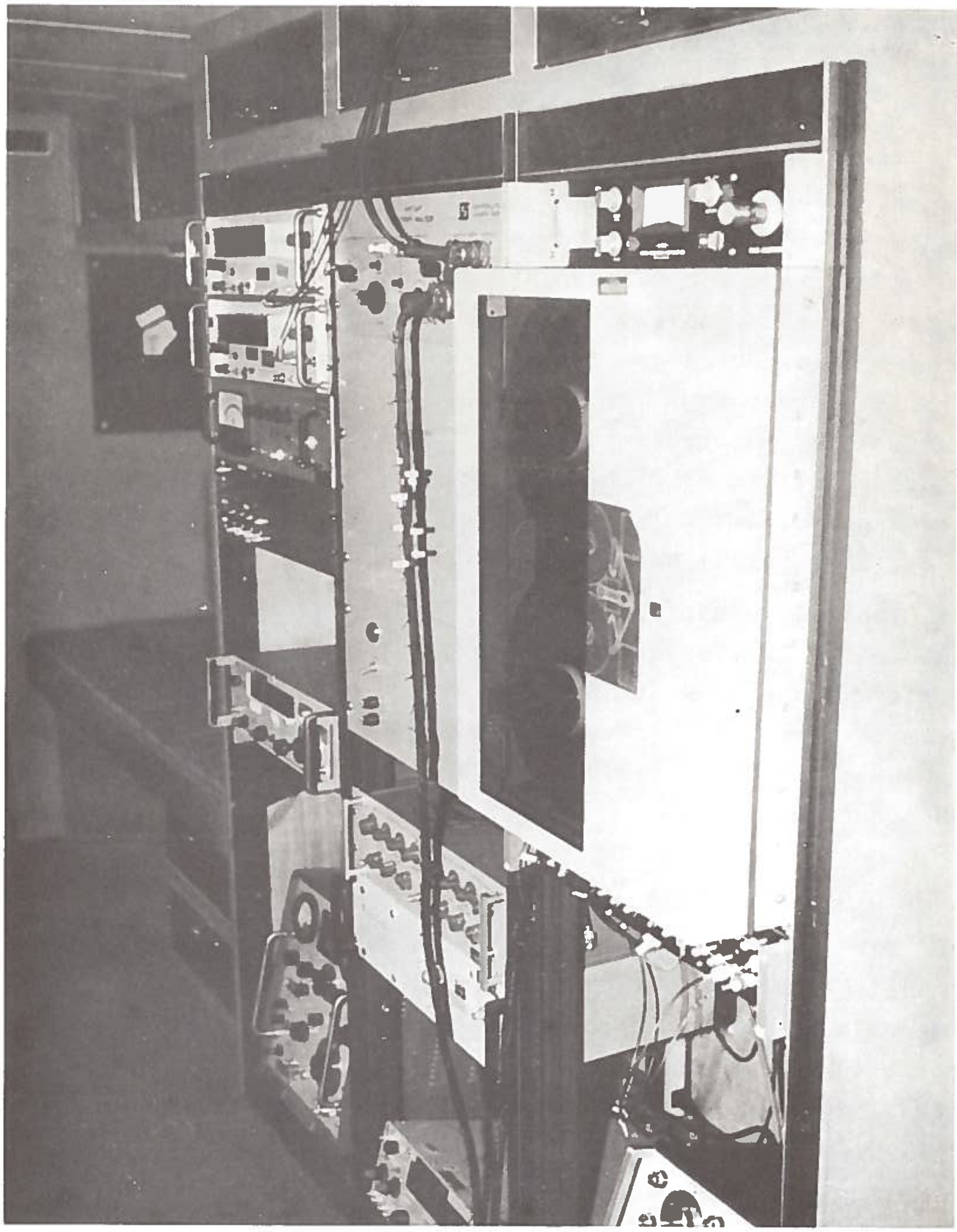


Figure 28. Interior of Mobile Laboratory

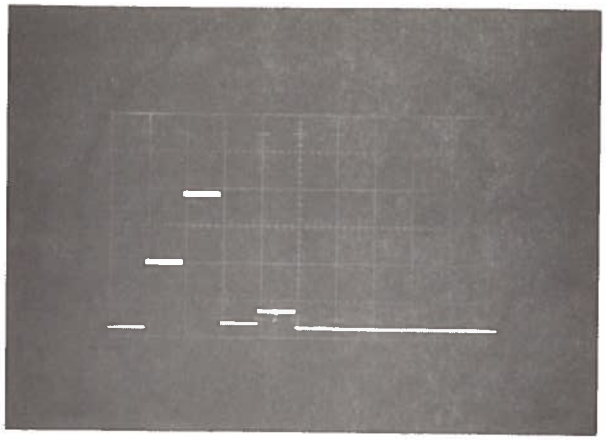
bandwidths. These bandwidths are selected to be wide enough to pass the highest expected Doppler rates. The highest carrier frequencies of interest for most mobile applications are on the order of 900 MHz. At such carrier frequencies, a Doppler rate of 120 Hz is produced if the mobile van speed exceeds 90 mph.

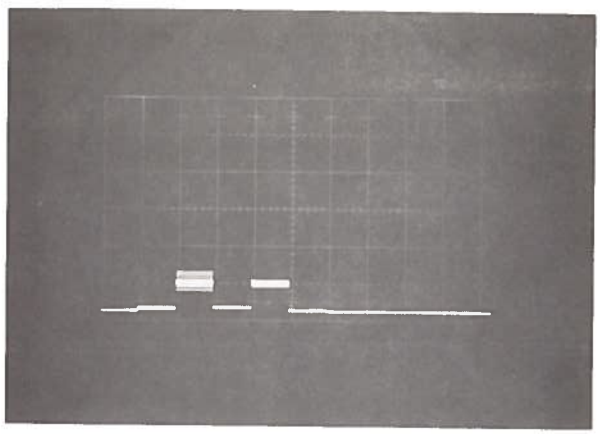
The baseband samples of the complex, time varying impulse response are multiplexed and recorded on an instrumentation tape recorder which is installed in the mobile van. The van is also equipped with a special purpose processor which smoothes the samples of the complex, time varying impulse response and displays is in the form of a bar graph in which the height of each of 10 bars is proportional to the average power observed in each of ten 5 usec delay intervals being monitored by correlation demodulators. Figure 29 illustrates the scope display. The dynamic range of the display (vertical axis) is roughly 28 dB. The scale of the delay (horizontal) axis is 5 usec/cm.

Table I summarizes the capabilities of the channel measurement equipment. As presently configured, the system will operate with carrier frequencies at 150 MHz, 450 MHz, or 900 MHz. Of course, other carrier frequencies can be readily implemented. Similarily, the equipment is readily modifiable to provide other code bit rates and sequence lengths.

3.6.6 Channel Simulator Subsystem

The channel simulator equipment reproduces the effect of channel propagation effects by implementing a tapped delay line channel model. The tapped delay line and its associated tap gain controllers are realized at baseband using digital techniques. A total delay of 50 usec is employed with 10 taps spaced 5 usec apart. The complex impulse response data recorded by the channel measurement equipment can thus be used directly to control the tap gains in the simulator. The signal input to the simulator can be at 150 MHz, 450 MHz, or, 900 MHz center frequency. The signal should be constant envelope for optimum performance of the simulator and the bandwidth must be 50 KHz or less. An L.O. reference





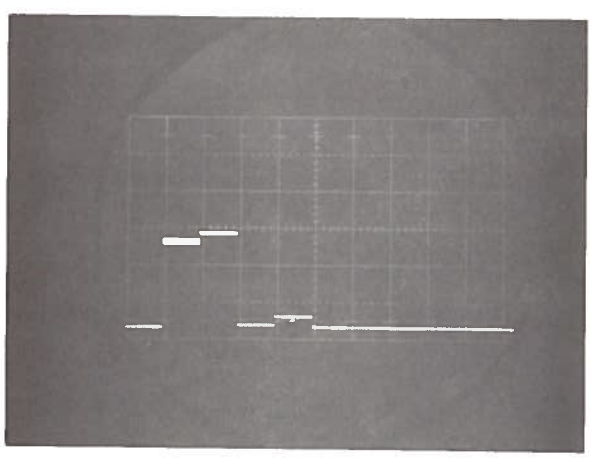


Figure 29. Channel Delay Power Spectrums

reference at 190 MHz, 490 MHz, or 430 MHz, must also be provided to the simulator for operation at 150 MHz, 450 MHz and 900 MHz, respectively. The dynamic range of the simulator with only one tap excited is in excess of 40 dB. The unit will not saturate with 9 of the 10 taps fully modulated. So, the total dynamic range of the device is on the order of 58 dB. The simulator includes provisions for the addition of impulsive noise to the multipath distorted output signal. This subsystem can generate wide band impulsive noise with dynamic range in excess of 60 dB when driven from suitably recorded impulse noise data. Table 2 summarizes the performance capabilities of the simulator system.

3.6.7 Preliminary Experimentation

The system has been set-up to take channel data in Boston, Mass at 150 MHz and in Chicago, Ill. at 450 MHz. Figure 29 shows some interesting multipath features observed in Boston. In particular, Figure 29 shows the real-time display of the delay power spectrum of the channel with the transmitter mounted on the roof of the D.O.T. Transportation Systems Center, in Cambridge and the mobile van located on Commonwealth Ave. Boston.

A 64 second average is used to obtain the result shown in Figure 29a. Note that significant multipath energy roughly 10 dB down is received at a delay of more than 15 usec from the earliest arriving signals. Figures 29b and 29c show the differences in delay power spectrum achieved by moving the mobile van 1 ft along Commonwealth Ave. Similar results were observed and recorded in Chicago at 450 MHz. In fact, delay spreads in excess of 20 usec were observed when signals were transmitted through the "Loop" area. For most geometries the delay spread is typically on the order of 10 usec.

The equipment configuration in Chicago was established to measure propagation paths which coincide with those of CTA-AVM signals. Thus, the prober transmitter was located with the CTA bus interrogation transmitter in the Lake Shore Towers. The mobile

TABLE 1. CHANNEL MEASUREMENT CAPABILITIES

R.F. Carrier Frequency	150 MHz, 450 MHz, or 900 MHz
Modulation	Phase Shift Keyed
Deviation	±80°
Prober Format	Pseudo Random Sequence
Bit Rate	200 kb/s
Code Length	511 bits
System Range	20 miles (typical, depends on ant. height)
Multipath Delay Resolution	5 usec
Max. Delay Spread Capability	50 usec
Max. Doppler Spread Capability	120 Hz (single-sided)
Analyzer Dynamic Range	40 dB
Max. Channel Recording Time	1.42 hours/tape reel
Display Dynamic Range	28 dB
Display Averaging Times	1/4, 1, 4, 16, or, 64 sec.

TABLE 2. SIMULATOR PERFORMANCE

R.F. Center Freq.	150 MHz, 450 MHz, or, 900 MHz
R.F. Bandwidth (constant envelope)	50 KHz
Max. Delay Spread Cap.	50 usec
Tap Spacing	5 usec
Max. Doppler Spread Cap.	120 Hz (single sided)
Worse Case Dynamic Range	40 dB
Total Dynamic Range	58 dB
Impulse Noise Dynamic Range	60 dB
Impulse Noise Bandwidth	1 MHz

laboratory was driven along several north-south and east-west bus routes during the data collection and recording effort. Both downtown and semi-suburban routes were traversed. A map was prepared by Motorola, Communications Div. Shaumberg, Ill. showing the distribution of "no replies" along the various CTA bus routes. The map is shown in Figure 30. Note that "no replies" occur all over the system. However, some areas indicate more frequent "no replies" than others. During the course of data collection, specific bus route areas were selected in which higher than average "no replies" and lower than average "no replies" were observed. The channel characteristics in these areas were analyzed using the real-time display in the mobile laboratory. No specific correlation between channel propagation characteristics and the density of "no replies" was observed. The median signal level was 10-15 dB lower at the southern end of the system where some bus routes exhibited a higher density of "no replies". However, the weaker signal could not account exclusively for the no replies because some routes with weak signals did not exhibit a high density of "no replies". It is possible that "no replies" result from a combination of weak median signal level and multipath fading.

3.6.8 Candidate Improvements to the CTA-AVM Bus Interrogation Link

The operation of this bus interrogation link is summarized as follows: The interrogation signal for each bus is a 41 bit sequence which is used to FSK the transmitted carrier. The 41 bit message contains the address of the bus being interrogated and other information, which is transmitted two times. At the bus, the received signal is decoded. If neither of the two interrogation sequences conforms to the proper format then the message is rejected and the bus does not reply.

The data bits in the message are carried in an unusual way. In particular, a form of pulse duration modulation is employed i.e., the dwell-time at one of the two frequencies determine whether a mark or a space was transmitted. Thus, the decoder is sensitive to sporadic transitions between the upper and lower

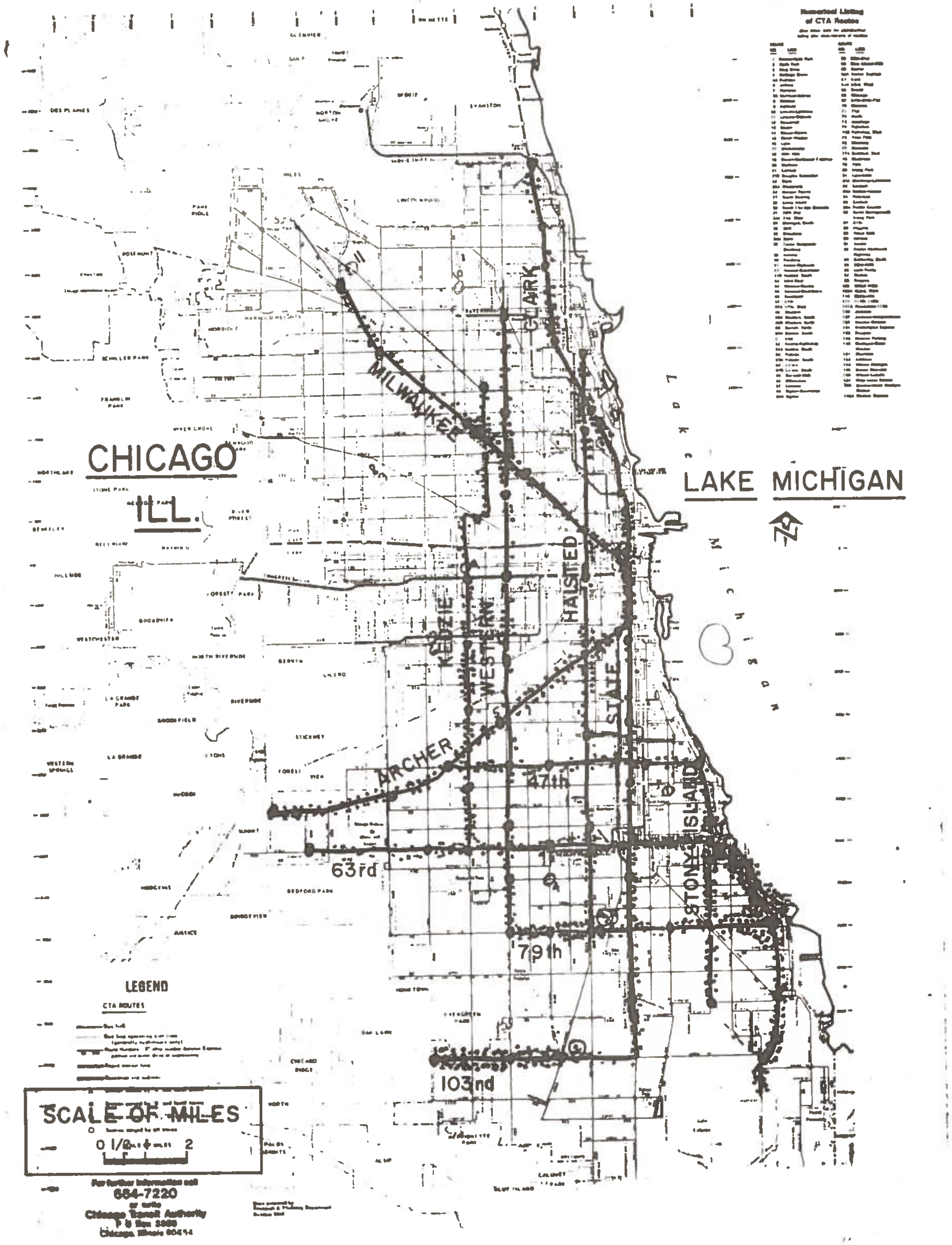


Figure 30. CTA Bus Non-Reply Frequency Map of Chicago

frequencies. These sporadic transitions will be detected as format errors and therefore cause rejection of the interrogation message. It is typical that multipath fading will cause sporadic transitions in an FM receiver. The transitions can be caused by the fast phase changes associated with multipath fades and/or by AM-to-PM conversion in the receiver IF limiter. Several fixes for the "no reply" problem were considered. First, the transmitted power could be increased with a very small expenditure of effort and money. Increasing the power would reduce the depth of the interference nulls as seen at the receivers. Clearly, this approach will only cause a marginal improvement in system operation because it can be seen from Figure 30 that "no replies" occur with considerable frequency in areas where the signal is quite strong near the transmitter. Next, some consideration was given to modification of the bus interrogation data signal transmissions and the data extraction equipment onboard the buses. This approach is prohibitively expensive since it involves the redesign and replacement of a great deal of equipment. Therefore, it can not be seriously considered for the CTA-AVM system. However, the experience gained from the Chicago system and the AVM systems tested in Philadelphia, PA indicate that an interrogation technique which utilized synchronous polling of the busses will provide superior performance. Such a technique is much less degraded by channel fading because averaging can be used to smooth out the effects of fading and impulsive noise. Finally, a diversity antenna system was considered for the CTA buses. This approach is discussed in more detail in the next section.

3.6.9 Antenna Design for Multipath Reduction

This section discusses the design of antenna systems for reduction of multipath effects in the urban environment. Specifically, the antenna could be used to collect data in the Boston Area. Then, a comparative analysis can be conducted to determine the merits of a scanned diversity antenna in the urban environment.

3.6.10 Energy Reception Concept

E.N. Gilbert analyzed a multipath reduction scheme (suggested by J.R. Pierce) in Energy Reception for Mobile Radio, BSTJ, Vol. 44, pg 1779-1804, October 1965. The energy reception technique is based on the idea that when a plane wave is reflected off a wall at normal incidence the minima of the electric field is co-located with maxima of the magnetic field and vice versa. Furthermore, the total electromagnetic energy at any point is a constant. In such a situation, a vertical whip antenna and a pair of loop antennas can be used to detect total incident energy. The output of the energy detection receiver remains constant in the vicinity of the wall.

In more realistic situations, the field at any given point is constituted of many waves with arbitrary amplitues, phases, and angles-of incidence. Gilbert analyzed the case of four waves with angles of 0°, 60°, 140°, and 260°, and equal amplitudes. He found that the energy density fluctuations are much smaller than the electric field fluctuations.

Gilbert has derived the correlation functions as a function of distance among the various energies, i.e., electric, magnetic, and total. For purposes of illustration, it is found that for a large number of equal strength waves, the electric energy auto-correltation is of the form

$$R_{EE} = J_o^2 \ (\beta r)$$

where

$$\beta = \frac{2\pi}{\lambda}$$

and r is distance. Similarily, it is found that the crosscorrelation between electric and magnetic energies is

$$R_{EH} = 1.414 \ J_1^2 \ (\beta r)$$

Note that $J_1^2\ (0) = 0$ and that the crosscorrelation function is never negative.

3.6.11 Preliminary Antenna Experimentation

Preliminary experimentation at DOT/TSC indicates that the type of antenna array suggested by Pierce is not easily implemented. Difficulties arise because the co-located antenna elements mutually interact. It was found, for example, that a quarterwave vertical whip immediately adjacent to a vertical loop has a significant effect on the loop characteristics. On the other hand, two vertical whips with appropriate spacing between them can be used to obtain the desired diversity effect.

In order to minimize the cost of the proposed diversity system, a nonoptimum switched diversity technique was considered for the CTA application. Some research was conducted to determine the availability of inexpensive RF switches for this purpose and a high speed RF switch was purchased for laboratory experiments. Work on the antenna diversity system was stopped because available funds were limited.

3.6.12 Modem Testing with the Channel Simulator Facility

In order to demonstrate the utility of the channel simulator for modem design and testing, the performance of a simple FSK modem was measured in the laboratory under a variety of channel conditions. The channel data used was collected in Chicago at 450 MHz. Nine, one minute channel data intervals were selected for the modem. The first 3 minutes are representative of suburban channels. The next three minutes are representive of typical urban channels. The last three minutes are representative of urban channels with very large delay spreads i.e., between 20 usec and 25 usec.

Three modem tests were carried out for each 1 minute channel data interval specifically, the probability of bit error was measured for three bit rates, 300 b/s, 600 b/s. The results achieved are summarized in Table 3.

TABLE 3. MODEM TEST RESULTS

BIT RATE	PROBABILITY OF ERROR		
	RUN #1	RUN #2	RUN #3
300 b/s	4×10^{-3}	1.22×10^{-3}	1.72×10^{-3}
600	3.44×10^{-3}	1.17×10^{-3}	1.28×10^{-3}
1200	3.4×10^{-3}	1.71×10^{-3}	1.22×10^{-3}
	RUN #4	RUN #5	RUN #6
300	2.88×10^{-3}	1.5×10^{-3}	5.05×10^{-3}
600	4.38×10^{-3}	1.28×10^{-3}	4.05×10^{-3}
1200	4.97×10^{-3}	1.60×10^{-3}	3.94×10^{-3}
	RUN #7	RUN #8	RUN #9
300	4.5×10^{-3}	6.61×10^{-3}	6.94×10^{-3}
600	5.83×10^{-3}	8.88×10^{-3}	bit synch unlock
1200	6.25×10^{-3}	6.7×10^{-3}	5.82×10^{-3}

The results tabulated above demonstrate the capabilities of the simulator to reproduce the channel affects on modem performance in a controlled and repeatable manner. These capabilities allow the designer to investigate the behavior of modems under adverse conditions induced by multipath fading. For example, the results of Table 3 show that the modem under test has a tendency to lose bit synch when the delay spread is larger than 20 usec.

Unfortunately, the simple FSK modem used to demonstrate the simulator capabilities is not comparable to the CTA-AVM interrogation modem. Thus, the results tabulated above can not be extrapolated for application to the CTA system. If an interrogation transmitter exciter and receiver were provided to TSC, detailed investigation of the CTA modem performance in the fading environment could be expeditiously carried out. In fact, it is possible that the transmitter exciter operation could be breadboarded at TSC so that only the bus receiver needs to be provided.

3.7 CONCLUSIONS

3.7.1 Chicago Propagation Measurements

The discussion of this section has described the propagation tests carried out in Chicago, IL in connection with the performance evaluation of the CTA-AVM system. Candidate methods for improving the performance of the system in the multipath environment were described. Although no distinct correlation between the density of AVM "no replies" and multipath parameters such as delay spread was found, it was concluded that multipath fading combined with reduced median signal level in some areas could cause the observed performance.

Based on this conclusion, several system modifications were suggested which would improve performance in the presence of multipath. In particular, increased transmitter power, receiver data extraction processing modification, and, diversity antenna implementation were considered.

Preliminary experimentation with a suitable diversity antenna technique was conducted at TSC. In addition, preliminary modem testing was conducted using the Channel Simulator facility at TSC. This latter effort investigated performance of a simple FSK modem under simulated Chicago's propagation conditions. It was found that certain multipath conditions will lead to modem failure (loss of lock). Unfortunately, these results can not be applied to the CTA-AVM bus interrogation link because the CTA-AVM modem technique is substantially different. The simulator system was demonstrated to be useful for the investigation and evaluation of the effect of multipath on modem performance.

3.7.2 CTA-AVM Adjacent Channel Interference

Three adjacent channel interference measurements were conducted on the CTA-AVM system: subjective listening, surveillance of the CTA-AVM spectrum, and wide band tape recordings of the CTA-AVM channel and its adjacent channels. The results of these measurements all confirmed that the CTA-AVM system is compatible with existing UHF land mobile communication channels

3.7.3 CTA-AVM Telephone Line Quality Measurements

Telephone line quality tests were conducted on the CTA-AVM dedicated data telephone lines. These lines transmit the bus messages received by the satellite receiving stations, to the base control station. The test was made by directly connecting a bus transmitter to the satellite receiver and repeatedly transmitting the bus message to the base control station via the telephone lines. The number of bus reply messages transmitted and the number of correct bus reply messages decoded at the control station were recorded. The test results were that the measured error rates were approximately 0.4%, well below the acceptable CTA-AVM bus non-reply rates.

3.7.4 Sign Post Field Strength Measurements

Field strength measurements of four CTA-AVM sign posts were made in the moving DOT/TSC mobile laboratory. The measurements were conducted on each side of the intersecting streets where the sign posts were located. The results of the tests were that the signal strengths of the four sign posts measured varied over a range of roughly 18 dB and that sign post signals were detected at some intersections where no sign posts were located. Therefore, it is recommended that each sign post output power be adjusted independently by measuring the field strengths of the various sides of the intersecting streets, of a sign post location, that the CTA buses would be scheduled to travel.

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