REPORT NO. DOT-TSC-FRA- 72-5

MEASUREMENTS AND ANALYSIS OF 115 KV POWER LINE NOISE AND ITS EFFECT ON PUEBLO TEST SITE RADIO LINKS

R. E. BUCK, R. E. ESPOSITO, R. GAGNON,
E. T. LEONARD, P. YOH
TRANSPORTATION SYSTEMS CENTER
55 BROADWAY
CAMBRIDGE, MA. 02142

MAY 1972
TECHNICAL REPORT

PREPARED FOR

DEPARTMENT OF TRANSPORTATION
FEDERAL RAILROAD ADMINISTRATION
OFFICE OF HIGH SPEED GROUND TRANSPORTATION
WASHINGTON, D.C. 20591

1. Report No. DOT-TSC-FRA-72-5	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle MEASUREMENTS AND ANALYSIS OF 115 kV POWER LINE NOISE AND ITS EFFECT ON PUEBLO TEST SITE RADIO LINKS		5. Report Date May 1972
		6. Performing Organization Code
7. Author(s) R.E.Buck, R.E.Esposito, R.Gagnon E.T.Leonard, P. Yoh		8. Performing Organization Report No.
9. Performing Organization Name and Address Department of Transportation Transportation Systems Center 55 Broadway, Cambridge, MA. 02142		10. Work Unit No. R-2305
		11. Contract or Grant No. RR-204
12. Sponsoring Agency Name and Address Department of Transportation Federal Railroad Administration Office of High Speed Ground Trans. Washington, D.C. 20591		13. Type of Report and Period Covered Technical Report Nov. 1971-May 1972
		14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Noise measurements were made for 115 kV power lines near the frequencies 166, 217 and 406.8 MHz with a receiver bandwidth of 1 MHz. The measurements consisted of counting the numbers of pulses per minute at preset threshold values and RMS. The variations of the noise level vs the lateral distance from the power line were also measured. The worst noise level, -40 dBm, was observed at 217 MHz under a noisy power line. The results of these measurements show that, under normal conditions, power line noise will not have significant effects on the radio links at the Pueblo Test Site. Recommendation is made for a monitoring system to detect the level of a noisy power line when its noise reaches a preset level. Further studies are recommended of other possible noise sources -- automobile ignition noise, electrical equipment noise -- and of the multipath effects.

17. Key Words ·Power line noise ·Radio noise ·Impulse ·Communications	18. Distribution Statement Availability is Unlimited. Document may be Released To the National Technical Information Service, Springfield, Virginia 22151, for Sale to the Public.

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 45	22. Price

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

1.0 INTRODUCTION

A number of radio links have been established between the prototype high speed and other improved ground transportation vehicles with a wayside station at the Pueblo Test Site. These radio links accomplish various functions: command and control, telemetry data transmission, and voice communication. These communications links are susceptible to electromagnetic noise, which distorts signals and degrades system performance. The amount of degradation depends on the noise power level, the noise characteristics - gaussian or impulsive, the characteristics and modulation of the transmitted signals and the receivers' characteristics. The Pueblo Site's major supply of electric power is a 115 kV High Voltage line, and this is one of the noise sources which could cause the degradation of the radio communication channels. The noise sources on the power line could be defective components, corona discharge, weather effects, and/or voltage gradients on the conductors.

This report is divided into two parts: measurements and results; and analysis and recommendations.

To estimate the effects of the 115 kV power line noise a series of measurements around the frequencies 166, 217 and 406.8 MHz were made near 115 kV lines located in the Boston area. A typical 115 kV line under measurement is shown in Figure 1-1.

Figure 1-1. Typical 115 kV Power Line

The figure shows a standard mount of 115 kV line (H-frame) which is similar to the one to be installed at the Pueblo Test Site. The mobile laboratory is shown in Figure 1-2. Some of the measuring equipment inside the van is shown in Figure 1-3. Assuming that the measurements made in the Boston area are representative of the situation existing in Pueblo, these results can be used to determine noise effects on the radio links.

The basic measurements consisted of counting the number of noise impulses per unit time that cross a preset threshold level or receiver sensitivity, and RMS noise measurements. A number of impulsive noise phenomena, other than the power line, were observed. These noise sources were most likely due to automobile ignitions. The ignition noise levels varied from car to car but all ignition noise had a very short duration, less than 1 μ sec. In addition, multipath phenomena were observed while making RMS measurements. (See Section 4.2). Sections 2, 3, and 4 will discuss the measuring procedure and results.

A detailed analysis of the power line noise effect on each radio link will be presented in Section 5. The analysis indicates that the effect of normal power line noise is negligible. However, a defective power line may generate a higher noise level than the maximum measured. Conclusions are presented in Sections 6 and 7 with a list of recommendations for further measurements. The main suggestions are to determine the multipath effects and the level of ignition noise.

In conclusion, noise generated from power lines (if normal) will not pose any problem to the existing communication systems at the Pueblo Test Site. However, noise from faulty power line equipment, vehicle ignition noise, electric motors and other industrial equipment, and multipath effects may cause significant degradation to these communication systems.

Figure 1-2. Mobile Noise Measuring Van

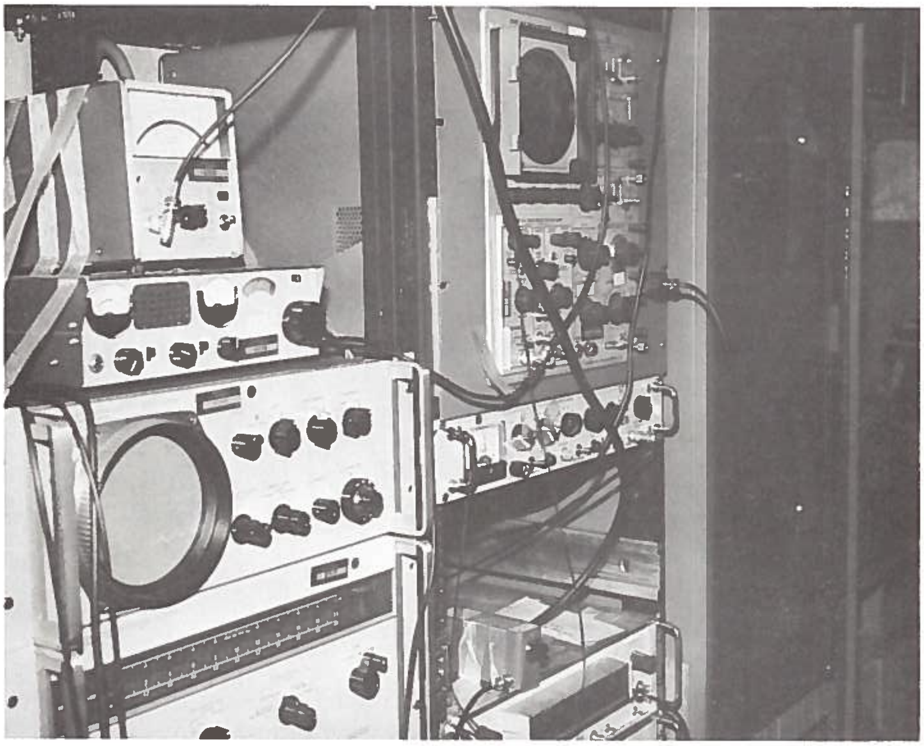


Figure 1-3. Measuring Equipment

2.0 PRELIMINARY PREPARATION

A series of measurements determining the impulse noise level generated by 115 kV transmission lines were made. These measurements consisted of counting, during one minute intervals, the number of noise impulses that crossed preset receiver sensitivity settings in a wideband receiver. Some RMS measurements were also made.

2.1 MEASUREMENT LOCATIONS

Eight locations were chosen according to the following criteria:

1. 115 kV overhead transmission lines
2. Access road for mobile laboratory
3. Rural area to avoid noise sources other than the 115 kV lines
4. Commuting distance from Boston.

These measurement locations were:

1. Tyler St., Methuen, MA.
2. Myrtle St., Methuen, MA.
3. Forest St., Methuen, MA.
4. Foster St., North Andover, MA.
5. Access Rd. to closed Nike Site, North Andover, MA.
6. Boxford St., North Andover, MA.
7. Access Road off Rt. 125 to Western Electric Substation, North Andover, MA.
8. Access Road to Substation off Dascomb Road, Andover, MA.

Even though these locations were chosen in rural areas, periodically vehicles would pass by the mobile laboratory and interfere with the impulse noise counting measurements. To avoid this problem, an impulse noise counting time interval of one minute was used. Thus, if a vehicle passed by the mobile laboratory during any one minute impulse noise counting interval, that interval would be discarded and only one minute of data taking time would be lost.

2.2 SPECTRUM SURVEILLANCE MEASUREMENTS

Prior to the impulse noise counting measurements, a spectrum surveillance was conducted in the frequency region of the three communication channels to be used at the Pueblo Test Site, i.e., 166, 217, 406.8 MHz. This surveillance was made to find a

3-MHz frequency band in each of the three frequency regions that was free of radio signals or noise. Impulse noise measurements made in one of these 3-MHz frequency bands would therefore only consist of noise generated by the 115 kV transmission lines. The 3-MHz bandwidth was required because of the roll-off of the receiver IF amplifier's filter skirts used in the impulse noise measurements. Figure 2-1 shows the receivers IF amplifier pass band characteristics.

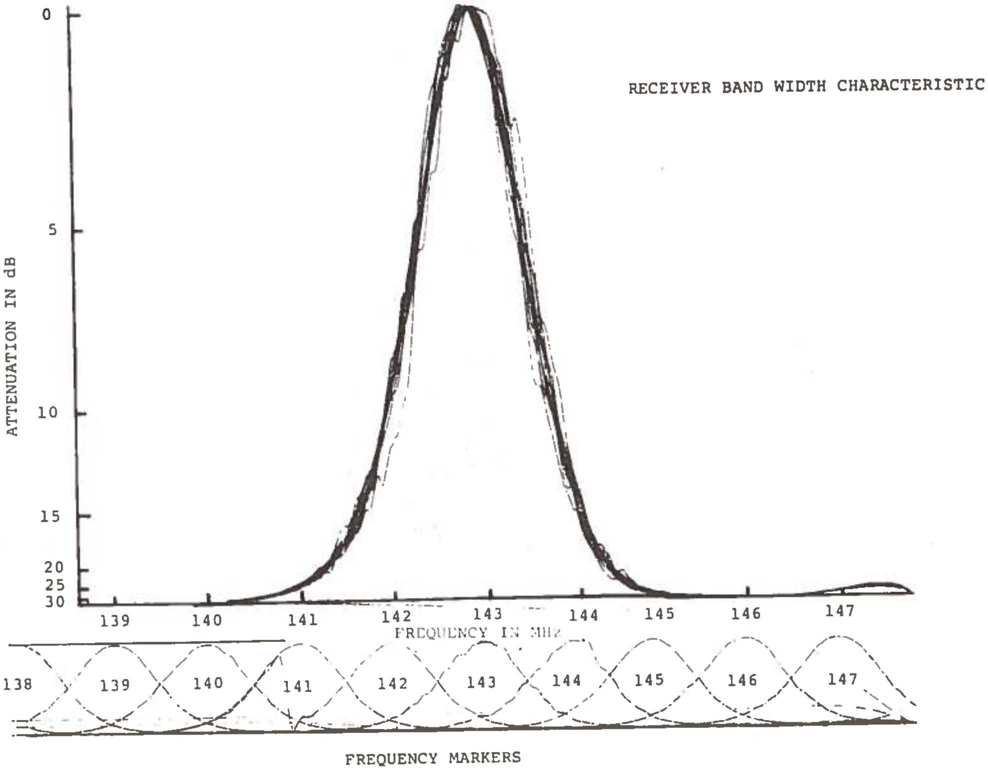


Figure 2-1. Receiver IF Pass Band Characteristics

The frequency surveillance measurement system consisted of unity gain dipole antennas, a Hewlett Packard 8551-B spectrum analyzer, and a Moseley X-Y recorder. The dipole antennas were mounted, one at a time, on a flat 13 ft by 6 ft by 1/4 inch thick aluminum ground plane located on the roof of the mobile laboratory. The antennas were connected directly to the input of the spectrum analyzer, and the spectrum analyzer output was recorded on the X-Y recorder. Figure 2-2 is a typical frequency surveillance spectrum recorded on the X-Y recorder. These recordings are the superposition of many spectrum analyzer sweeps made over a time interval of approximately 10 minutes.

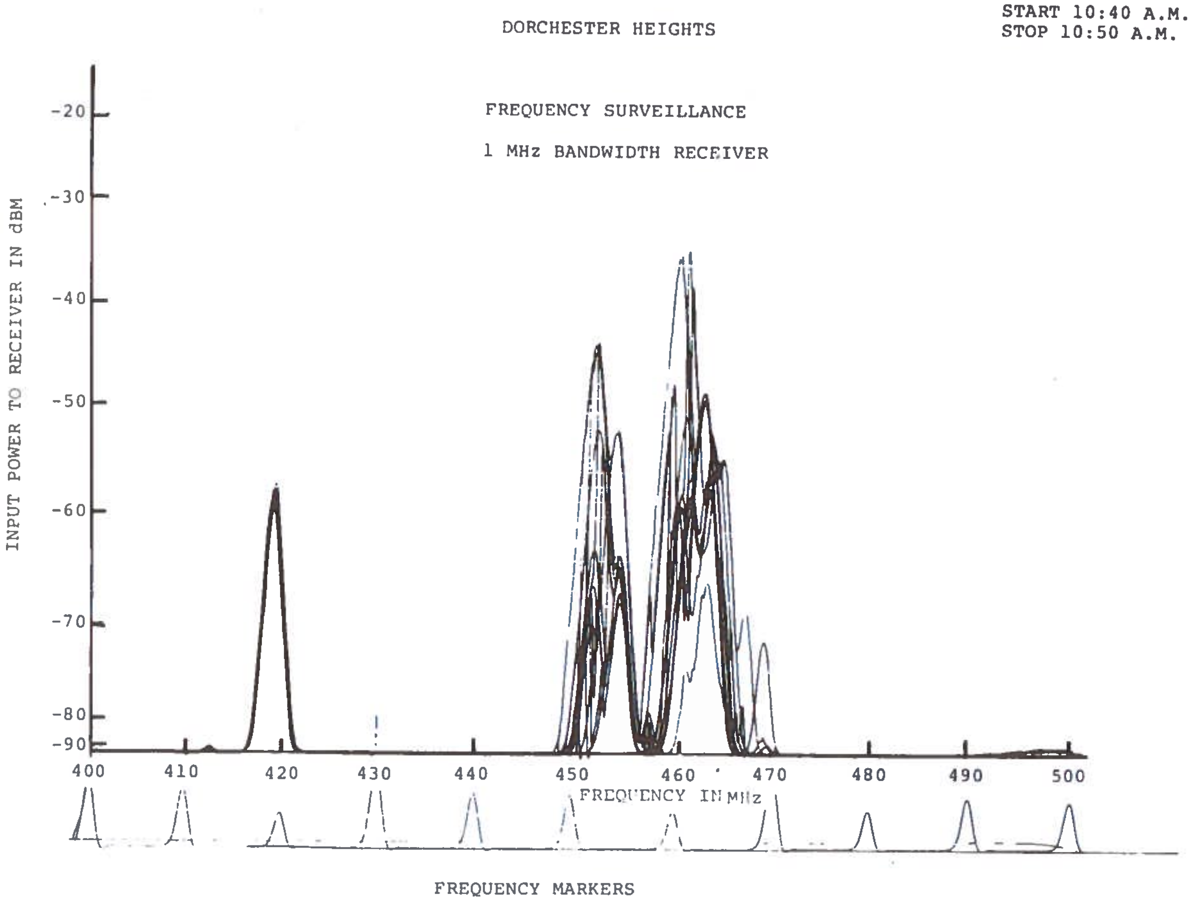


Figure 2-2. Typical Frequency Surveillance

The frequency surveillance measurements resulted in the selection of 143 MHz, 217 MHz, and 435 MHz as the center frequencies to be used in the 115 kV transmission line impluse noise measurements.

3.0 IMPULSE NOISE MEASUREMENTS SYSTEM

The measurement system consisted of a unity gain dipole antenna, a receiver, threshold detector and counter (Figure 3-1). The signal received at the antenna was sent to a wideband receiver which has a 6 dB Noise Figure and 1 MHz bandwidth. The video receiver was threshold detected by an adjustable voltage level sensor. The output pulses of the threshold detector were accumulated and displayed by an electronic counter. An oscilloscope provided a visual display of the impulse noise.

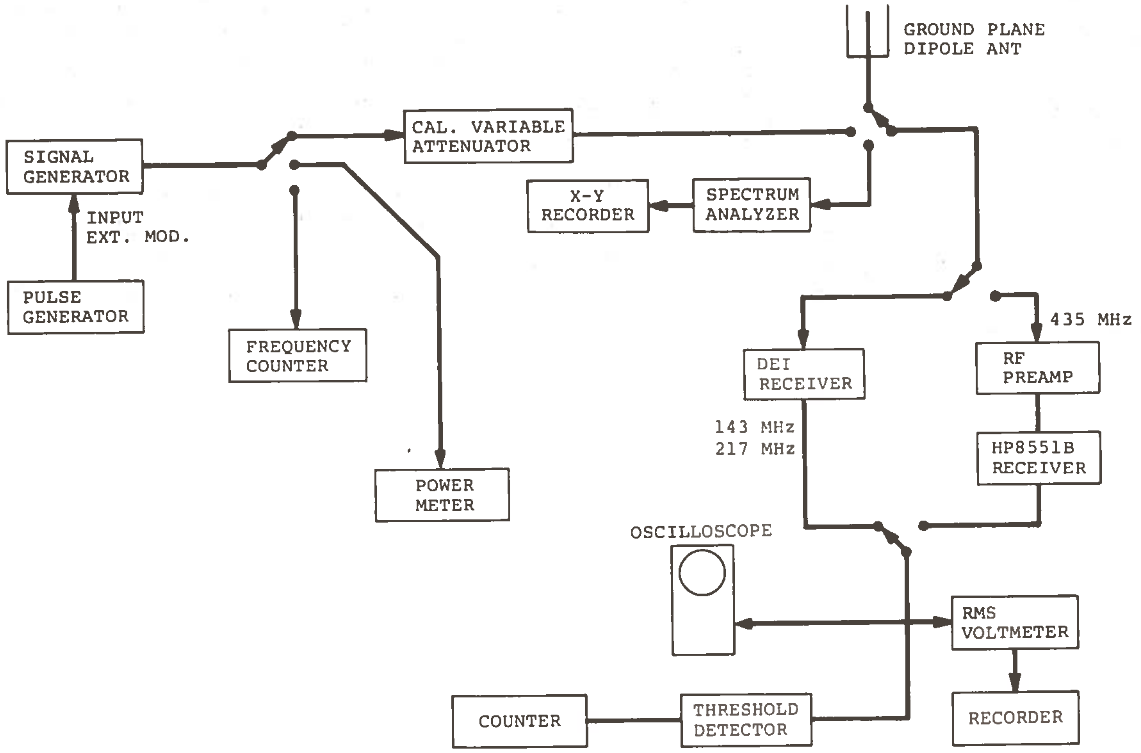


Figure 3-1. Impulse Noise Measurement Systems

The antennas were unity gain dipoles and their VSWR did not exceed 2.0 at the frequencies used. This VSWR represents approximately a 0.6 dB antenna mismatch loss. The antennas were mounted, one at a time, on a flat 13 ft by 6 ft by 1/4 inch thick aluminum ground plane located on the roof of the mobile laboratory. The antenna ground plane was approximately 8.5 ft above the ground, or road surface.

The receiver used for the 143 MHz and 217 MHz measurements was a DEI receiver. The DEI receiver had a 1 MHz bandwidth and a 6 dB Noise Figure. At 435 MHz a Hewlett Packard 8551 spectrum analyzer, in an unswept frequency mode, was used as a receiver. A RF preamplifier was placed in front of the spectrum analyzer to improve its sensitivity from -80 dBm to -107 dBm at 1 MHz bandwidth. The gain of both receivers were adjusted so that saturation did not occur at the levels set for the threshold detectors.

3.1 SYSTEM CALIBRATION

A Hewlett Packard 608E signal generator was used to calibrate the impulse noise measuring system. The signal generator frequency and power was monitored by the HP frequency meter and PRD power meter. The output power of the signal generator was adjusted by two variable calibrated attenuators.

The system was calibrated prior to each set of measurements. This was accomplished by applying a calibrated input power from the 608E signal generator into the receiver. The threshold detector was then set to "fire" corresponding to this calibrated input power.

4.0 RESULTS

Impulse noise measurements were conducted at eight locations. These locations are broken down into two groups, seven transmission lines having normal noise levels and one having a high noise level. The seven locations included two substations locations.

The measurements were conducted over a period of approximately 2 1/2 months under a variety of weather conditions, clear, raining, and snowing. Temperature ranged from 10°F to 54°F and relative humidity from 42% to 98%. No clear correlation was found between the weather and noise levels from normal or noisy lines when comparing measurements on a day to day basis. The day to day noise variation could be as large as 15 dB, without any correlation with the weather. But, on two occasions when measurements were made in a continually changing weather condition, overcast to snowing, the noise level increased by 5 dB. This 5 dB increase was less than the day to day 15 dB variations. A considerable amount of data would be required to make a valid statistical evaluation of weather effects on power line noise, if indeed there is any. It is noteworthy, for example, that Mather and Bailey did not find any correlation between weather conditions and noise generated on the McNary-Ross and Grand Coulee Olympia 345 kV transmission lines.[1]

4.1 MAXIMUM NOISE LEVELS

Maximum impulse noise measurements of the transmission lines were made by locating the mobile laboratory directly under the lines. These measurements were made on both the seven normal lines and the one noisy line at 143, 217 and 435 MHz. During the entire 143 MHz measurements the one "noisy" line, Tyler St., Methuen, MA., was producing the same level of noise as the seven other locations, but it became noisy toward the end of the 217 MHz measurements. Since the 143 MHz measurements were made to determine noise levels in the voice channel used at the Pueblo Test Site, which is not as important as the 217 MHz Telemetry Channel and 416 MHz command and control channel, we did not repeat the 143 MHz measurements after Tyler Street became noisy.

The data from the impulse noise measurements on the eight high voltage transmission lines are shown in Figures 4-1, 4-2 and 4-3. The ordinate is the receiver input power level that triggers the threshold level detectors. The abscissa is the accumulated number of noise impulses that crossed the threshold

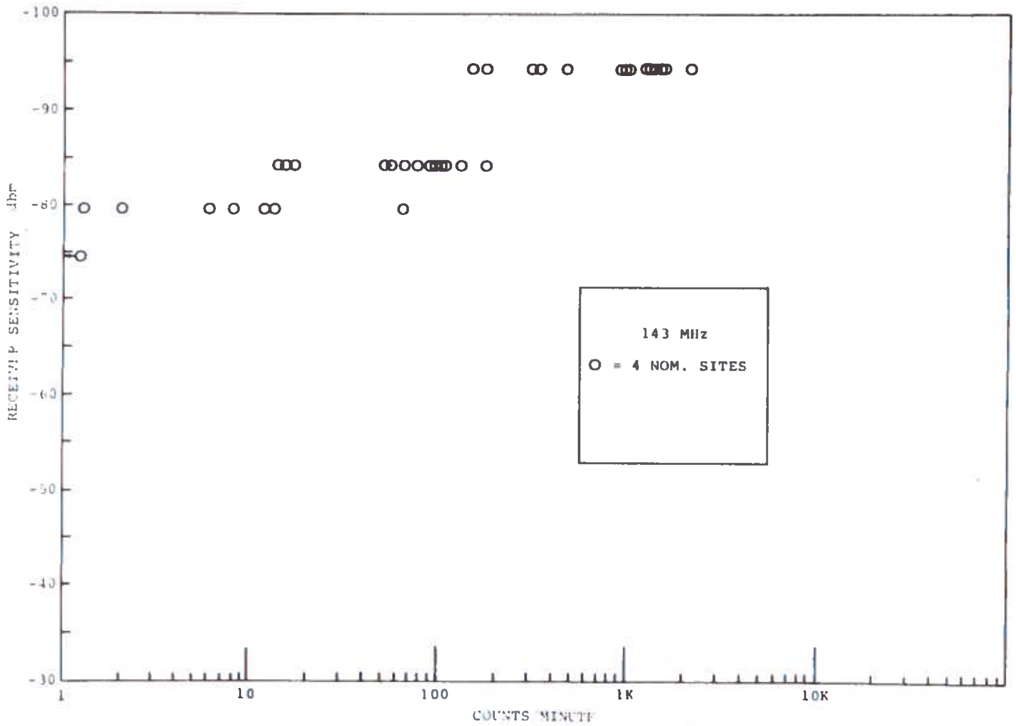


Figure 4-1. Number of Noise Impulses Exceeding Receiver Sensitivities from 115 kV Lines at 143 MHz

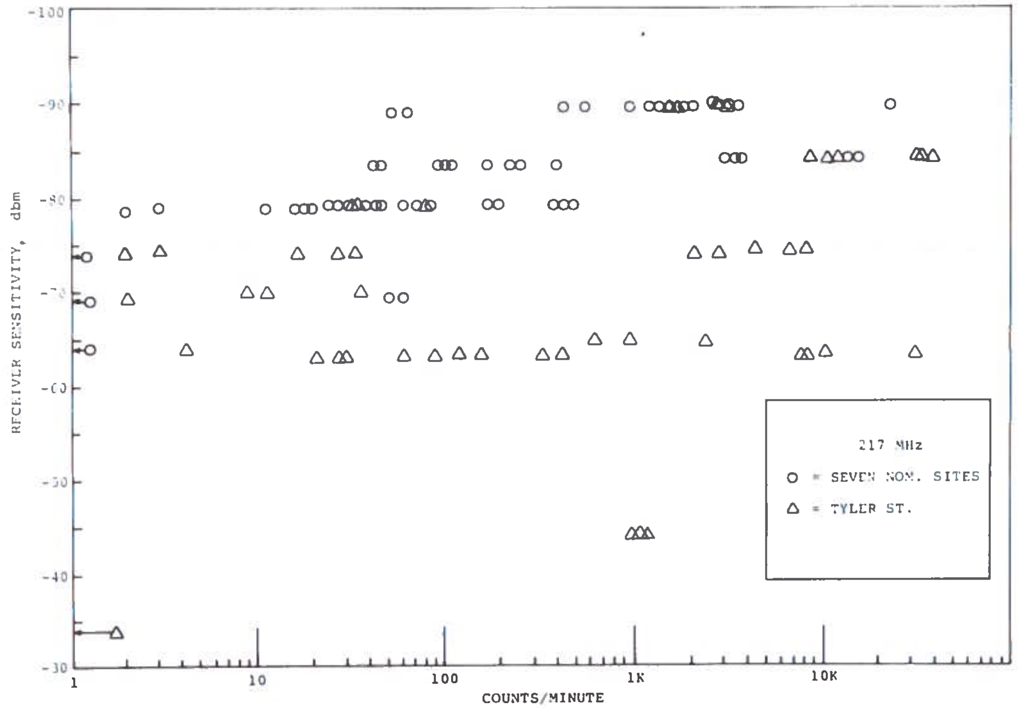


Figure 4-2. Number of Noise Impulses Exceeding Receiver Sensitivities from 115 kV Lines at 217 MHz

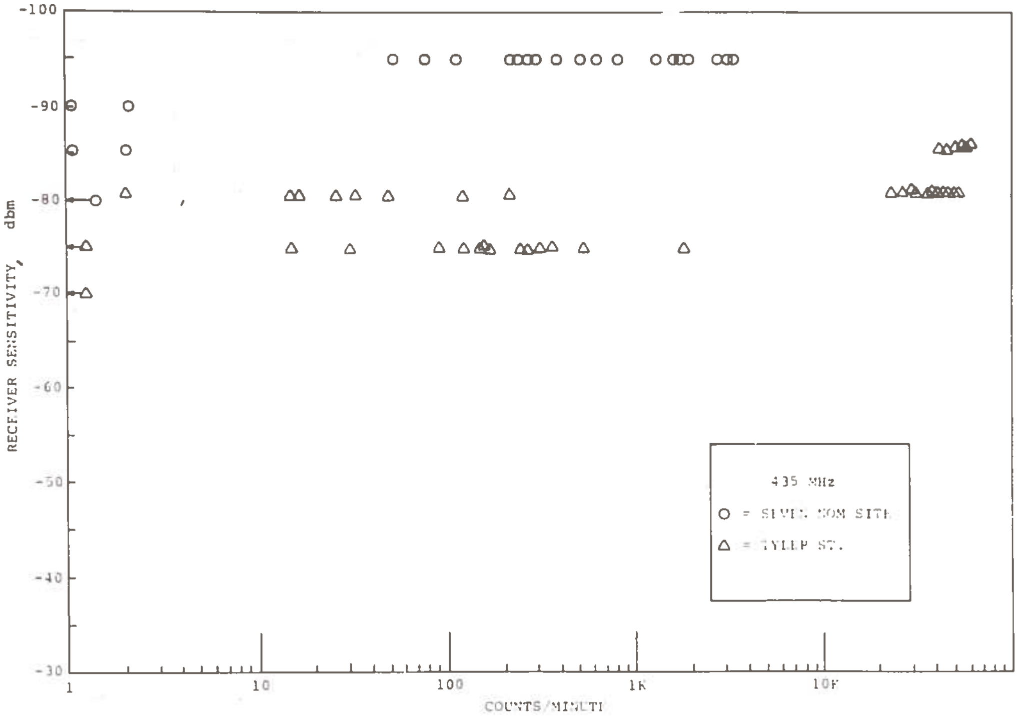


Figure 4-3. Number of Noise Impulses Exceeding Receiver Sensitivities from 115 kV Lines at 435 MHz

level in a one minute interval. The spread of points is due to the statistical variations of the measurements.

4.2 NOISE LEVEL VS. DISTANCE FROM TRANSMISSION LINES

In the seven normal transmission lines the decrease in impulse noise level vs. increase of distance from the 115 kV lines could not be measured. This was because a 13.4 kV power line, that ran along the access roads, generated noise levels comparable to those of the 115 kV lines. Therefore, only at the Tyler Street location [where the impulse noise from the 115 kV lines was appreciably larger] could noise vs. distance decrease noise measurements be made. Figures 4-4 and 4-5 show the measurements taken from the mobile laboratory parked at fixed distances from the lines. From these measurements, little more can be said, than the noise level does decrease with distance. The rate of decrease is not clearly indicated and considerable more data is required to take into account statistical variations in the noise level.

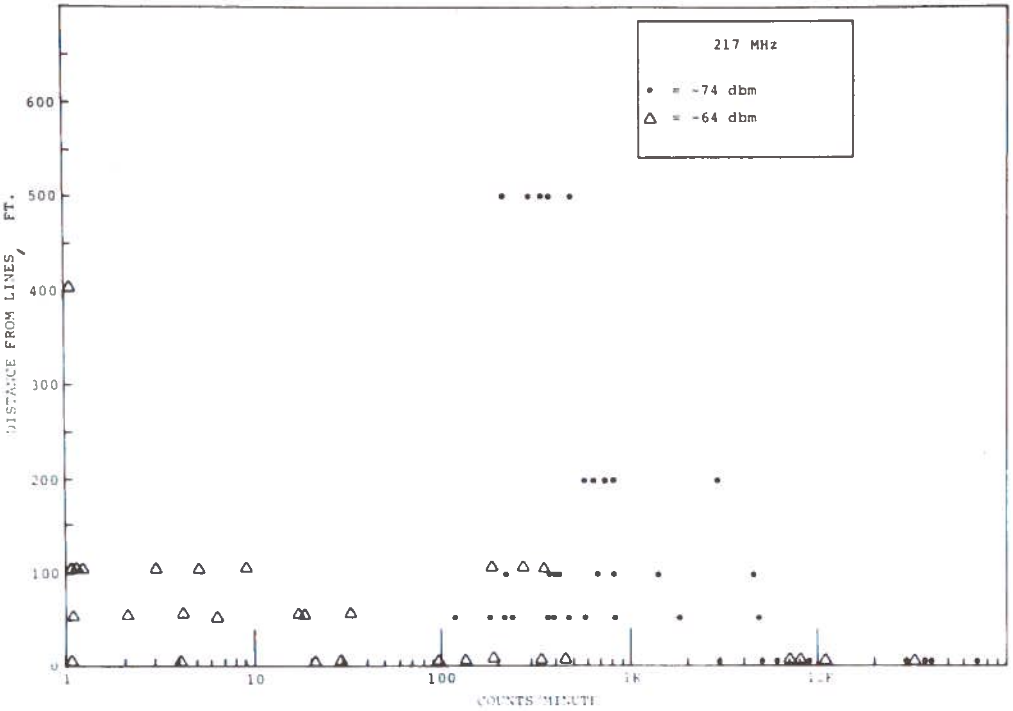


Figure 4-4. Number of Noise Impulses Exceeding Fixed Receiver Sensitivities vs Distance at 217 MHz

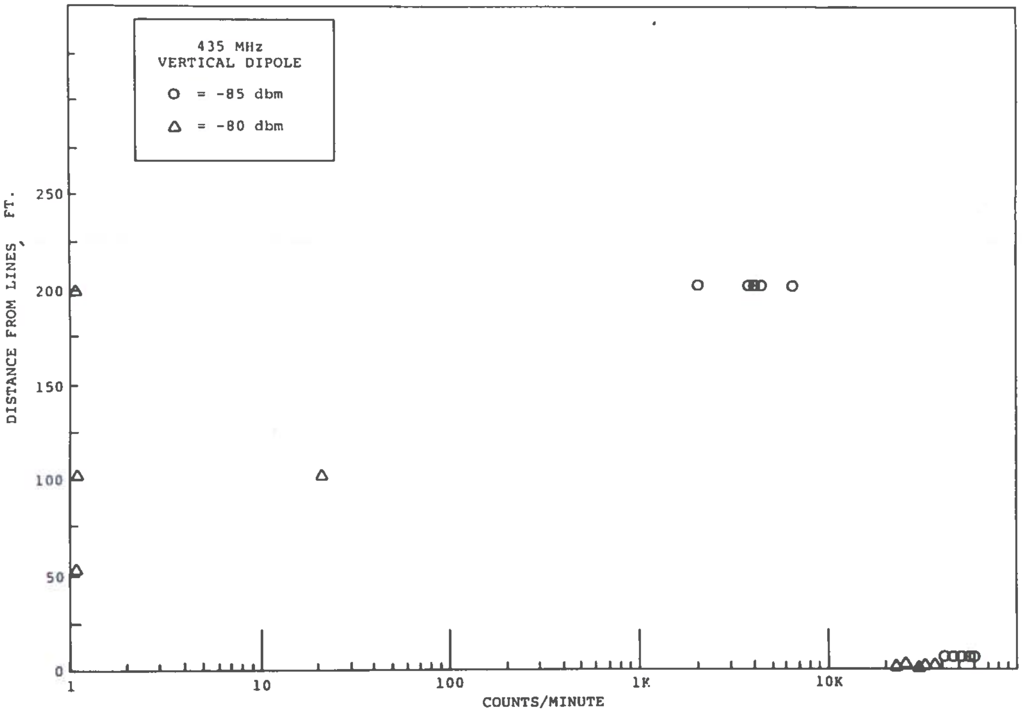


Figure 4-5. Number of Noise Impulses Exceeding Fixed Receiver Sensitivities vs Distance at 435 MHz

Another series of measurements were made to obtain the rate of noise level decrease with distance from the transmission line. During this test the RMS noise level of the transmission line was recorded on a strip chart as the mobile laboratory moved away from the 115 kV line at a velocity less than 1 mile per hour. We found periodic fluctuations in the noise level with distance away from the lines. These fluctuations, or standing wave patterns, were probably due to multipath effects. From the rather inconclusive data (Figures 4-6, 4-7, 4-8 and 4-9), there appears to be a decrease in the RMS noise level at a rate directly proportional to the distance measured from the power lines.

4.3 VISUAL OBSERVATION OF IMPULSE NOISE

There was a distinct difference in the impulse noise display of the Tyler Street location and the other seven. In the seven normal lines, the noise impulses appeared to be occurring randomly [Figure 4-10]. In the noisy line, the noise impulses occurred in bursts. The bursts occur at a 120 Hz rate (Figure 4-11). This 120 Hz burst rate is undoubtedly due to a faulty insulator breaking down about the positive and negative peaks of the 115 kV, 60 Hz, 3-phase power lines. If there were two insulators located on different phases of the power line breaking down, then there would be two sets of noise impulses separated by the phase differences of the two lines of 120°. The noise impulses from the normal lines were random in general. These may be generated at the insulators on all three phases of the power lines (115 and 13.4 kV).

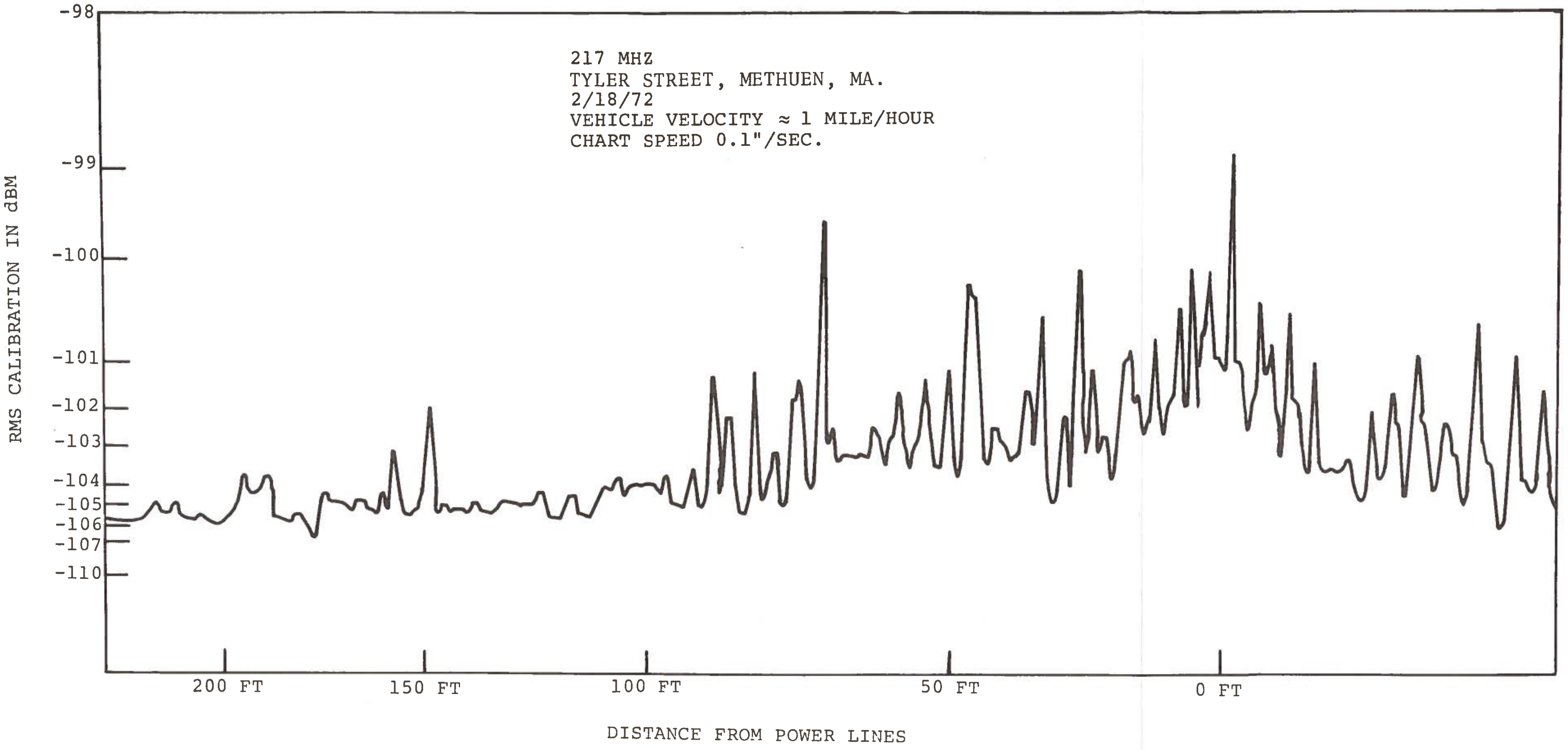


Figure 4-6 RMS Noise vs. Distance at 217 MHz First Run

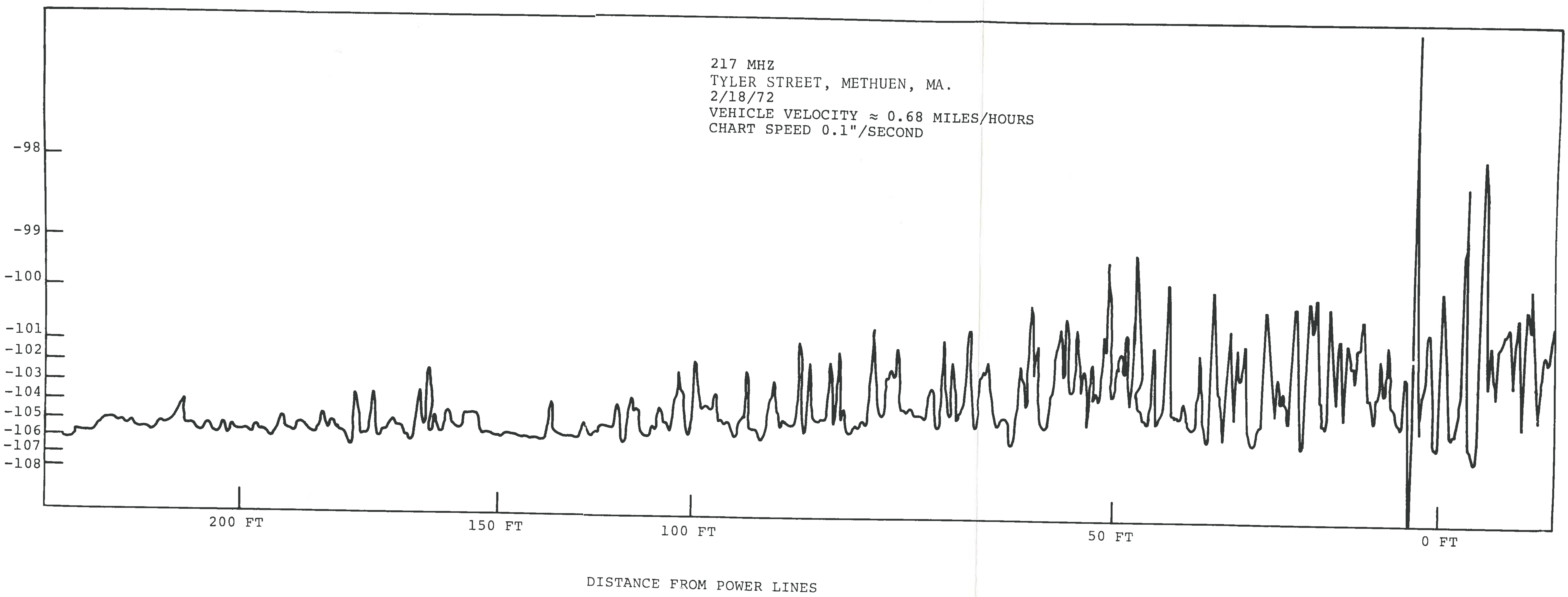


Figure 4-7 RMS Noise vs. Distance at 217 MHz Second Run

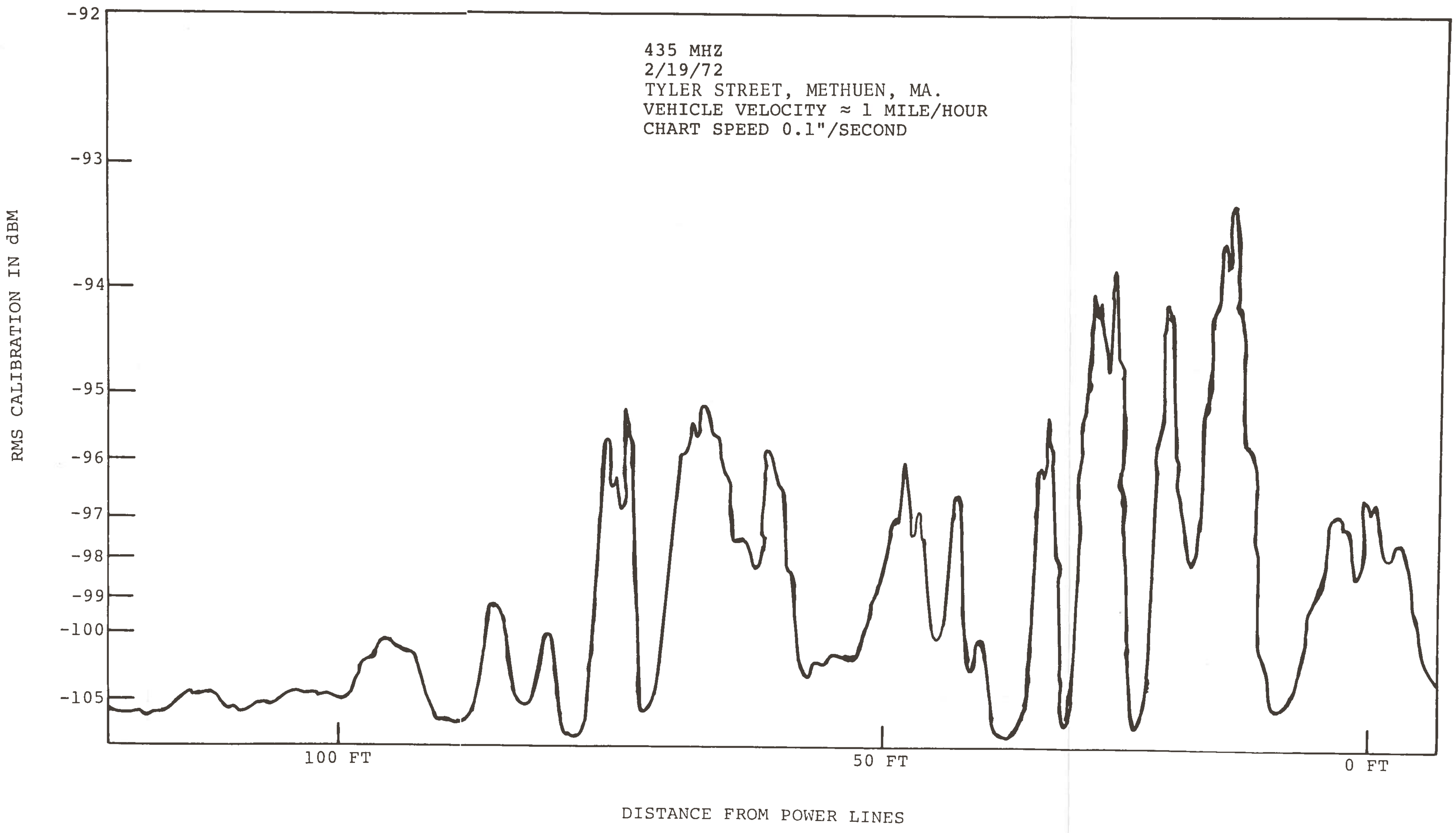


Figure 4-8 RMS Noise vs. Distance at 435 MHz

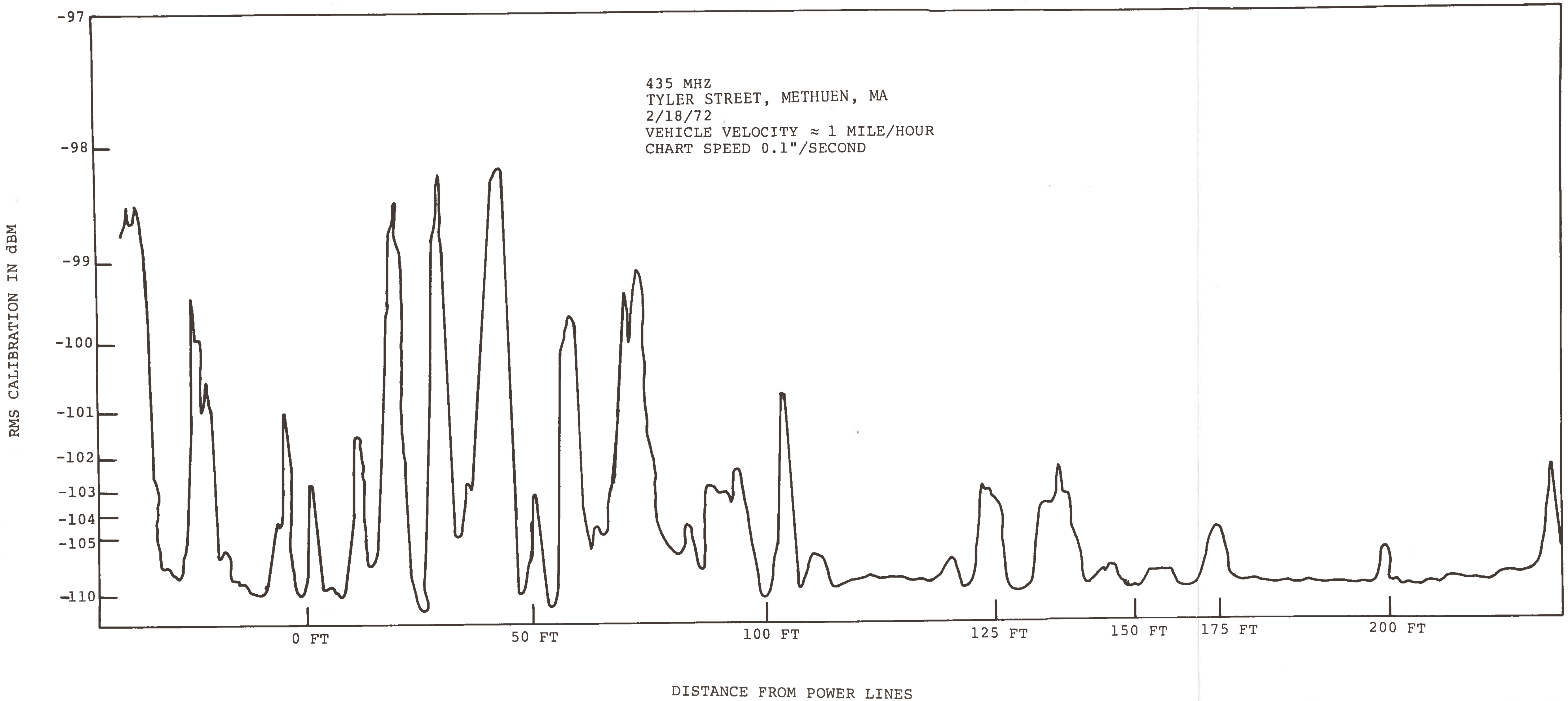
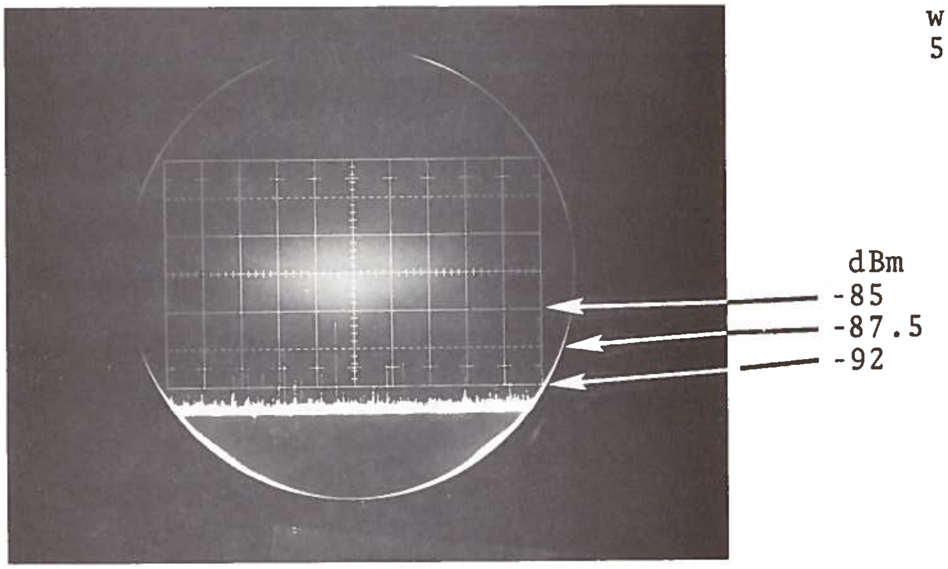


Figure 4-9 RMS Noise vs. Distance at 435 MHz

Dascomb
Shawsheen
Substation
433.7 MHz
1 MHz Band-
width.
5 msec/cm



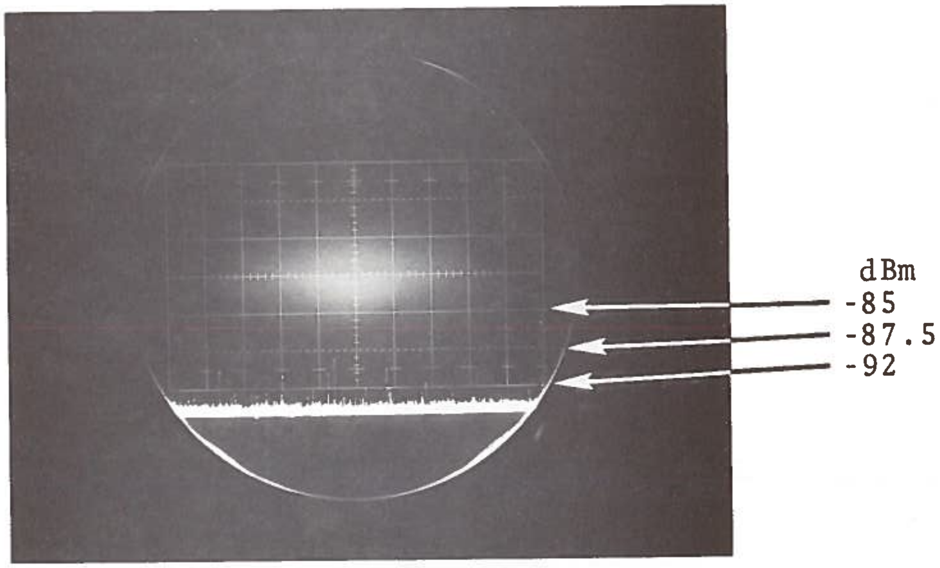
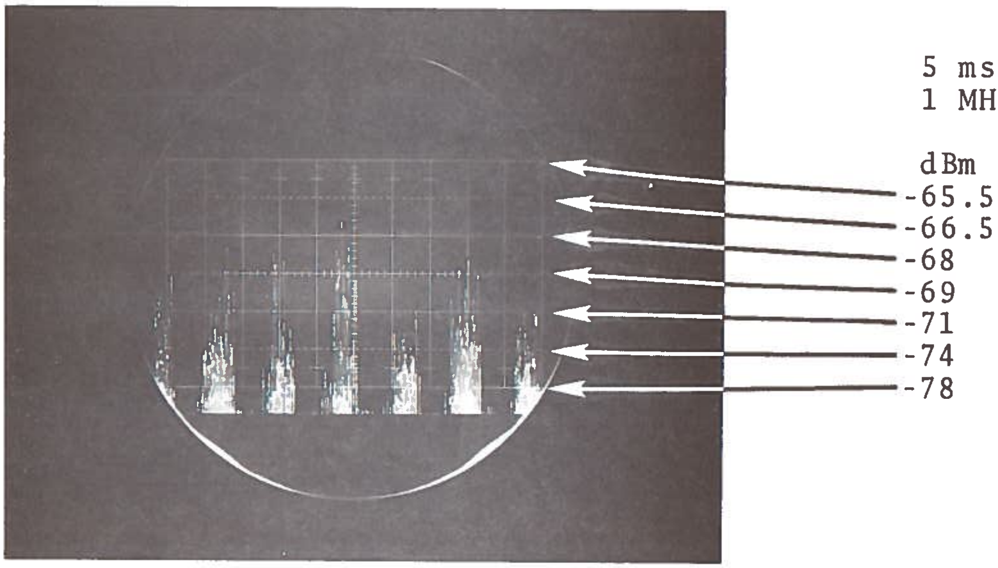
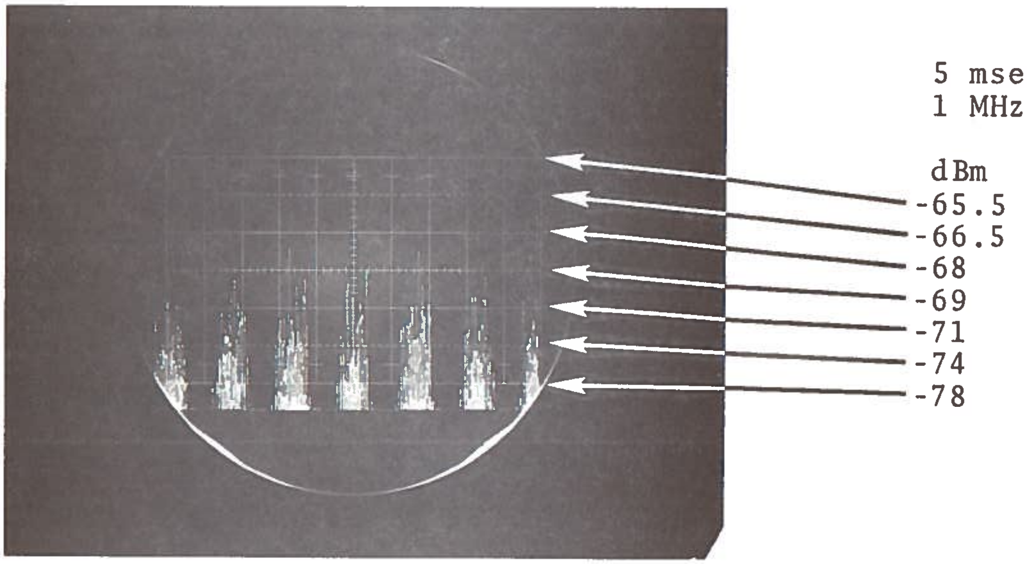


Figure 4-10. Impulse Noise from Normal Line at 433 MHz

433.7 MHz
Tyler St.



5 msec/cm
1 MHz Bandwidth



5 msec/cm
1 MHz Bandwidth

Figure 4-11. Impulse Noise from Noisy Lines at 433 MHz

5.0 ANALYSIS OF THE CONTROL AND INSTRUMENTATION SYSTEMS OF THE PUEBLO TEST FACILITY IN THE PRESENCE OF POWER LINE NOISE

Based on power line noise measurements made in the Boston area and assuming that similar noise conditions exist in the Pueblo Test Facility, an analysis has been performed determining the possible control and instrumentation system degration due to this type of interference. Assuming that this degradation would be small, the analysis has been performed by using a "worst case" approach, i.e., the worst combination of parameters (maximum distance between transmitter and receiver, worst noise conditions, etc.). However, no significant multipath or fading measurements have been included in the analysis although tests are definitely recommended to ascertain the extent of anomalous propagation effects.

5.1 PATH LOSSES AND PROPAGATION CONSIDERATIONS

At the Test Facility the maximum distance between the vehicle and the Base Station will be 5 miles (8 km). The antenna height at the Base Station is 140 ft. Therefore, line-of-sight propagation will essentially prevail. Path loss in free space between isotropic antennas is $L = 36.6 + 20 \log f + 20 \log d$, when the path loss is in dB, the frequency f is MHz and the distance d in miles.

f (MHz)	Free Space Path Loss (dB)
406.8	102.8
217	97.3
166	95

Since we deal with propagation over a somewhat irregular terrain it is advisable to consider an excess path loss. A recent survey is available with estimates of this effect.[2] From these results we have choosen an excess path loss of approximately 10 dB at the three considered frequencies. Perhaps this value is on the high side, but it has been chosen to keep the analysis at a very conservative level compensating for the lack of knowledge on the extent of fading phenomena. Therefore, we will work with the following path losses:

f (MHz)	Path loss (dB)
406.8	113
217	107
166	105

Significant multipath and fading effects will depend, essentially, on the terrain characteristics, the effective antenna patterns, and on the presence of reflecting surfaces (building, etc.) At the frequencies considered the terrain will behave essentailly as a dielectric as far as its reflecting properties are concerned. The reflection coefficient will depend on the dielectric constant, the conductivity, and the angle of incidence. The dielectric constant and conductivity may vary widely. An example considered in Stratton,[3] assumes a value of 6 for the dielectric constant and 10^{-5} mho/meter for the conductivity. With these values and vertical polarization the reflection coefficient has a value of about 0.17 for zero angle of incidence. The value of the reflection coefficient decreases monotonically until it reaches zero at the Brewster angle which in this situation is about 70°. Then it increases quite rapidly to a value of unity when the angle of incidence is 90°. To obtain a deep fade it is necessary that the direct and reflected components have opposite phase and approximately equal amplitude. Assuming a reflection coefficient of unity, and using the values mentioned above for the terrain characteristics, it is obvious that significant fading can be experienced only when the vehicle is relatively close to the base station.

If δ = distance then:

f (MHz)	δ (m)
406.8	350
217	188
166	144

For other vehicle positions, assuming a reflection coefficient of 0.17, the fading will be very shallow ($\approx$ 3 dB). The fading rate will depend on the position and vehicle speed. At a speed of 250 mph (111 m/sec) and at 406.8 MHz (λ = 0.74 m), the maximum fading rate (Doppler Spread) will be $\approx$ 300 Hz with lower values expected for lower velocities and frequencies.

5.2 REMOTE CONTROL LINK

The Remote Control Link (Station-to-Vehicle) consists of 12 FM/FM channels in the typical IRIG configuration.[4] Note that the receiver's IF bandwidth is 300 kHz. The transmitter power is 10 watts and (according to the path losses calculated above) the received power is -73 dBm. If we assume 50 ohms input impedance this corresponds to a signal level at the input of the FM receiver of $S = 5.10^{-5}$ volts. The worst impulsive noise power measured at this frequency (and corresponding to a few impulses/min) is approximately -70 dBm or 10^{-10} watts. Assuming an input impedance of 75 ohms for our measuring equipment, the resulting impulse voltage is 8.65×10^{-5} volts. However, this is relative to a 1 MHz bandwidth. With a 300 kHz bandwidth the impulse voltage is 2.9×10^{-5} and therefore, less than the input signal. Notice that this relatively small impulse disturbance happens very infrequently and that, most of the time, the actual noise has a much lower level. Theory of the impulsive noise effects on a FM receiver is well understood[5] and is briefly presented in Appendix A: In short, due to the "capture" effect in FM reception, no significant signal distortion can be expected if the impulsive disturbance is less than the useful signal. One can then safely conclude that the first FM discriminator suppresses the relatively weak impulses coming from the power lines and, therefore, an essentially undistorted waveform is presented to the second set of FM demodulators.

The situation would be different (as explained in Appendix A) if the incoming impulses were larger than the signal: the input waveform is distorted for the duration of the "capture time", a duration depending on the impulse strength relative to signal strength and the receiver configuration. Detailed waveform perturbation can be predicted from the theory.

5.3 TELEMETRY LINK

The Telemetry Link (vehicle-to-station), is a PCM/FM system using NRZS Format. The transmitted power is 25 watts (44 dBm). Therefore, the received power [assuming an effective path loss of 107 dB] is -63 dBm. The resulting signal level (assuming 50 ohms input impedance) is $S = 1.6 \times 10^{-4}$ volts. The worst noise power measured (at approximately 10 impulses/min) is -40 dBm. The corresponding signal voltage using a 1 MHz bandwidth (the bandwidth of the receiving equipment) is 2.75×10^{-3} volts.

An explicit theory evaluating a digital FM system's performance (when the receiver is a conventional demodulator) is not available. However, a impulsive noise effect theory on digital FM receivers with integrated-and-dump filters has recently been developed[6] and will be used to predict systems performance. The difference between the two receivers is small (1 dB) for Gaussian noise[7] and it is reasonable to assume that this is the case for impulsive noise.

The impulsive noise theory in PCM/FM receivers is summarized in Appendix B. It states, that for any given impulse the error probability depends on the normalized parameter $\gamma = \Gamma/ST$ where Γ is the incoming pulse area (in volts x sec), S is the signal level in volts and T is the duration of a digital symbol. An important result is that no error is possible if $\gamma < \gamma_T$ where γ_T is a threshold value which depends on the detailed structure of the receiver, the modulation index etc. However, when $\gamma > \gamma_T$ the curve representing the probability of error vs the normalized impulse strength γ, grows quite rapidly when the receiver is not protected by a hard limiter and less rapidly when a limiter is used. For this case (IF limiter bandwidth = 0.5 MHz, information bandwidth = 256 kHz) the value of the threshold has been found to be ≈ 5 dB. The value of γ (worst case) is

$$\gamma = \frac{2.75 \cdot 10^{-9}}{1.6 \cdot 10^{-4} \cdot 4 \cdot 10^{-6}} \cong 13 \text{ dB}.$$

It follows that if the largest impulses recorded are 8 dB above threshold there is a good chance (≈ 0.15) for digital error. However, they are very infrequent. A crude error probability bound can be established. As mentioned above there can be no error if the impulsive noise is below the threshold γ_T. At the signal level that we are considering this threshold corresponds to a noise power of about -50 dBm. At this level the number of counts is 10^3/minute. Assume that each impulse, independent of its magnitude, has a probability 0.15 of causing an error (this is a very conservative estimate since this value applies to impulses of strength -40 dBm) then the error probability would be:

$$\frac{0.15 \cdot 10^3}{250 \cdot 10^3 \cdot 60} = 10^{-5} \; .$$

The actual error rate will be significantly lower than this limit. Therefore, at worst noise levels measured at this frequency in the Boston area, no significant degradation of error probability can be expected.

5.4 VOICE LINK

The Voice Link consists of a two-way, single frequency FM DSB system. The power radiated from the base station is 35 watts and its antenna has a 6 dB gain. Thus the power received at the vehicle is -54 dBm. The power radiated at the vehicle with an omnidirectional antenna is between 6 and 10 watts. Therefore, the power received at the base station is from -61 to -59 dBm.

The maximum power line noise power recorded in the Boston area was ≈ -90 dBm. Therefore, the system has a signal-to-interference ratio of ≈ 30 dB which is clearly adequate. If higher levels of noise are expected the degradation of the voice link could be evaluated by using several available methods: intelligibility, quality degradation using listening tests, 20 dB quieting sensitivity degradation, etc.

6.0 CONCLUSIONS

Considering the limited number of power line noise measurements taken in the Boston area and a survey on power line noise literature, it appears that this type of interference will not cause a significant degradation of the communication, command, and control links performance (a summary is shown in Table 1). However, it is important to underline some of the assumptions made and to point out other factors which may influence system performance:

a. The limited number of measurements made in the Boston area is a reasonably representative sample of the conditions which will prevail at the Pueblo Test Site. Note that with abnormal conditions (faulty line components, for example) the noise level increases substantially. Because such events are rare it is far from certain that our measurements contain the "worst" noise level that a faulty power line is capable of radiating.

b. While evaluating system performance, path loss computations did not include propagation anomalies such as multipath, fading etc. Such anomalies could degrade system performance, especially if they happen simultaneously with the "worst" noise level.

c. Although only power line noise has been considered in this study there are additional noise sources present with noise levels higher than those attributable to transmission lines. Automotive ignition and electrical equipment on the vehicle itself are the most likely sources.

TABLE 1. SUMMARY

System	Frequency (MHz)	Effective Path Losses (dB)	Minimum Receiver Signal Level	Maximum Power Line Noise Level Measured	Effect on System Performance (Worst Case)
Remote Control Link	406.8	113	-73 dBm	-70 dBm (10imp/min)	Negligible
Telemetry Link	217	107	-63 dBm	-40 dBm (10imp/min)	Negligible ($P_e < 10^{-5}$)
Voice Communications Link	166	105	-60 dBm	< -90 dBm (in the receiver bandwidth)	Negligible

7.0 RECOMMENDATIONS

The following recommendations reflect the data provided in the preceding sections:

a. The possibility of implementing a simple monitoring system ascertaining the presence of interference levels higher than considered harmful for correct communication, command, and control system's operation. The monitoring system could, for example, consist of two simple receivers, one located at the base station and one on the vehicle, and would operate simultaneously with the transmission of information. This would alert system operators of excessive interference levels.

b. As mentioned previously, little attention has been given to the analysis of possible anomalous propagation effects such as multipath, fading, etc., which could result in additional degradation of the communication, command, and control links performance. However, considering calculations reported in Section 4-1 it is apparent that some fading will be experienced, especially in base station vicinity. It is therefore, recommended that a brief study be conducted defining a simple set of propagation experiments determining path losses, presence and extent of fading multipath, Doppler spread etc.

c. Considering that source of man-made noise may be present and that their level may be higher than the noise generated by power lines, it is recommended that attention be given to this possibility. Specifically, that tests be made on the interference level generated by electrical equipment located on board the vehicle and by additional sources such as automotive traffic which may be present in the immediate Test Site neighborhood.

APPENDIX A

This Appendix describes the analysis method used to evaluate the impulsive noise effect on a FM receiver.[5] The receiver considered consists of a linear band-pass filter, possibly including de-emphasis, and a low-pass filter.

When a noise impulse occurs, whose amplitude is larger than the signal at the output of the IF filter, the detector is momentarily "captured" and its output will be a function of the random instantaneous phase of the impulse, whose effect will be dominating with respect to the phase of the signal. For a filter constituted by n identical single-tuned stages the normalized capture time has the expression:

$$\tau \cong 2(2^{1/n}-1)^{1/2}\ 2(n-1)^{1/2}(\ell n\ s)^{1/2} \qquad (A.1)$$

where the normalization is such that 1 time unit is equal to one radian of the maximum deviation frequency, and S is the ratio of the noise peak to signal strength. Figure A-1 reveals that the capture time is practically independent of n and that the dependence on S is rather weak. In general, τ is usually three or four. Therefore, if the noise pulse at the input of the detector is not as strong as the signal there is no serious effect, whereas if the noise "captures" the detector, the duration of the disturbance depends very little on the actual impulse strength. For example, the value of τ changes from 4 to 5 when S ranges between 20 and 100.

Two markedly different effects can occur during the capture time (depending on the value of the random phase of the impulse): the resulting phase may be slightly perburbed with respect to the signal phase or it may sharply drop of 2π radians. The resulting effects of these phase perturbations are quite different: for example, in an audio receiver the first type of perturbation gives a barely audible "click", whereas the second one yields a rather loud "pop". The probability of having a "pop" is

$$P = \frac{k\tau}{2\pi} \qquad (A.2)$$

where k is the ratio of the instantaneous deviation, at the time of the impulse, to the deviation correspondent to 100 percent modulation. If the average rate of noise impulses of sufficient intensity to capture the detector is given by R, then, on the average there will be RP "pops" and R(1-P) clicks. The difference between a "pop" and a "click" can be easily understood by realizing that the detector forms, in essence, the derivative of the phase waveform: therefore, a sharp discontinuity causes a large spike (of amplitude 2π) whereas a mild perturbation will yield a mild perturbation of the output waveform.

The effect of both perturbations on the output low-pass filter can then be easily derived by using standard linear systems analysis.

It is obvious that the differences between the two types of perturbation will still be significant in a FM control system, where the demodulated FM waveform will contain a number of spikes of approximately the same amplitude and duration at a rate equal to RP.

APPENDIX B

This Appendix describes the method used to evaluate the effects of impulsive noise in a digital FSK receiver. The method is the one developed by Bello and Esposito for phase-modulated systems, which recently has been extended to FSK Transmission.[6]

The general model considered for the receiver includes a linear filter, a hard limiter, and two channels corresponding to the Mark and Space signals. Each channel contains a demodulator, an integrator-and-dump filter, a square law detector and a comparator is indicated in Figure B-1.

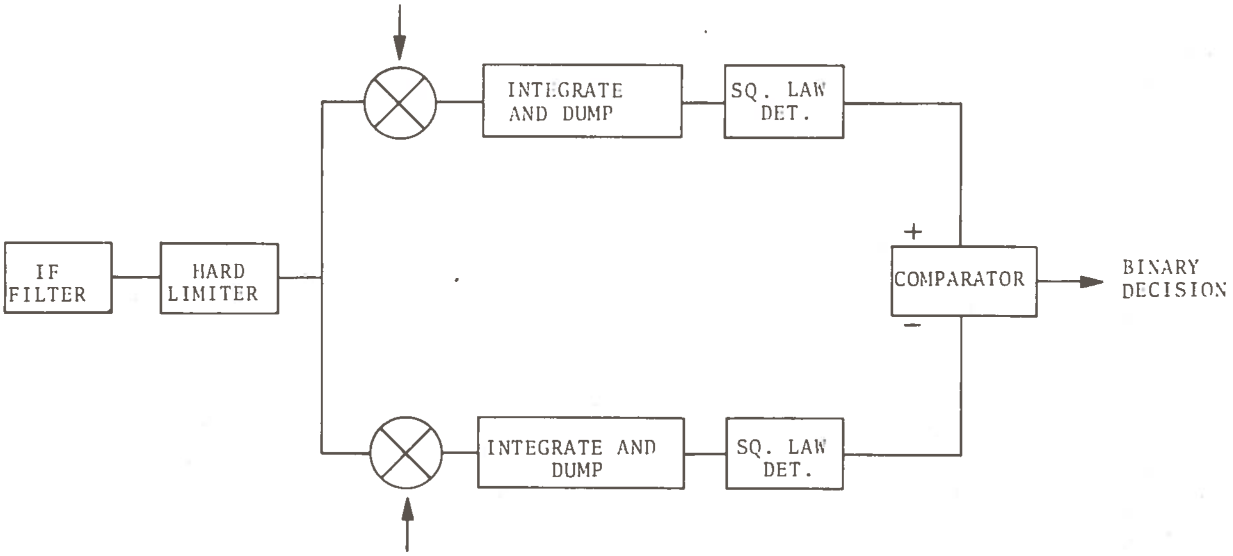


Figure B-1. Ideal FSK Receiver with Hard Limiting

Assuming that the impulsive noise is the dominant cause of errors and that the impulses have a flat spectrum across the RF bandwidth W of the receiver. If H(t) is the complex envelope of the impulse response of the receiver, the output of the input IF filter can be written, in complex notation, as

$$i(t) = \sum \Gamma_k \exp(j\psi_k) H(t - \delta_k) \qquad (B.1)$$

where Γ_k is the random area of the k-th impulse, ψ_k its phase relative to the phase of the carrier frequency, and δ_k its time of arrival. The procedure consists, essentially, in computing the error rate by averaging a hierarchy of conditional error probabilities, called receiver impulsive characteristics (RIC) over the relevant statistics of the impulsive noise, namely, Γ_k, δ_k and ψ_k. The theory is considerably simplified if one considers the situation where errors are caused by single impulses. In this case it can be shown that the error probability P(E) can be evaluated by means of a simple integration, i.e.,

$$P(E) = \alpha \int_0^\infty W(\Gamma) R(\Gamma) d\Gamma \qquad (B.2)$$

where $W(\Gamma)$ is the first-order pdf of Γ and $R(\Gamma)$ is the first order RIC defined as

$$R(\Gamma) = \int \frac{1}{2\pi} \int P(E|\Gamma,\delta,\psi) \, d\psi d\delta \; . \qquad (B.3)$$

It is clear that (B.3) contains the assumption that the time of arrival of the impulses is uniformly distributed and that, in essence, the noise can be modeled as a Poisson process. The quantity α is the average number of pulses per unit time.

The analysis of the hard limiter uses a technique which, in a sense, is similar to the one described in Appendix A. Here the chief assumption is that the noise impulses are large enough to swamp the signal so when they occur, the output of the limiter can be approximated by considering only the noise pulse. The duration of such a pulse, i.e., the "capture" time, is again defined as the time interval during which the magnitude of the noise exceeds the magnitude of the signal. The limiter output is then dichotomized into disjoint intervals that are either signal-controlled or noise controlled. For example, if a mark has been transmitted, the output of the limiter ℓ_o will be

$$\begin{aligned} \ell_o(t) &= \pm \exp(j\theta) && \text{during the noise controlled intervals} \\ \ell_o(t) &= \exp(j\pi F t) && \text{during the signal controlled intervals} \end{aligned} \qquad (B.4)$$

The use of this characterization allows, with some labor, to compute the conditional error probabilities once the detailed structure of the receiver (the shape of the IF filter) has been assigned.

It can be shown, for example, that if the envelope of the impulse response of the filter is monopolar, the conditional error probability has the expression,

$$P(E|\gamma,\tau) = \frac{1}{2} - \frac{1}{\pi} \sin^{-1} \frac{1}{2|L|}$$

$$P(E|\gamma,\tau) = 0, \text{ if arg } \sin^{-1} > 1 \qquad \text{(B.5)}$$

where K and L are specified functions of the normalized strength of the impulse, the pulse arrival time normalized to the bit duration, the normalized duration of the noise controlled interval, and time coordinate of the mid-point of that interval.

The threshold effect is very apparent from (B.5) since no error can occur if the argument of the arcsine is less than one. In turn, this determines a value of γ, i.e., a value of impulse strength below which the FSK system is essentially unaffected by impulsive noise. The value of 5 dB for the threshold quoted in the text has been obtained by specializing (B.5) to the approximate structure of the receiver used for the telemetry link.

REFERENCES

1. R.J. Mathew and B.M. Bailey, "Radio Interference from High Voltage Lines". AIEE Transactions Power Apparatus and Systems, October 1963.

2. A.P. Barsis, "Radio Wave Propagation Over Irregular Terrains in the 76- to 9200-MHz Frequency Range". IEEE Transactions on Vehicular Technology, Vol. VT-20, No. 2, August 1971, pp 41-62

3. J.A. Stratton, "Electromagnetic Theory", McGraw-Hill, 1941, pp 510.

4. E.L. Gruenberg, Editor, "Handbook of Telemetry and Remote Control", McGraw-Hill, 1967, Ch. 6.

5. D.B. Smith and W.T. Bradley, "The Theory of Impulse Noise in Ideal Frequency-Modulated Receivers", Proc. IRE, 34, pp 743-751, October 1946.

6. P.A. Bello and R. Esposito, "The Effect of Impulsive Noise on FSK Digital Communication", Raytheon Research Division Technical Memorandum T-918, 11 May 1972.

7. P.D. Shaft, "Error Rate of PCM-FM Using Discriminator Detection", IEEE Trans. on Space Electronics and Telemetry, Vol. SET-9, No. 4, pp 131-137, December 1963.