AFIT/GE/ENG/00M-22

EFFECTS OF JAMMING ON RADARS

THESIS

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Ahmet Okuyucu

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ABSTRACT

Although jamming of radars has been in vogue for nearly 50 years there appears to be no comprehensive report on the subject matter. The purpose of this research is to fill this gap. The methodology consisted of analysis, simulation, and where feasible experimental demonstrations.

Experimental equipment consisted of a digital noise generator whose output was used to modulate a high frequency carrier in various fashions. The modulated output was fed into a very sensitive super-heterodyne receiver whose Intermediate frequency (IF) bandwidth could be varied from tens of Hz to mega Hz range. The detected output was displayed on a sampling oscilloscope. The display was in turn digitized and stored to make hard copies for documentation purposes. There was enough flexibility in the equipment to make a wide variety of observations.

Experiments showed that the victim receiver should have sufficient bandwidth to fully respond to the jamming signal. In the case of pure tone jamming, IF bandwidth requirements were minimal and any increase beyond the minimum did not improve jamming effectiveness. In case of pseudo random analog or digital noise, increasing the shift register sequence length and clock frequency made it more difficult for the receiver to recover the jamming waveform and identification. This implied inability to devise quick countermeasures. As follow-on to this research, more precise experiments involving FM by noise and random pulses are suggested.

EFFECTS OF JAMMING ON RADARS

CHAPTER 1

INTRODUCTION

1.1 Motivation

Although jamming of radars has been in vogue for nearly 50 years there appears to be no comprehensive report on the subject matter. Moreover, many of the techniques, especially those employed against tracking radars, are not fully understood. The purpose of this research is to fill this gap. The research methodology consists of analysis, simulation, and where feasible experimental demonstrations. Various jamming waveforms and victim radars are investigated. Since random noise is the most important ingredient to generate an effective jamming signal. Our first task is to understand how to generate random noise and convert it into a useful jamming waveform. In addition, we will discuss noise effects on different kinds of radars. We will also investigate different kinds of jamming waveforms, specifically, Amplitude Modulation (AM) by noise, Frequency Modulation (FM) by noise, Direct Noise Amplification (DINA) and Pseudo-Random analog and digital sequences. Wherever feasible, theoretical results are supplemented by simulation and experimental results.

1.2 Background

Electronic Warfare (EW) is defined as any military action taken to prevent effective use of the electromagnetic spectrum and the employment of electronic weapons by enemy forces, yet allowing effective use by friendly forces. One of the major components of EW is Electronic Countermeasures (ECM) (7:10). The processing of random noise-like waveforms is a fundamental limitation to radar performance and therefore can be used as an effective countermeasure. Raising the noise level by external means, for example by jamming, degrades the radar effectiveness. A jammer with noise energy concentrated entirely within the radar's receiver bandwidth is called a *spot jammer.* A jammer which radiates over a wide band of frequencies, typically greater than or equal to the radar's receiver bandwidth, is called a *barrage jammer.* A combination of these techniques may be employed in what is called *swept spot jamming* (5:548).

Noise can be used to directly modulate a high frequency carrier in both AM and FM modulation schemes. To be effective, FM by noise should have a peak-to-peak deviation wide enough to create sufficient depth of modulation and also accommodate Voltage Controlled Oscillator (VCO) tuning tolerances, but, not so wide as to lower the ECM efficiency. AM by noise can be used to produce multiple false targets against scanning search radars or fouling of Automatic Gain Control (AGC) of tracking radars (6:23-28).

DINA is a classical form of jamming and has the most general utility. Although it may not be the best jammer for a specific situation, it provides good overall jamming performance in many practical situations. In practice, DINA is generated by directly amplifying low-level noise that has been spectrally filtered to obtain the desired jamming waveform characteristics. Frequency modulation by noise is divided into two categories: FM by Wide Band (WB) noise and FM by Low Frequency (LF) noise. In FM by WB noise, each time the frequency modulated carrier sweeps across the victim's Radio Frequency (RF) passband, the victim's receiver filter circuits are set to "ringing" by the impulsive character of the input. If the modulation is random, the receiver input is a random series of short pulses and the output of the receiver demodulator is noise-like. Thus, FM by WB noise produces results similar to DINA. In FM by LF, ringing of the receiver output still occurs but the ringing nature is more distinct and separated by dead times. In this case, the receiver output consists of random but distinct pulses whose duration is approximately equal to reciprocal of the receiver bandwidth. In randomly pulsed barrage jamming, a background level of jamming is induced and maintained but its level is increased by random pulse modulation (width, position, amplitude). The barrage jamming signal before pulse modulation is either DINA or FM by WB noise (2:14-9).

1.3 Scope

The first goal of this report is to discuss how to generate noise and explain its characteristics. The second goal is to explain how to use generated noise to obtain different kinds of jamming signals. The third goal is to examine the effects of various jamming signals on different types of radars by using simulation and/or experimentation. The last phase of this report is to compare results.

1.4 Assumptions

The first assumption made is that all noise sources may be represented as uncorrelated Gaussian random noise; the probability distribution of a sum of independent random variables tends to become Gaussian as the number of random variables being summed increases without limit. Also, if Gaussian random variables are all uncorrelated they are statistically independent (2:145). The second assumption is that the jammer frequency and receiver frequency coincide, i.e., the jammer's center frequency identically matches the center frequency of the receiver's RF bandpass filter. This represents a "best case" scenario from the jammer's perspective

1.5 Overview

In chapter II the focus is on the literature review conducted in support of the research and a discussion of specific jamming techniques is provided. In chapter III, the theoretical and analytic aspects of jamming waveform generation and utilization are presented. Chapter IV presents experimental arrangements and results. Research conclusions and recommendations are presented in Chapter V.

CHAPTER 2

LITERATURE REVIEW OF JAMMING

Jammers may be classified as barrage jammers, spot jammers, swept jammers, and sweep-lock jammers. Barrage jammers are wideband noise transmitters designed to deny use of frequencies over wide portions of the electromagnetic spectrum; these jammers may be used against radar and communication receivers. The use of this type of jammer is attractive because a number of enemy receivers can be jammed simultaneously or frequency-diversity radars can be jammed without readjusting the jamming frequency. The modulating signal is amplified noise. The type of modulation determines whether an RF amplifier or an RF oscillator is used for the final stage. If frequency modulation by noise is desired, the last stage might be a voltage-tunable oscillator such as a carcinotron. If the desired output is amplitude modulation by noise, the last stage would be an RF amplifier. The advantages of barrage jammers are their simplicity and their ability to cover a wide portion of the electromagnetic spectrum. The latter advantage can turn into a disadvantage when the systems against which the jammer is working utilize high-powered transmitters. In such cases, the jammer power may not be sufficiently high enough to effectively mask the receiver the transmitted signals. Spot jammers are narrowband, manually tunable transmitters that are amplitude or frequency modulated by random noise or a periodic function. These jammers are used to mask specific communications or radar receivers. Spot jammers can deny range and angle information to radars and can degrade the intelligibility of speech or of other types of modulated signals in communications receivers. Many spot jammers use amplitude modulation by noise in which at least half of the RF energy remains in the carrier. The output power spectrum of a spot jammer can be continuous over a band representing up to five percent of the carrier frequency because oscillators such as magnetrons are frequency modulated by the frequency pushing factor. A " look through " capability is desirable so that the jammer frequency may be kept on the frequency of the transmitter being jammed. The chief advantage of the spot jammers is that their output power may be concentrated in a narrow portion of the spectrum. Thus, spot jammers have the capability of degrading a radar or communication receiver at longer distances than can a broadband or barrage-type jammer having the same power output. Also, for a given distance, a spot jammer can be smaller and lighter than a barrage jammer. Since spot jammers can concentrate large amounts of power in a narrow portion of the spectrum, they have the capability under certain conditions to insert enough power into a receiver to saturate the IF amplifier and reduce the gain of the amplifier via its Automatic Gain Control (AGC) action. These conditions include those of short range and proper antenna orientation. Where space requirements prohibit tunable receivers as an anti-jam feature, e.g., in Velocity-Time (VT) fuzes used in some missiles, spot jammers can be used to good advantage. Disadvantages, as well as advantages, arise out of the narrow frequency spectrum of spot jammers. An operator must be available to tune out the jammer. The application of spot jamming requires a jamming transmitter for each radar or communication transmission channel to be masked or degraded. The complexity of spot jammers increases when they are to be used against transmitters capable of rapid tuning. Some means of rapidly retuning the jammer to the proper frequency must be provided. Power may be wasted by concentrating too much jamming power in a single channel. Swept jammers are transmitters which employ a narrowband jamming signal tuned over a broad frequency band. These jammers have been developed to combine the high power capabilities of spot jammers and the broad bandwidth of barrage jammers. Swept jammers can be employed effectively against radar and communications receivers. The jamming signal is generated in a narrow frequency band and this band is then swept over a broad portion of the frequency spectrum. Two factors which are important in swept jamming are the noise power per megacycle and the sweep rate. The sweep rate, the bandwidth of the swept jammer, the bandwidth of the receiver being jammed, the geometric relation between the jammer and the receiver, and the characteristics of the jammer and receiver antennas all play important roles in determining the dwell time, the period during which the jammer noise is in the receiver bandpass. All these factors must be taken into consideration on order to maintain a balance between the dwell time and the silent periods between dwell times; otherwise, a swept jammer can be rendered ineffective. Swept jammers combine the advantage of concentrating noise power in a narrow band and of effectively covering a large bandwidth. Such jammers can be used more effectively than spot jammers against radar nets in which the various radars are tuned to different frequencies. Several swept jammers, sweeping rapidly at different rates, can with high probability obscure most signals in a given frequency band. Because of the large number of factors affecting the effectiveness of a swept jammer, there must be comprehensive knowledge of the systems against which the jammer is to be used. The swept jammer is generally more complex than either the spot or barrage jammers. A swept frequency, lock-on jammer is a transmitter which uses a narrowband jamming signal which is tuned over a broad frequency band and the signal locked on a particular frequency. This type of jammer is essentially a swept jammer with the additional feature of lock-on capability. However, the receiver and jamming transmitter are simultaneously swept over the same frequency band. When the receiver encounters a signal, the frequency sweep is halted and the jamming transmitter acts as a spot jammer at that frequency. By providing the jammer with a "look-through" capability, the receiver can be made to start sweeping again when the original signal being jammed disappears. It is well to point out here that many jammers are constructed to operate in several modes, i.e., they are capable of operating in spot, swept, or sweep-lock modes. Swept frequency lock-on jammers can also be programmed in various ways. One way is to sweep the jammer signal and the receiver over a specified band. Another way is to sweep the receiver over a specified band until a signal is received and then to turn on the jammer transmitter at the received frequency. The sweep lock-on jammer, like the spot jammer, can concentrate much noise power in a narrow band. In addition, it can lock on to a second signal much more quickly than can a spot jammer. The sweep lock-on jammer suffers from the same limitations as the spot jammer. Only a narrow frequency band can be jammed at any time and more noise energy than is required may be concentrated in that band if the jammer is being used against a receiver other than the ones for which the jammer had been specifically intended. The automatic tuning feature of lock-on jammers can cause two or more such jammers to lock on each other's transmissions (2:12-7,12-8,12-9).

Noise modulation can be imposed with either amplitude modulation or frequency modulation. FM noise should have a peak-to-peak deviation wide enough to create AM noise with sufficient depth of modulation and also allow for VCO tuning tolerances, but not so wide as to lower the ECM efficiency. AM can be used for false angle targets against scanning search radars, or fouling the AGC of tracking radars (6:28).

Amplitude modulation by noise is easily generated at relatively high power levels and for this reason is often used in applications where a fixed or slowly tunable spot jammer can be used, e.g., against fixed frequency radars. The development of voltage tunable power tubes has also made this type of jamming practical against even rapidly tuned radars with the help of some sort of automatic frequency lock-on technique. The jammer output spectrum must be at least as wide as the passband if the victim radar in order to insure sufficiently high frequencies in the resulting video. This means of course that the jammer modulating noise would have a spectral distribution roughly equivalent to the passband of the victim radar's video amplifiers. Amplitude modulation by noise enjoyed considerable early usage, and approximates DINA in effect. However, it is difficult to produce a broad barrage, since the frequency coverage from a single AM-by-noise source is limited to twice the bandwidth of the modulating signal (2:14-11,1438).

There are two ways to modulate the jammer amplitude. One, called inverse gain, derives phase information from the scan pattern of the radar antenna to modulate the jammer power out of phase. In-phase modulation of such a jammer would result in a radar with rapid response and overshoots but with a stable tracking point on the target. The second approach is simply modulate the amplitude of the jammer output, usually in the form of a square wave. In this case, the jammer amplitude modulation rate selected is that believed to be best for defeating the specific radar. Selection of the rate may be automatic or manual based on the output of a radar warning receiver, or it may be preset before a specific mission in anticipation of a specific radar threat (4:106).

Direct Noise Amplification (DINA) is simply bandlimited Gaussian noise which is directly amplified prior to transmission. In practice DINA is generated by amplifying low level noise that has been filtered to obtain the desired jamming frequency spectrum. The DINA output stage consists of a power amplifier of the traveling wave or distributed amplifier type. FM by noise can be examined in two ways; FM-by-WB (wide band) noise and FM-by-LF (low-frequency) noise. The jamming mechanism is quite different in two cases. Frequency modulation by WN noise attempts to produce the same result as DINA, using a rapidly tunable oscillator, such as the backward wave oscillator. Selection of the best jamming source will obviously depend on such factors as the relative size, weight, cost, and reliability of the power tubes that are available in the frequency range interest. It is of interest, however, to investigate the mechanism by which FM by noise techniques can be used to produce jamming that is essentially indistinguishable from DINA at the output of a given radar receiver, and to determine the requirements that must be placed on the FM modulation parameters. Each time the frequency modulated carrier sweeps across the victim's passband, the victim receiver's filter circuits are set to "ringing'' by the impulsive character if the input. If the modulation is random, then the receiver input is a random time series of short pulses. If, further, the average frequency of these pulses is much greater than the victim bandwidth, then the conditions for the Central Limit Theorem are approximated, and the output of the receiver filter (usually IF) is very nearly Gaussian in its first order statistics. Thus one expects the IF output for FM-by-WB noise to be the same as the DINA. Frequency modulation by LF noise uses the same microwave sources for its generation, but restricts the modulating noise bandwidth to be much less than the victim bandwidth. Thus, the ringing caused by one receiver crossing is usually nearly over before another crossing occurs. The IF output wave is therefore a random time series of distinct pulses whose duration is approximately the reciprocal bandwidth. This jamming, when directed against search radars, exhibits two principal advantages and one principal disadvantage. It has increased effectiveness because the ordinary radar second detector produces more video power for a given IF output (or receiver input) power with FM-by-LF noise than with FM-by-WB noise or DINA. Thus, this source is more is more efficient in producing video jamming than are the others. Also, a given video power is more effective in jamming small target displays on a Pulse-Position Indicator (PPI) if FM-by-LF noise is used. This may be associated with a confusion effect caused by the resemblance of many of the bright spots to small target echoes. The principal disadvantage of FM-by-LF noise is that is relatively easy to counter, since the jamming is discontinuous even at the receiver output, and many or most of the target echo pulses are free of jamming if observed in real time. In randomly pulsed barrage jamming, a background level of jamming is maintained, and the level is increased by the pulse modulation. The duration, amplitude, and spacing of the modulating pulses should be varied randomly to prevent easy countering by the victim. The average jamming pulse duration should match that of the expected victim radars, and the average jamming Pulse Recurrence Frequency (PRF) must be much greater than the radar PRF. The barrage jamming signal before pulse modulation can be either DINA or FM-by-WB noise. Randomly pulsed barrage jamming achieves high effectiveness due to the intermittent character of the jamming in the victim receiver output, in the same manner as FM-by-LF noise. In addition, it is difficult to counter since the background jamming is continuous. This jamming technique is best applied by pulse modulating a tube having a higher peak than average power rating (2:14-9).

SUMMARY

In this chapter, we examined the nature of several jamming waveforms and the various ways to produce them. Although achieved similarly, i.e., simple modulation of a carrier frequency, the jamming waveforms provide different effects on radars while providing specific advantages and disadvantages. In this review, the focus was on noise characteristics and different types of modulations employed for various jamming techniques.

CHAPTER 3

CONVENTIONAL RADAR RECEIVER RESPONSE TO DIFFERENT TYPES OF JAMMING SIGNALS

In this chapter we present theoretical results largely paralleling well-known textbooks on the subject (10:143-148; 2:Chap. 14).

3.1 DINA or Amplified RF Noise

It is possible to obtain noisy RF energy by simply amplifying shot noise obtained from a diode operating in the temperature limited region or by some other noise source such as a back-biased Zener diode. The Central Limit Theorem assures us that the RF voltage has Gaussian or normal probability distribution. However, when such noise enters a radar receiver the output v_o (t) of the IF amplifier becomes narrow-band Gaussian noise and can be written as

$$v_o(t) = \alpha(t)\cos\omega_c t + \beta(t)\sin\omega_c t, \tag{3-1}$$

where $\alpha(t)$ and $\beta(t)$ are slowly varying functions of time, statistically independent with Gaussian distribution having zero mean and identical standard deviations σ , which is related to the noise energy contained in the IF bandwidth centered at $\omega_c = 2\pi f_c$, $f_c =$ IF, the amplifier center frequency. For practical purposes, it is more useful to talk in terms of the envelope and phase of $v_o(t)$. Hence, an equivalent expression is

$$v_o(t) = \rho(t)\cos[\omega_c t - \phi(t)], \tag{3-2}$$

where $\rho(t) = \sqrt{\alpha^2 + \beta^2}$ is the envelope and $\phi(t) = \tan^{-1}\frac{\beta}{\alpha}$ is the phase. It is easy to show that the probability density function of the envelope is given by the well-known Rayleigh distribution given by:

$$W(\rho) = \frac{\rho}{\sigma^2} e^{\left\{-\frac{\rho^2}{2\sigma^2}\right\}} , \qquad 0 \le \rho < \infty \tag{3-3}$$

Some useful moments are

$$\overline{\rho(t)} = \sqrt{\frac{\pi}{2}}\sigma , \tag{3-4}$$

$$\overline{\rho^2(t)} = 2\sigma^2 , \tag{3-5}$$

$$\overline{\rho^4(t)} = 8\sigma^4 , \tag{3-6}$$

The phase ϕ has uniform distribution over a full cycle and is given by

$$W(\phi) = \frac{1}{2\pi} , \qquad -\pi \le \phi \le \pi \tag{3-7}$$

Note that the envelope and the phase are statistically independent. One generally uses either a linear or a square-law device for detection of the video which is further amplified before display on an A-Scope or Pulse Position Indicator (PPI). Jamming efficiency is defined as the ratio of the fluctuating part to the total power. We'll now consider two cases.

3.1.1 Linear Envelope Detection

$$\text{D.C. Power} = \overline{\rho(t)}^2 = \frac{\pi}{2}\sigma^2 \tag{3-8}$$

$$\text{Total Mean Square Power} = \overline{\rho(t)^2} = 2\sigma^2 \quad (3\text{-}9)$$

$$\% \text{ D.C. Power} = (\text{D.C. Power/ Total Mean Square power})*100 = 78.5\ \% \quad (3\text{-}10)$$

$$\text{Jamming efficiency} = (2- \pi/2)/2 = 21.5\ \% \quad (3\text{-}11)$$

3.1.2 Square-Law Envelope Detection

$$\text{D.C. Power} = (\overline{\rho^2(t)})^2 = 4\sigma^4 \quad (3\text{-}12)$$

$$\text{Total Mean Square Power} = \overline{\rho^4(t)} = 8\sigma^4 \quad (3\text{-}13)$$

$$\% \text{ D.C. Power} = (\text{D.C. Power/ Total Mean Square Power})*100 = 50\ \% \quad (3\text{-}14)$$

$$\text{Jamming efficiency} = 50\%. \quad (3\text{-}15)$$

Now if one were define Jamming efficiency as the ratio of the fluctuating part (variance) to the non-fluctuating part, it is seen that that the square law operation is more prone to jamming. Hence, in practice one typically uses the linear operation.

3.2 Receiver Response to AM-by-Noise Jamming

It is possible to modulate a continuous wave carrier by audio or video noise. The RF output consists of a strong carrier and noise side-bands. The total band of frequencies occupied by these noise side-bands is, in general, just twice the band-width of the modulating noise. The effect of carrier is like tone-jamming. The analysis is similar to **DINA** considered in the previous section.

3.3 Receiver Response to FM-by-Noise Jamming

If the video noise function is used to modulate the carrier frequency, an essential advantage gained is that a relatively large RF band can be covered by a given jammer. The total jamming frequency excursion is customarily made several times as large as in the AM by noise case. Effects of this kind of interference are totally different from the previous cases. The noise amplitude in the receiver is determined by the excursions of the jamming signal across the IF acceptance bandwidth of the receiver. If one assumes that the total frequency excursions are large compared to the bandwidth of the receiver, while the frequencies contained in the modulating noise are small compared to the bandwidth of the receiver, then the receiver output will contain a number of pulses whose shapes in the time-domain are similar to the IF response as a function of frequency. These pulses will be repeated at random times.

It is not possible to conduct an exact analysis of FM by Noise. It will be helpful to consider the simple case of a signal that is swept linearly in frequency through the receiver pass-band. The IF amplifier response can be approximated by a Gaussian response. The transfer function of the IF amplifier is

$$G(\omega) = A_1 \exp[-(\omega-\omega_o)^2/2b^2], \tag{3-16}$$

where A_1 is is the gain at the mid-band frequency and b is related to the usual 3-db bandwidth β by the relation $b^2 = \beta^2/(4\ln 2)$. The linearly swept signal can be written as:

$$v_i(t) = A_2 \cos(st^2/2), \tag{3-17}$$

where s = sweep rate in Hz/sec for the system is depicted below

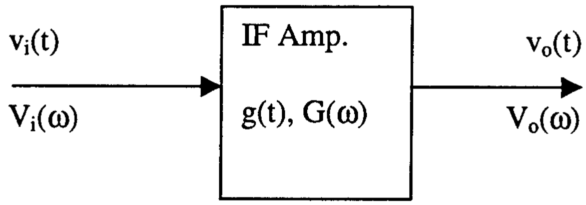

Figure 3-1 Linear Swept Frequency Model

The impulse response of the amplifier is given by

$$g(t) = b/\sqrt{2}\ \exp[-b^2t^2/2 + j\omega_0 t] \tag{3-18}$$

and the output $v_o(t)$ is given by the convolution integral

$$v_o(t) = \int_{-\infty}^{\infty} v_i(t-x)\, g(x)\, dx \tag{3-19}$$

Envelope of $v_o(t)$ becomes,

$$Envelope\{v_o(t)\} = \frac{A_1A_2}{\sqrt[4]{1+a^2}}\, e^{\left\{\frac{-as(t-t_o)^2}{2(1+a^2)}\right\}} \tag{3-20}$$

where $a = s/b^2$ and $t_o = \omega_o/s$.

We now consider two special cases.

3.3.1 Slow Sweep FM

For Slow Sweep FM, $a \ll 1$, Eq (3-18) becomes:

$$\begin{aligned} Envelope\{v_o(t)\} &\approx A_1A_2\, e^{\left\{\frac{-as(t-t_o)^2}{2}\right\}} \\ &\approx A e^{\left\{\frac{-(t-t_o)^2}{2\left(b/s\right)^2}\right\}} \quad \text{for } A = A_1A_2 \end{aligned} \tag{3-21}$$

This case for a given bandwidth and several sweep speeds is illustrated below:

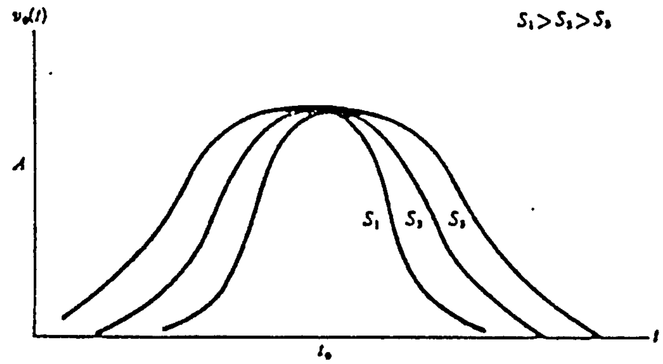

Figure 3-2 Slow Sweep FM.

The following observations for Slow Sweep FM are in order:

- The output is a pulse of constant amplitude.
- Pulse width varies directly as the receiver bandwidth.
- Pulse width varies inversely as the sweep speed.

3.3.2 Fast Sweep FM

For fast sweep FM, $a >> 1$, and Eq (3-18) becomes:

$$v_0(t) \approx \frac{Ab}{\sqrt{s}} e^{\left\{ \frac{-(t-t_o)^2}{2\left(\frac{1}{b}\right)^2} \right\}} \qquad (2\text{-}22)$$

For this case, the situation as illustrated below is quite different.

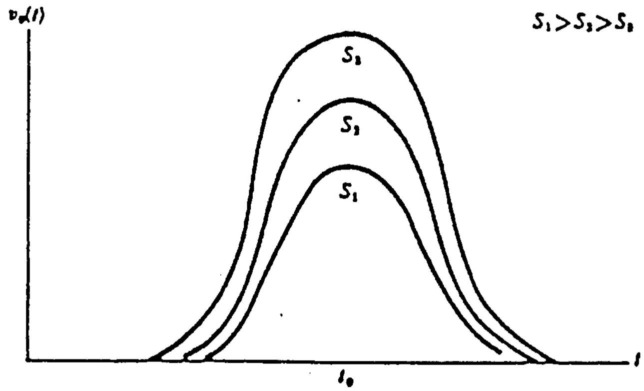

Figure 3-3 Fast Sweep FM.

The following observations for Fast Sweep FM are in order:

• Output pulse amplitude is directly proportional receiver bandwidth and decreases as sweep speed increases.

• Pulse width remains essentially unchanged with slower sweep speeds.

• Pulse width depends upon the reciprocal of the receiver bandwidth.

3.4 Receiver Response to FM-by-LF noise.

The receiver output can be calculated to a good approximation using a quasi steady state analysis.

Let x, a random variable, denote the frequency of a noise waveform with a normal pdf

$$W(x) = \frac{1}{\sqrt{2\pi\sigma}} \exp-[\frac{x^2}{2\sigma^2}] \tag{3-23}$$

Where σ is the RMS bandwidth. If this waveform frequency modulates a high frequency carrier w_c, one can write approximately

$$v_i(t) = \cos(w_c t + xt) \tag{3-24}$$

Let this jamming waveform be applied to a receiver with an IF response given by

$$G(w) = e^{\left\{\frac{-2\ln(2)}{\beta^2}(w-w_0)^2\right\}} \tag{3-25}$$

where β is the 3 dB bandwidth and for simplicity, center frequency has been set equal to the carrier frequency of the jamming signal. Based on steady state circuit theory, the envelope of the output is given by

$$v_o(t) = e^{\left\{\frac{-2\ln(2)}{\beta^2}x^2\right\}} \tag{3-26}$$

$$\overline{v_o(t)} = \frac{\beta}{\sqrt{\beta^2 + 4\sigma^2 \ln 2}} \tag{3-27}$$

$$\overline{v_o^{\,2}(t)} = \frac{\beta}{\sqrt{\beta^2 + 8\sigma^2 \ln 2}} \tag{3-28}$$

$$\%\ \text{D.C.} = \frac{\overline{v_o(t)}^2}{\overline{v_o^{\,2}(t)}} = \left[\frac{\beta\sqrt{8\sigma^2\ln(2) + \beta^2}}{4\sigma^2\ln(2) + \beta^2}\right] \approx 85\ \beta/\sigma \text{ for } \sigma >> \beta \tag{3-29}$$

For typical values of bandwidth β and deviation σ this indicates that the majority of the video jamming power is contained in the A.C. or the fluctuating component. This kind of jamming is superior and very desirable. It is also possible to produce multiple false targets to occur at different ranges.

CHAPTER 4

EXPERIMENTS AND RESULTS

This chapter will discuss the test equipment and procedures used to obtain various jamming waveforms and receiver outputs.

4.1 TEST EQUIPMENT

Test equipment is used to simulate a jammer and a victim receiver. Simulations for AM-by-noise and FM-by-Noise of a sine wave, Analog Random Pseudo noise, and Digital Random Pseudo Noise are conducted. Noise is used to amplitude modulate a signal generator set to a specific center (carrier) frequency and receiver demodulator output characteristics are investigated for different Intermediate Frequency (IF) bandwidths. The receiver demodulator output was observed and measurements made using a digitizing storage oscilloscope. As shown in Figure 4-1, the test equipment consisted of a Wavetek Model 132 VCG/Noise Generator, an HP 8672A Synthesized Signal Generator, a Microtel MSR 904A Heterodyne Receiver, and a LeCroy digitizing storage oscilloscope.

4.1.1 Noise Generator. This equipment is a source of analog and digital noise as well as a precision source for sine, triangle and square waveforms. Waveforms can be varied over a frequency range of 0.2 Hz to 2.0 MHz. The length of the digital sequence is selectable to a maximum of $2^{20}-1$ bits. Clock rate is variable from 160 Hz through 1.6 MHz, providing added versatility to the noise generation process. These clock rates allow selectable noise bandwidths which vary from 10 Hz to 100 kHz. Square wave, triangle wave, and sinewaves can also be selected as a signal source. The noise source is derived from a digital filter. A clock oscillator operating over the range of 160 Hz to 1.6 MHz functions as a trigger source for the digital Pseudo-Random Sequence Generator (PRSG). The PRSG output is a maximal-length random binary sequence (signal) which functions as the source for producing digital noise and analog noise via a digital-to-analog conversion in the digital filter, Figure 4-2. The number of bits in each sequence is selected by the SEQUENCE LENGTH controls. Parallel data is fed from the PRSG to the digital-to-analog converter where the information is summed and filtered to provide a random analog noise signal (8:1-12).

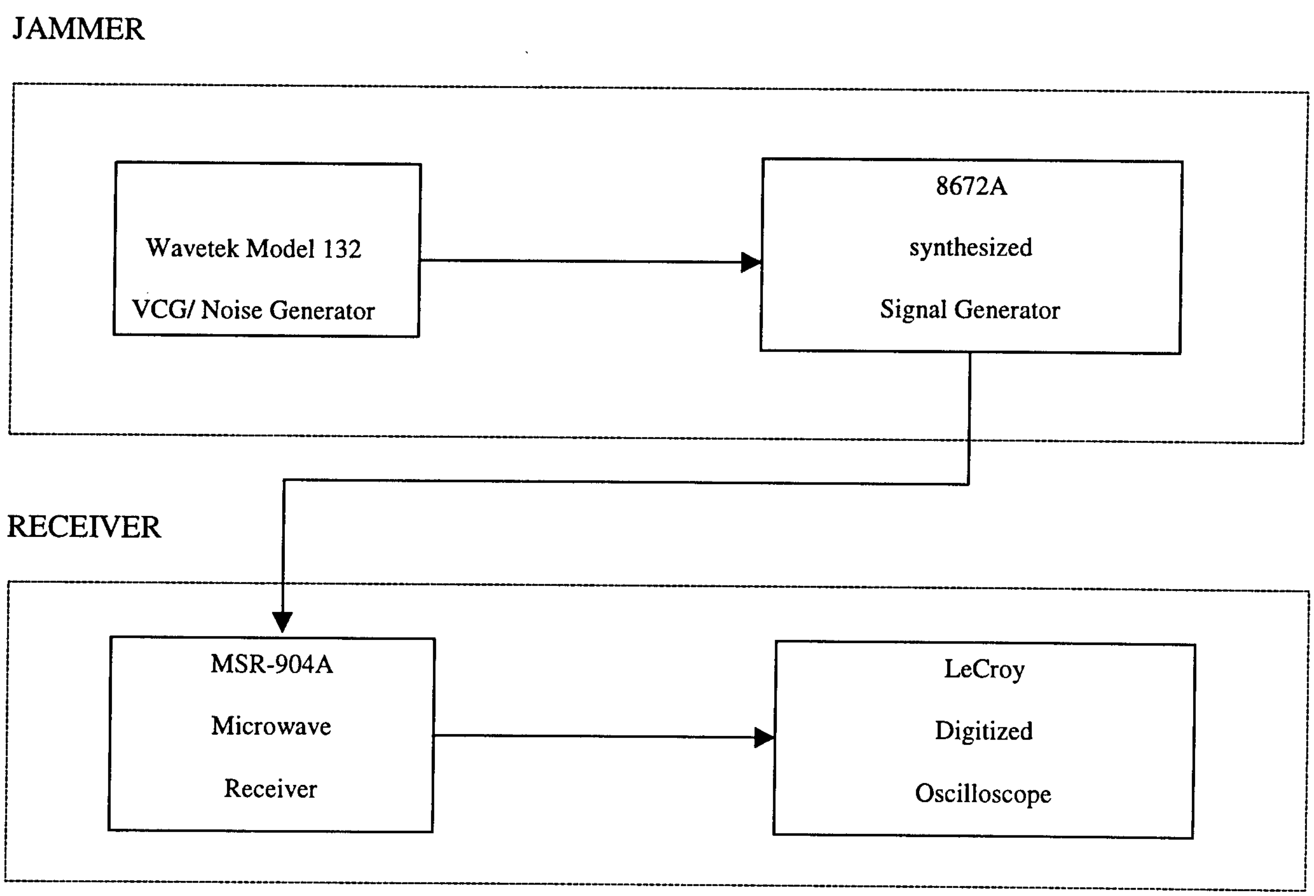

Figure 4-1 Block Diagram of Equipment

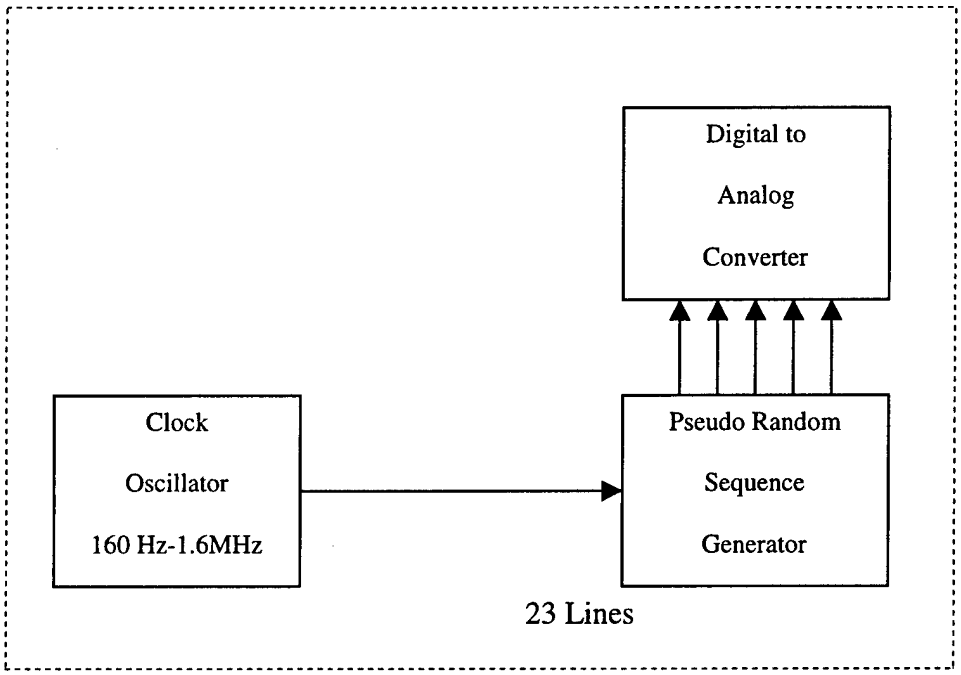

Figure 4-2 Digital Filter of the Noise Generator

4.1.2 Signal Generator. The HP Model 8672A Synthesized Signal Generator has a frequency range of 2000 to 18000 MHz. The output is leveled and calibrated from +3 to –120 dBm. AM and/or FM modulation modes can be selected. The frequency, output level, modulation modes, and most other modes or functions can be remotely controlled using the HP-IB programming format. Frequency stability is dependent on the time base, either an internal or external oscillator. The internal crystal oscillator operates at 10 MHz while an external oscillator must operate at 5 or 10 MHz. The heart of the synthesizer is phase-locked to the time base oscillator. Both amplitude and frequency modulation capabilities are available in the instrument using either front panel switches or remote programming. External drive signal are used for both AM and FM operation. AM depth and FM deviation are linear with the applied external voltage. Full-scale modulation is attained with 1.0 V-peak (9:1-5).

4.1.3 Heterodyne Receiver. The MSR-904A is a compact heterodyne receiver covering a frequency range from 0.50 to 18.0 GHz in its standard form, with fundamental mixing. An IF attenuation factor of 0 to 99 dB is available and IF bandwidths of 0.1, 1.0, 5.0 and 30 MHz are available in both linear or logarithmic detection modes (see Figure 4-3). AM and FM audio and video outputs are provided for all four selectable bandwidths. Microwave signals enter the receiver via one of the antenna ports and are applied to the RF Tuner consisting of RF filters and oscillators designed to reject undesired signals while generating an IF centered at 250 MHz. The IF is applied through a remotely-controlled attenuator to the linear and log IF amplifiers. The AM video output is available at the rear panel and at the front panel panoramic display and is also applied to a peak detector prior to display at an external monitor. The control section consists of several PC boards performing the automatic switching necessary to select the appropriate RF components, IF attenuation, IF bandwidth and to control the peak detector and some remote functions. The tuning section consists also of several PC boards. The tuning generator provides the tuning waveforms necessary to tune the receiver to one of five modes of operation. Crossband switching provides tuning control in the 0.5-18 MHz (or 0.03 to 18 MHz) multiband sweep. Tracking and high-current drive is provided to the RF oscillators and filters. The display section consists of: function selector, a group of PC boards mounted to the front panel, containing all pushbutton controls and generating all codes needed by the control and tuning sections; meter tracking and frequency display; and scope module (1:3-4).

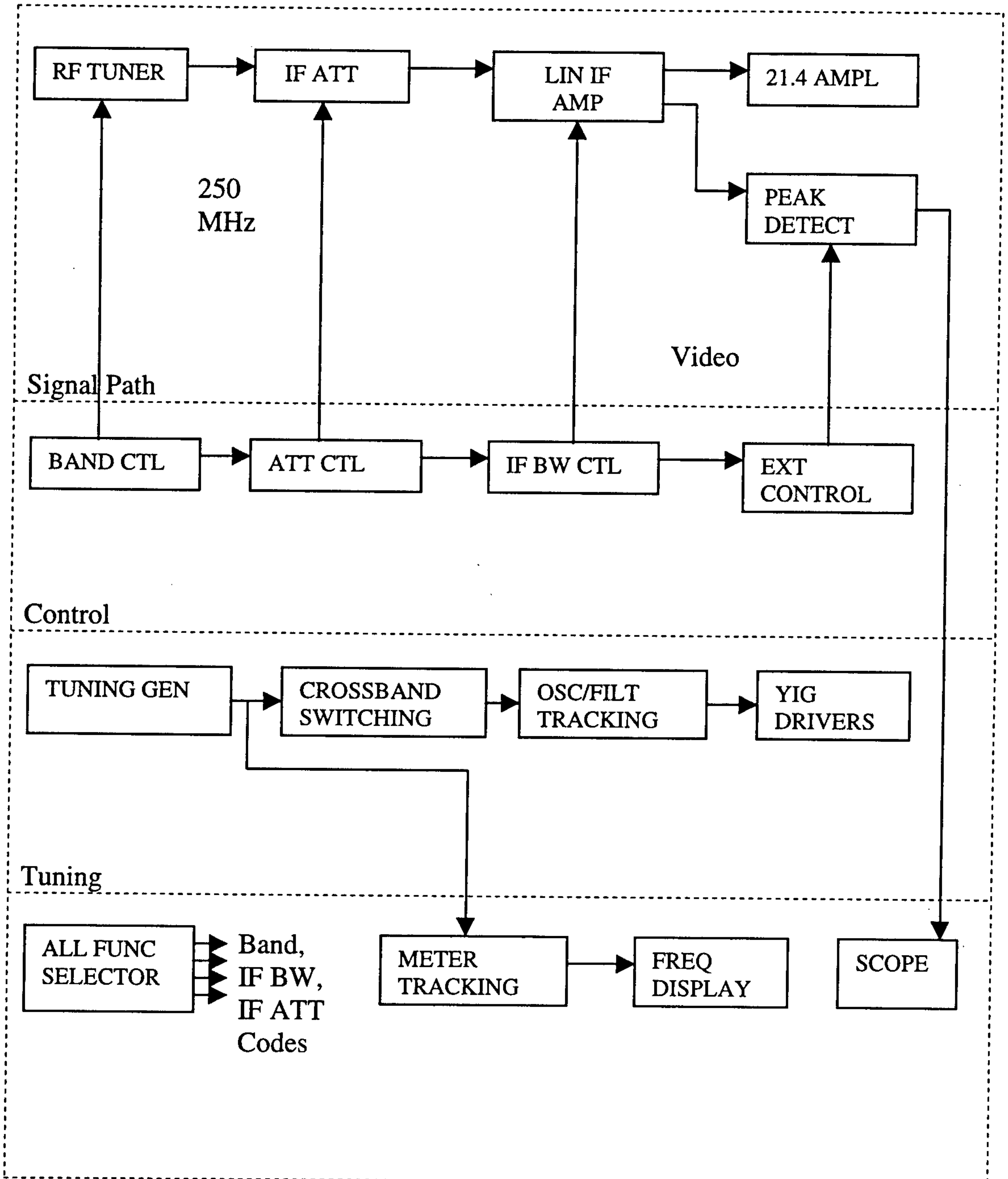

Figure 4-3 MSR-904A Block Diagram (1:5)

4.2 EXPERIMENTAL RESULTS. Various noise signals either AM or FM modulate a carrier at center frequency of 2.1 GHz. To recover signals in the receiver, different receiver IF bandwidths are selected and the demodulator output characteristics analyzed. Because of the limited scope of this research, only the 0.1 and 1.0 MHz IF bandwidth results are presented for discussion/comparison purposes (these results are typical for all cases considered).

4.2.1 AM by Sinewave. Sinewave amplitude modulation is used to represent a tone jammer situation. The sinewave frequency can be selected to be between 10 Hz and 1 MHz in 0.2-2.0 Hz step sizes. For these experiments, the modulating sinewave frequency was set to 10 Hz and measured by the oscilloscope using 1 V/div and 50 ms/div as shown in Figure 4-4.

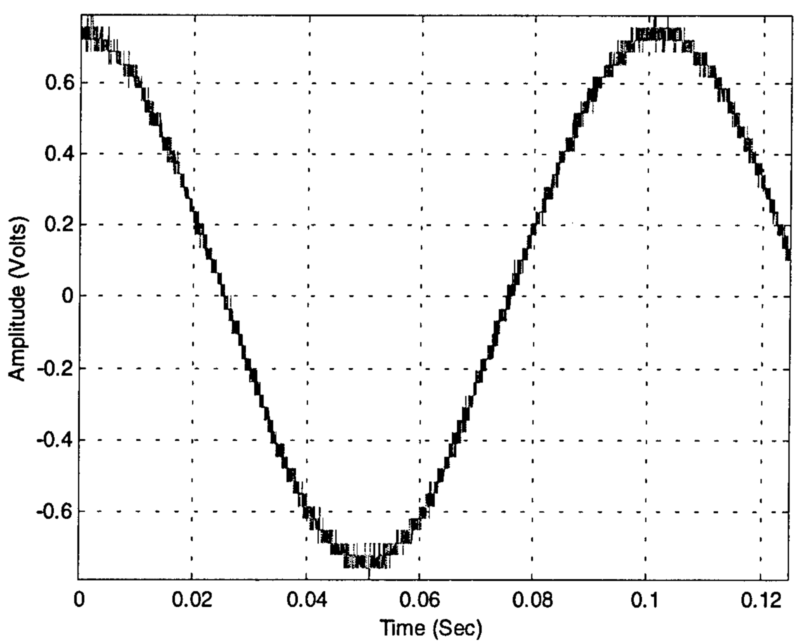

Figure 4-4 Modulating Waveform: 10 Hz Sinewave Noise

This sinewave modulates the signal generator carrier frequency of 2.1 GHz and the signal is passed into the receiver. In the receiver, the signal passes through the RF bandpass filter with a 2 GHz bandwidth (2-4 GHz). The IF bandwidth is sequentially selected as 0.1, 1.0, 5.0 and 30 MHz producing the receiver demodulator outputs of Figures 4-5, 4-6, 4-7 and 4-8, respectively.

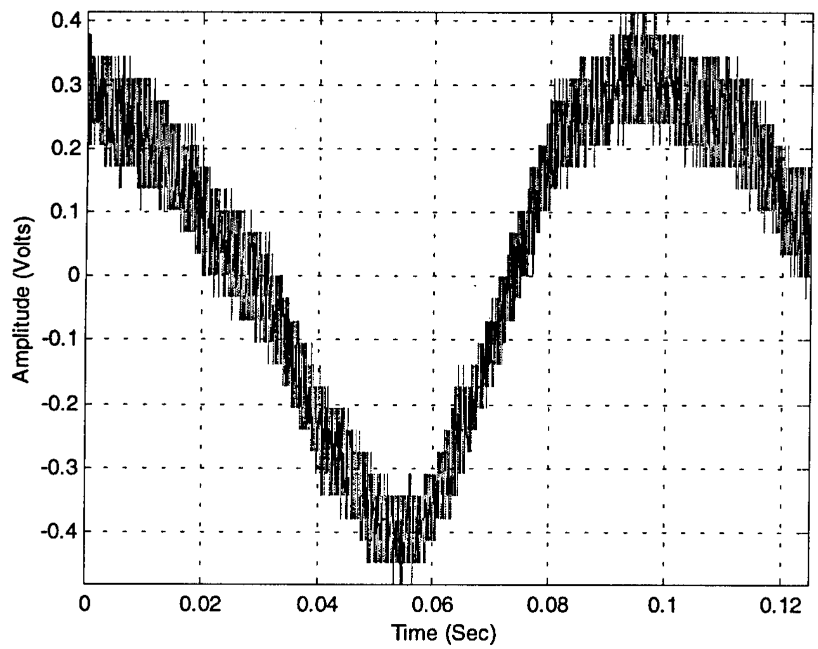

Figure 4-5 10 Hz Sinewave Noise Modulation, IF Bandwidth = 0.1 MHz

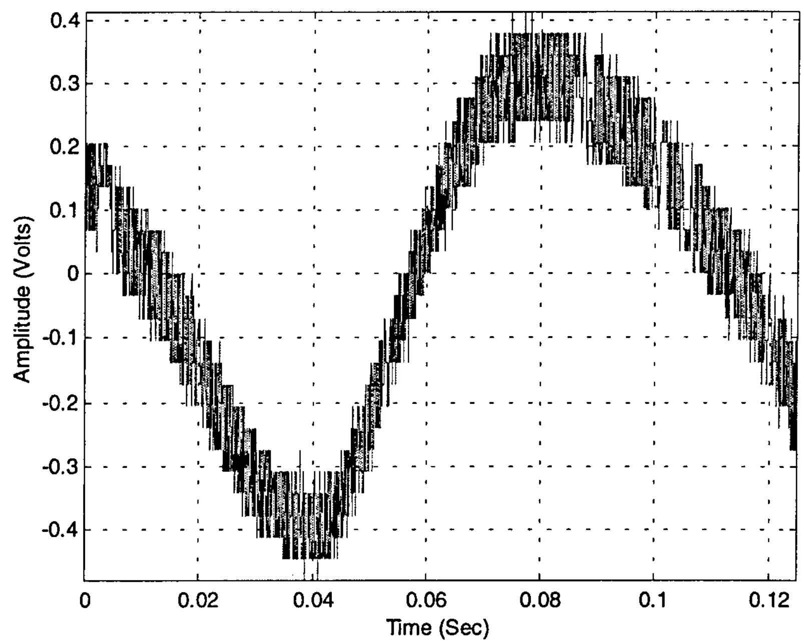

Figure 4-6 10 Hz Sinewave Noise Modulation, IF Bandwidth = 1.0 MHz

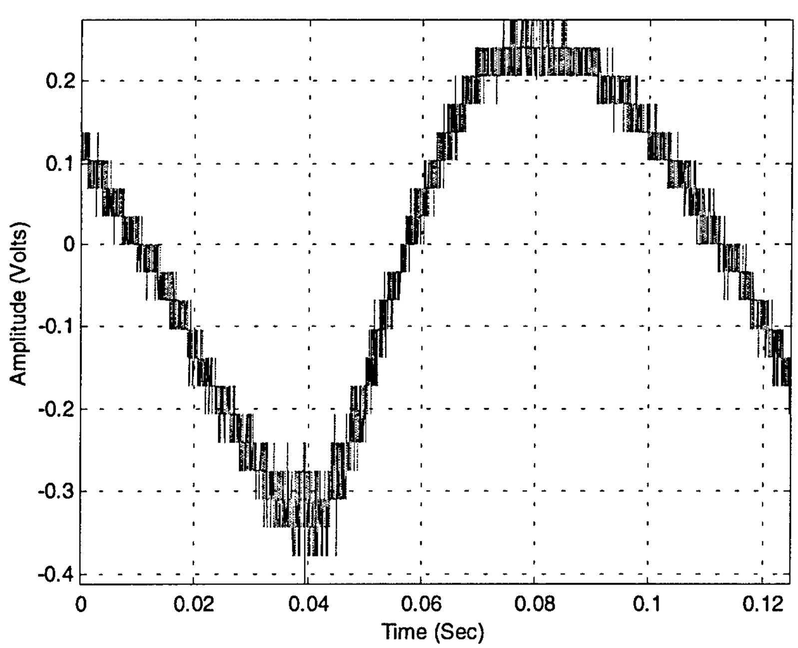

Figure 4-7 10 Hz Sinewave Noise Modulation, IF Bandwidth = 5.0 MHz

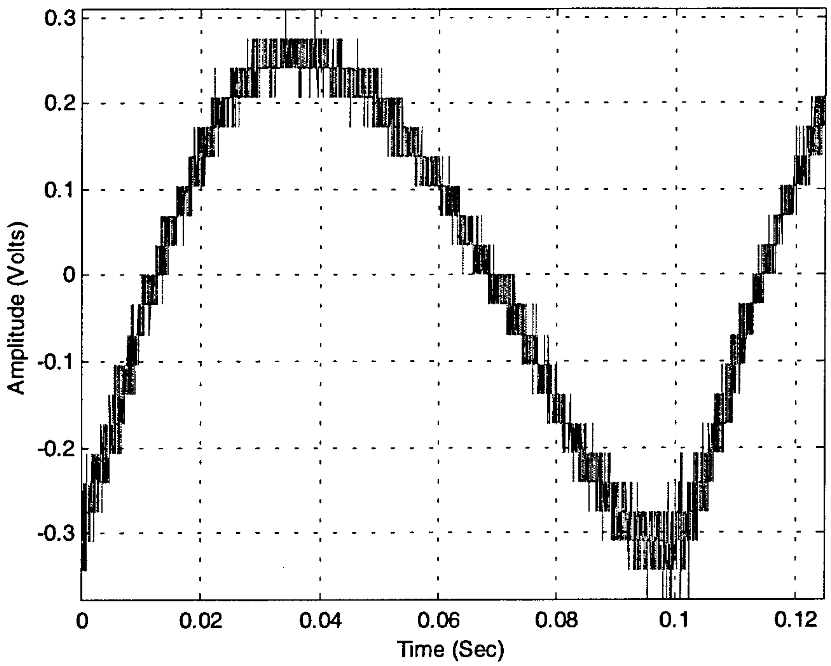

Figure 4-8 10 Hz Sinewave Noise Modulation, IF Bandwidth = 30 MHz

4.2.2 AM by Pseudo-Random Analog Noise. Pseudo-Random analog noise can be generated between 160 Hz-1.6 MHz. Using a shift register in the noise generator, the length of the signal can be selected 2^{10}-1, 2^{15}-1 or 2^{20}-1. For these experiments, we examined a 16 KHz signal using code lengths of 2^{10}-1 and 2^{15}-1. The signal modulated the signal generator setting at a carrier frequency of 2.1 GHz. A receiver RF bandwidth of 2 GHz (2-4 GHz) was used with IF bandwidths 0.1 and 1.0. As measured by the storage oscilloscope using 1.0 V/div and 5 ms/div, the receiver demodulator outputs of Figures 4-9 through 4-14 resulted.

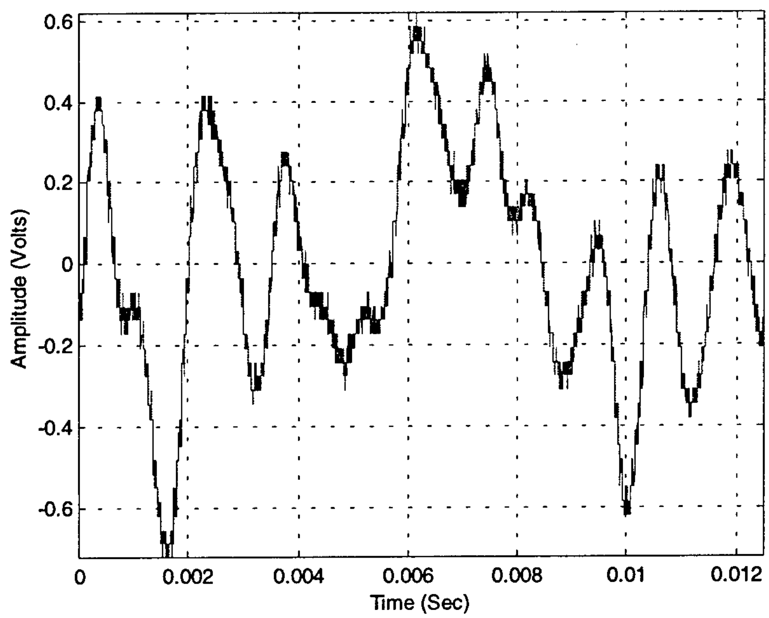

Figure 4-9 Modulating Waveform: Pseudo-Random Analog Noise using a 16 KHz Clock Rate and a 10 stage register (Sequence length = 2^{10}-1)

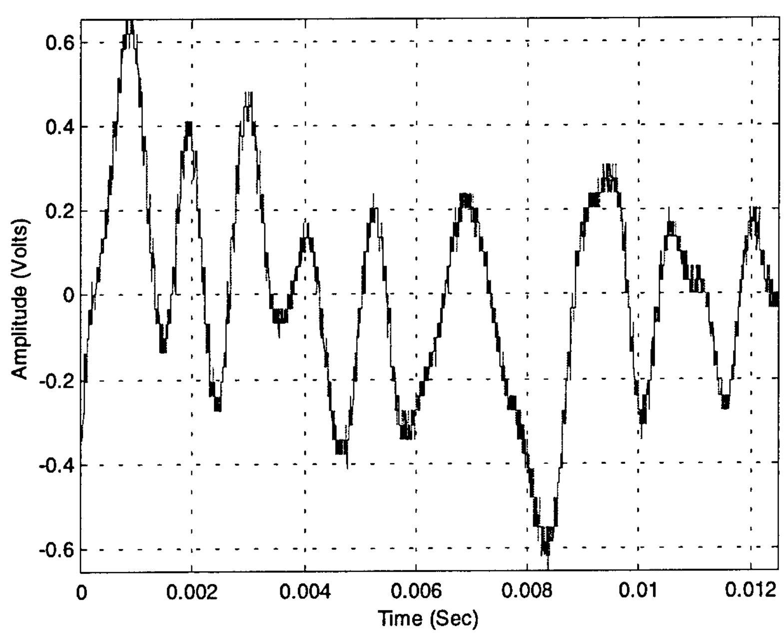

Figure 4-10 Modulating Waveform: Pseudo-Random Analog Noise using a 16 KHz Clock Rate, a 15 stage register (Sequence length = 2^{15}-1).

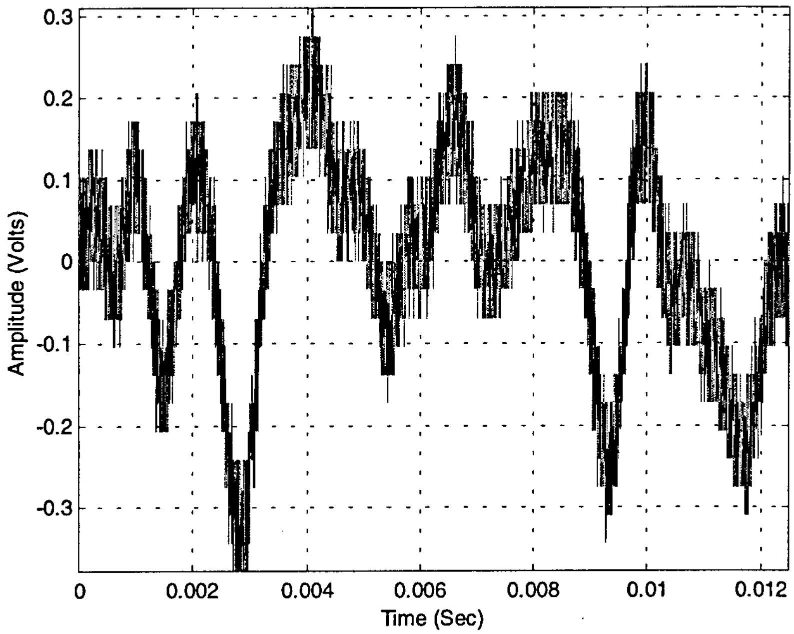

Figure 4-11 Demodulator Output: Pseudo-Random Analog Noise using a 16 KHz Clock Rate, a 10 stage register (Sequence length = 2^{10}-1), and IF Bandwidth = 0.1 MHz.

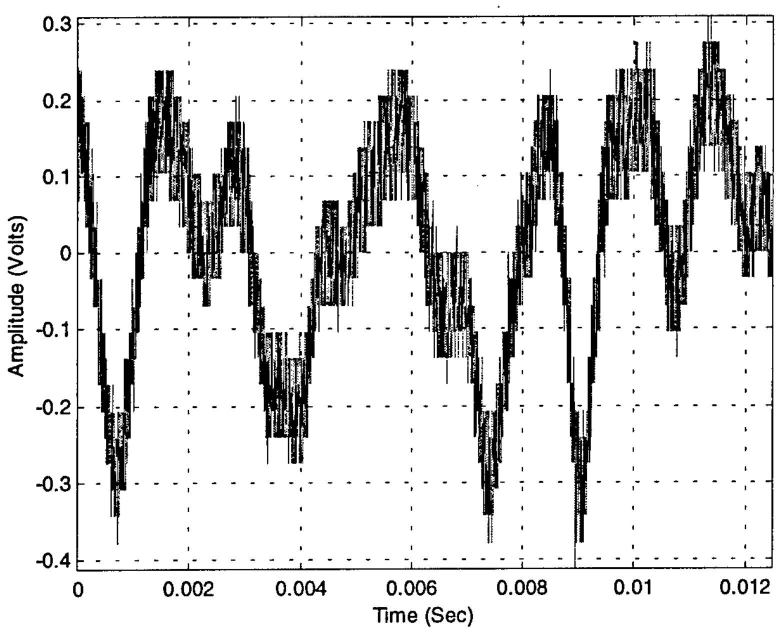

Figure 4-12 Demodulator Output: Pseudo-Random Analog Noise using a 16 KHz Clock Rate, a 15 stage register (Sequence length = 2^{15}-1), and IF Bandwidth = 0.1 MHz.

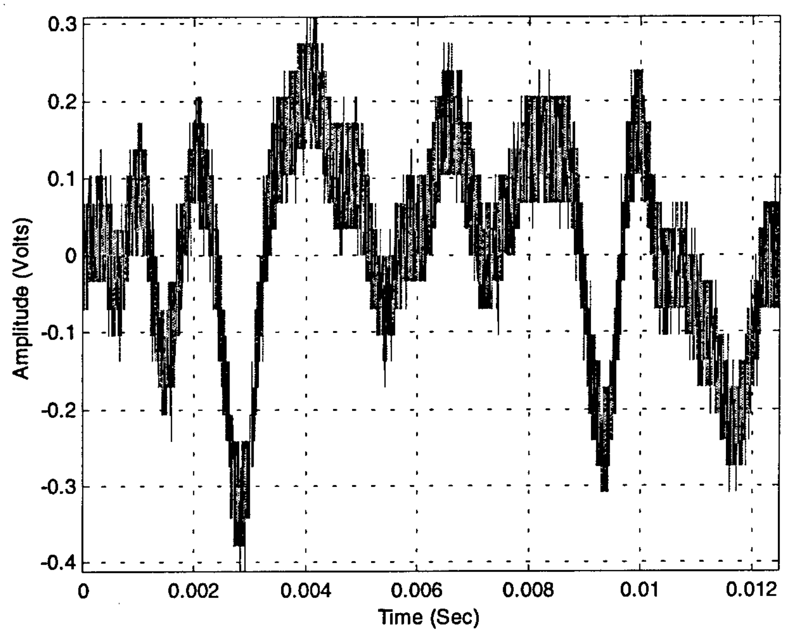

Figure 4-13 Demodulator Output: Pseudo-Random Analog Noise using a 16 KHz Clock Rate, a 10 stage register (Sequence length = 2^{10}-1), and IF Bandwidth = 1.0 MHz.

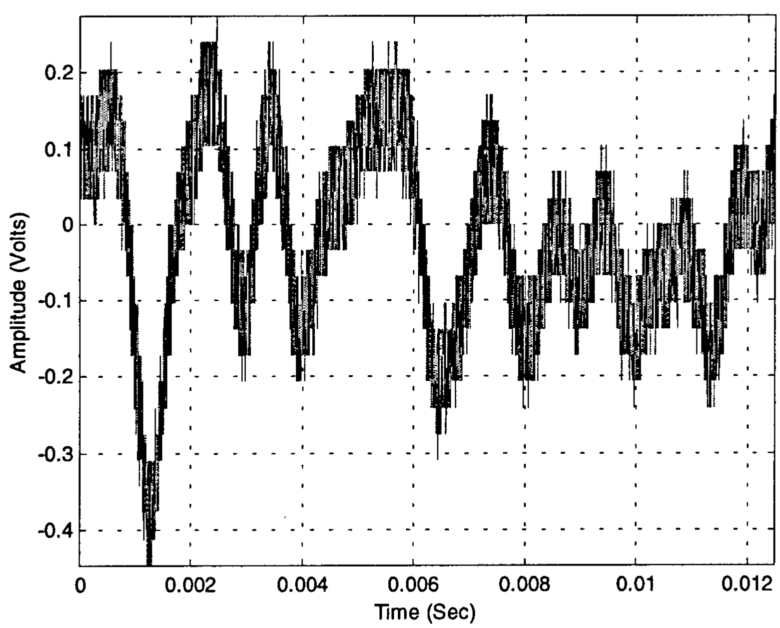

Figure 4-14 Demodulator Output: Pseudo-Random Analog Noise using a 16 KHz Clock Rate, a 15 stage register (Sequence length = 2^{15}-1), and IF Bandwidth = 1.0 MHz.

4.2.2 AM by Pseudo-Random Digital Noise. Pseudo-Random digital noise also can be generated at clock frequencies in the range of 160 Hz to 1.6 MHz using the maximal-length shift register. The length of the code signal can be selected as 2^{10}-1, 2^{15}-1 or 2^{20}-1. For these experiments, we examined a signal with a clock frequency of 16 KHz and codes of length 2^{10}-1 and 2^{15}-1 using a carrier frequency of 2.1 GHz. A receiver RF bandwidth of 2 GHz (2-4 GHz) and IF bandwidths of 0.1 and 1.0 MHz were used. The receiver demodulator output was observed and measured by the oscilloscope using 1.0 V/div and 0.2 ms/div and results are plotted in Figures 4-15 through 4-20.

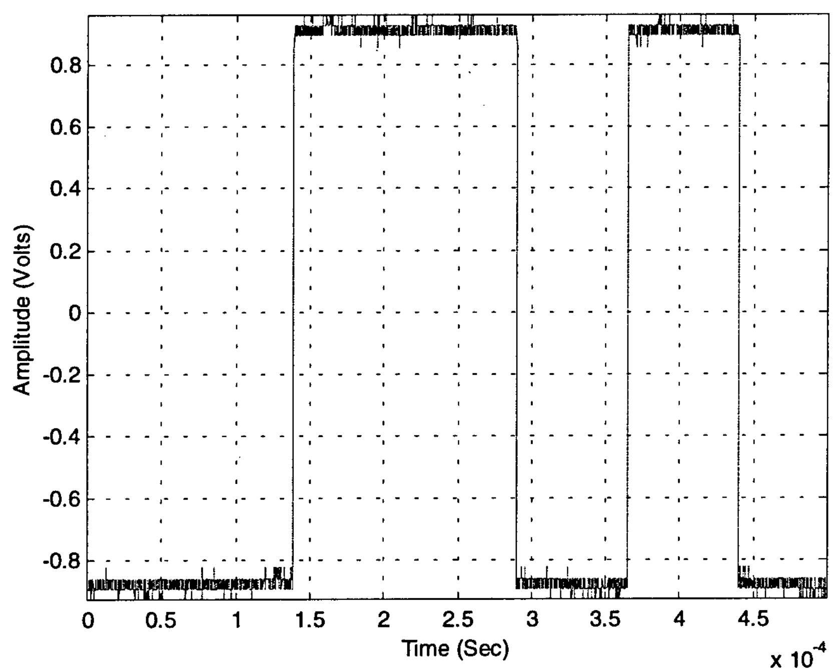

Figure 4-15 Modulating Waveform: Pseudo-Random Digital Noise using a 16 KHz Clock Rate and a 10 stage register (Sequence length = 2^{10}-1).

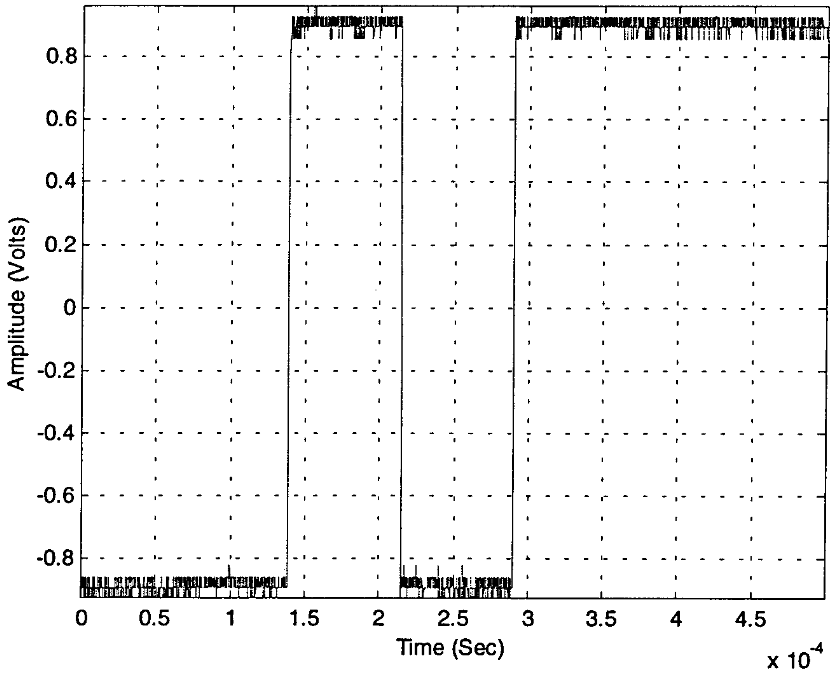

Figure 4-16 Modulating Waveform: Pseudo-Random Digital Noise using a 16 KHz Clock Rate and a 15 stage register (Sequence length = 2^{15}-1).

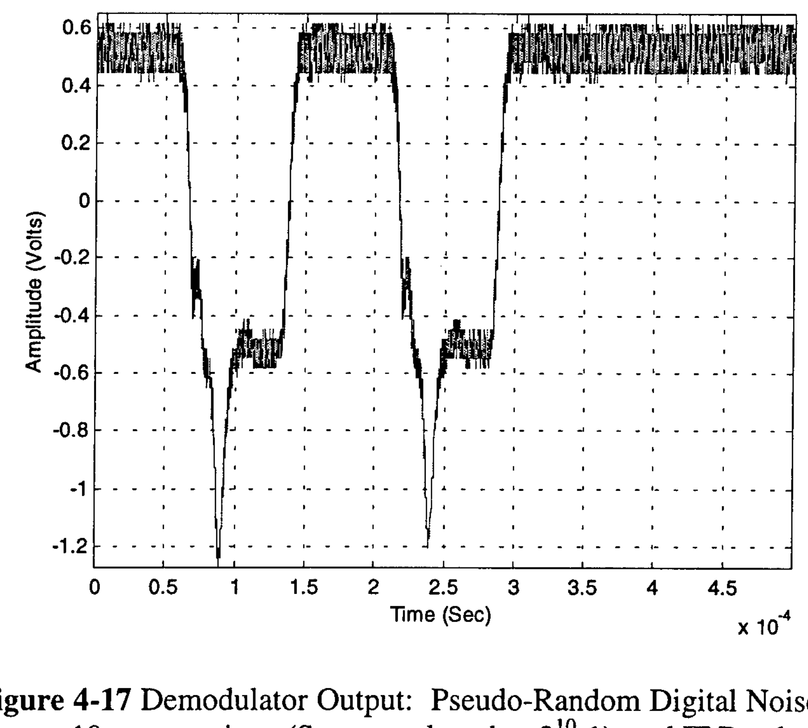

Figure 4-17 Demodulator Output: Pseudo-Random Digital Noise using a 16 KHz Clock Rate, a 10 stage register (Sequence length = 2^{10}-1), and IF Bandwidth = 0.1 MHz.

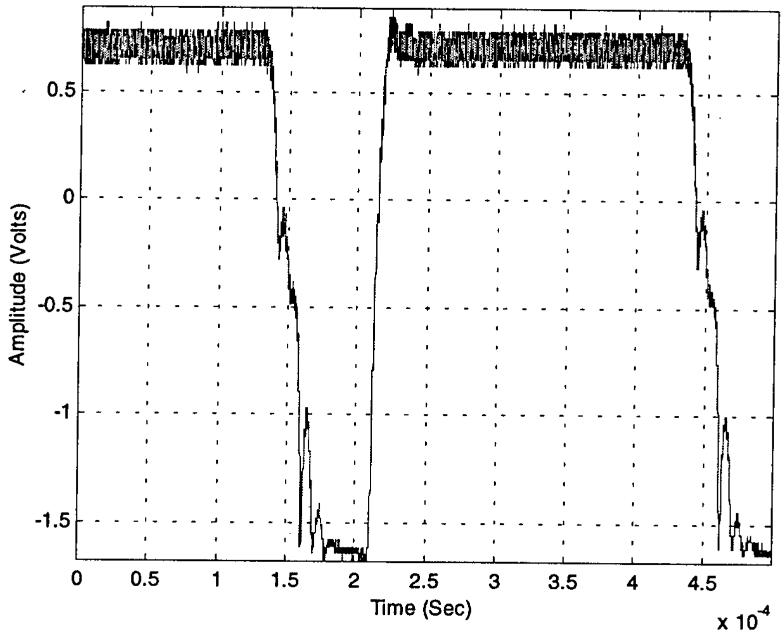

Figure 4-18 Demodulator Output: Pseudo-Random Digital Noise using a 16 KHz Clock Rate, a 15 stage register (Sequence length = 2^{15}-1), and IF Bandwidth = 0.1 MHz.

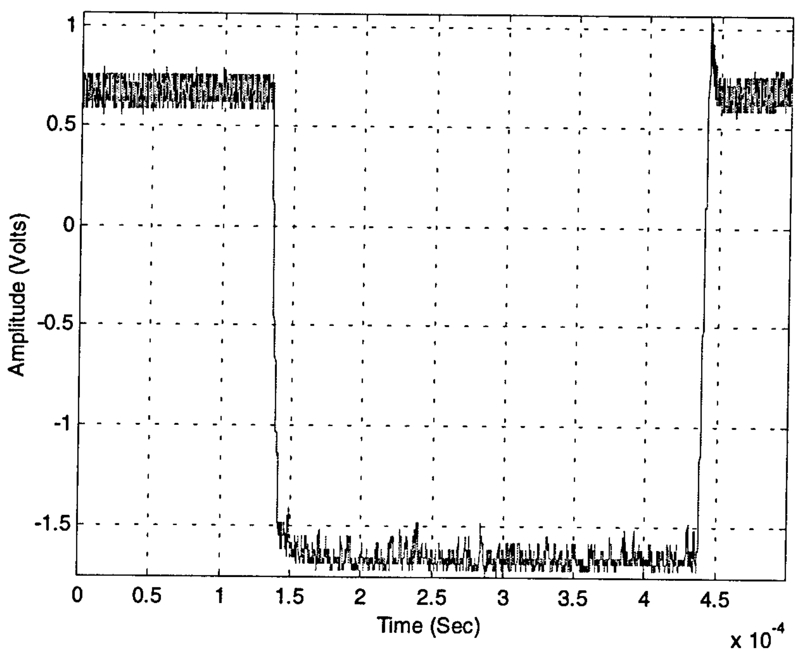

Figure 4-19 Demodulator Output: Pseudo-Random Digital Noise using a 16 KHz Clock Rate, a 10 stage register (Sequence length = 2^{10}-1), and IF Bandwidth = 1.0 MHz.

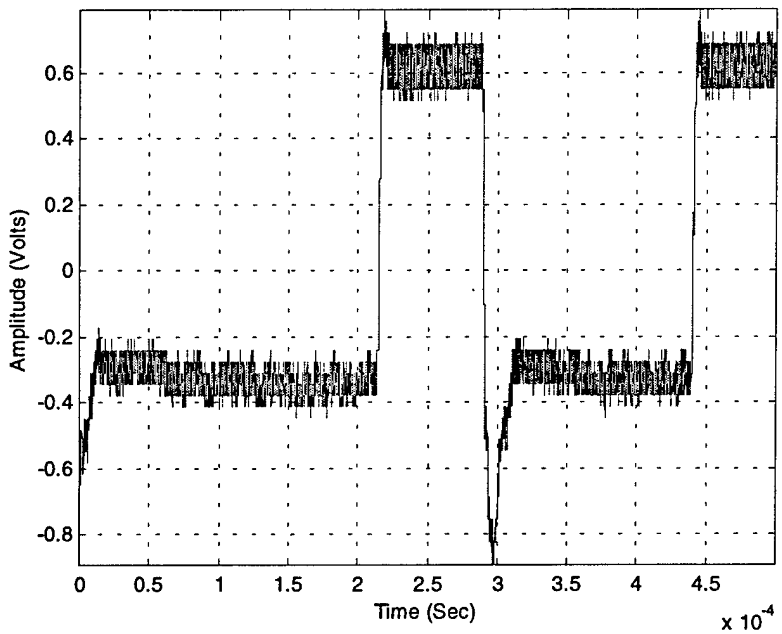

Figure 4-20 Demodulator Output: Pseudo-Random Digital Noise using a 16 KHz Clock Rate, a 15 stage register (Sequence length = 2^{15}-1), and IF Bandwidth = 1.0 MHz.

Recovering signals in the receiver is equivalent to maximizing the Signal-to-Noise Ratio (SNR) which is achieved by tuning the signal generator (changing the carrier frequency) to obtain maximum D.C. power at the demodulator output. For smaller IF bandwidths, carrier frequency alignment, i.e., matching the jammer and receiver frequencies, is more critical than for larger IF bandwidths and the receiver output exhibits more distortion. Compare Figures 4-5 to 4-8.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

Experiments show that a victim receiver should have sufficient IF bandwidth flexibility and be able to respond to host jamming waveforms. For tone jamming, variation in the IF bandwidth had minimal impact on the demodulated receiver output, i.e., as IF bandwidth was changed the response of the receiver remained relatively constant. In the pseudo-random analog or digital noise cases, increasing the length of the sequence decreased the receiver's capability to accurately recover the signal. For example, jamming signals generated by a 10-bit shift register could be more easily identified than those generated by the 15-bit shift register.

For future studies we recommend using more than one jamming signal accompanied by different kinds of noise and a receiver properly designed to handle specific jamming scenarios. Also computer simulations such as MATLAB and SIMULINK could be used to verify/validate results obtained from experiments using physical equipment.

REFERENCES

1. Micro-Tel Corporation, *MSR-904A Microwave Receiver Manual*, 1983.

2. Boyd, J.A., et.al. *Electronic Countermeasures.* California: Peninsula Publishing, 1978.

3. Davenport, Jr., Wilbur B. and William L. Root. *An Introduction to the Theory of Random Signals and Noise.* IEEE Press, 1987.

4. Golden, Jr., August. *Radar Electronic Countermeasures.* Air Force Institute of Technology, 1983.

5. Skolnik, Merril I. *Introduction to Radar Systems* (Second Edition). New York: McGraw-Hill Book Company, 1980.

6.Wiegand, Richard J. *Radar Electronic Countermeasures System Design.* Boston: Artech House Inc., 1991.

7. Schleher, D. Curtis, *Introduction to Electronic Warfare.* Norwood, MA: Artech House Inc., 1986.

8. Wavetek, *Model-132 VCG/Noise Generator Manual*, 1981.

9. Hewlet Packard, *8672A Synthesized Signal Generator Manual*, 1983.

10. Lawson, James L. and Uhlenbeck, George E. *Threshold Signals.* New York: Dover Publications Inc., 1950.

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13. ABSTRACT *(Maximum 200 words)*

Although jamming of radars has been in vogue for nearly 50 years there appears to be no comprehensive report on the subject matter. The purpose of this research is to fill this gap. The methodology consisted of analysis, simulation, and where feasible experimental demonstrations.

Experimental equipment consisted of a digital noise generator whose output was used to modulate a high frequency carrier in various fashions. The modulated output was fed into a very sensitive super-heterodyne receiver whose Intermediate frequency (IF) bandwidth could be varied from tens of Hz to mega Hz range. The detected output was displayed on a sampling oscilloscope. The display was in turn digitized and stored to make hard copies for documentation purposes. There was enough flexibility in the equipment to make a wide variety of observations.

Experiments showed that the victim receiver should have sufficient bandwidth to fully respond to the jamming signal. In the case of pure tone jamming, IF bandwidth requirements were minimal and any increase beyond the minimum did not improve jamming effectiveness. In case of pseudo random analog or digital noise, increasing the shift register sequence length and clock frequency made it more difficult for the receiver to recover the jamming waveform and identification. This implied inability to devise quick countermeasures. As follow-on to this research, more precise experiments involving FM by noise and random pulses are suggested.

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