INFRARED TARGET DETECTION:

SIGNAL AND NOISE SENSITIVITY ANALYSIS

THESIS

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Preface

The purpose of this study was to determine the effect of the statistical properties of the signal and the noise on IR detection performance.

Different signal and noise sources were identified and characterized. Their effects on IR detection performance were evaluated using an IR system detection model. The results demonstrate that system performance is greatly affected by the statistical properties of the signal and the noise. There were still numerous assumptions and limitations to the model used in this study. Further efforts should include modeling atmospheric effects and addressing imaging system designs used for automatic target detection and recognition.

I wish to thank my faculty advisor Dr. T.E. Luke for continually asking me to learn a little more. Answering his questions made this study very fulfilling. I would also like to thank Maj Tatman for his assistance at an important point in the research.

Christopher W. Keefer

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Abstract

The purpose of this study was to determine the effect of the statistical properties of the signal and the noise on an IR system's detection performance. Noise sources identified and characterized include Johnson noise, shot noise, generation-recombination noise, and photon noise. The signal was characterized as either constant or fluctuating.

A computer model was used to evaluate system detection performance for various combinations of signal type and noise distribution. Results were presented in terms of probability of detection versus signal to noise ratio. Analysis of the results suggest that an IR system's detection performance cannot be measured in terms of signal to noise ratio alone. The system designer needs to take into account the statistical properties of the signal and the noise to accurately predict system performance with an IR detection model.

INFRARED TARGET DETECTION:
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I. Introduction

General Issue

Two questions to ask about an infrared (IR) detection system are: Can it detect the target? How reliably can it detect the target? The answers to these questions establish the IR system's detection capabilities with respect to other systems, as well as indicate the usefulness for a particular application.

There are two methods for answering the questions about a system's detection capability. The first method is to build an IR system and perform operational tests to characterize the detection capability. This technique can prove to be very costly and time consuming, but it will provide the most accurate answers. The preferred method is to develop an analytical model that simulates the scenario and IR system. The analytical model consists of a set of equations, which relate the scenario's characteristics to the IR system's characteristics. The model's output includes a figure of merit for detection performance which is related to various input variables. The advantage of the model is that detection capability can be predicted quickly and inexpensively for various scenarios and system designs. However, analytical models are always approximations because they contain assumptions concerning the scenario and the IR system.

A critical assumption is that the IR system's detection performance can be judged by its signal to noise (S/N) ratio. The signal is represented by a peak value. The noise is represented by a root mean square (rms) value, which is the variance about the mean level of the noise. Detection is based on probability theory, which dictates the use of statistical distributions of the signal and the noise, not just the peak or rms values. The pertinent question is how do the statistical properties (distribution, mean, and variance) of the signal and noise effect the detection capability of an IR system?

Statement of the Problem

The problem is to identify the sources of signal and noise, characterize the magnitude and statistical properties, and determine the effect on discrimination techniques used in IR target detection. This problem needs to be solved for both radiometric detection systems and imaging systems.

Background

The infrared spectrum is useful for detection because the radiometric properties (emissivity and reflectivity) of targets and the background are usually different. Target detection is possible if this difference can be discriminated by the IR receiver and decision making system. Throughout this study the term signal will refer to the radiation coming from the target. The radiation from the surrounding background effects the mean and variance of the noise. The IR radiation is converted into an electrical current for use by an electronic processor to make a decision regarding the presence of a target. The process of changing the IR radiation into an electrical current distorts the effective radiation from the target and background (14:601). The amount of distortion is a function of the background, target, atmosphere, detector, and/or signal processing electronics.

Noise Sources. The distortions, which appear as statistical fluctuations in the electrical current, are referred to as noise. Some of the noise is generated in the detector and processing electronics and is called system noise. The noise generated in the detector will be the main interest of this study. Different detector noises are thermal noise, shot noise, generation-recombination (GR) noise, photon noise, and 1/f noise (18:98). Each of these noise sources in the detector needs to be examined in terms of how they effect the system's noise magnitude and randomness. However, 1/f noise will not be studied in this report, because of the limited current understanding (6:41).

Clutter, which is the spatial variations in the average radiance of the background, are a source of noise in detection and more significantly imaging systems (18:127-130). Because imaging systems create a reproduction of many localized areas of a scene, the variation between each localized area affects the detection criteria for the whole scene. The atmosphere also distorts the energy coming from the scene. Atmospheric effects including scattering and turbulence are a function of different environmental parameters. Atmospheric effects are beyond the scope of this study, however, they are well addressed in the literature (14:43-101).

Detection of a target is effected by the noise in the electrical current coming from the IR sensor, although noise from signal processing can dominate if proper care is not taken. The noise in the electrical current may be dependent on both characteristics of the system and the scenario. The fluctuations of the signal and of the noise, regardless of its source, indicate the need for statistical decision theory to determine the presence or absence of a target in the scene.

Signal Processing. The electronic signal processing uses the output from the detector and has a built in criteria for deciding whether the output current is noise or signal plus noise. The process being performed is discrimination. Discrimination is accomplished by establishing a threshold and declaring a target when the threshold is exceeded by the current from the detector. The randomness of the signal and noise makes target detection a statistical problem (7:6). Figure 1 helps explain the function of the signal processor. The distributions of the noise and signal plus noise are shown. A threshold is selected based on the decision criteria, which are the probability of false alarm and the probability of detection.

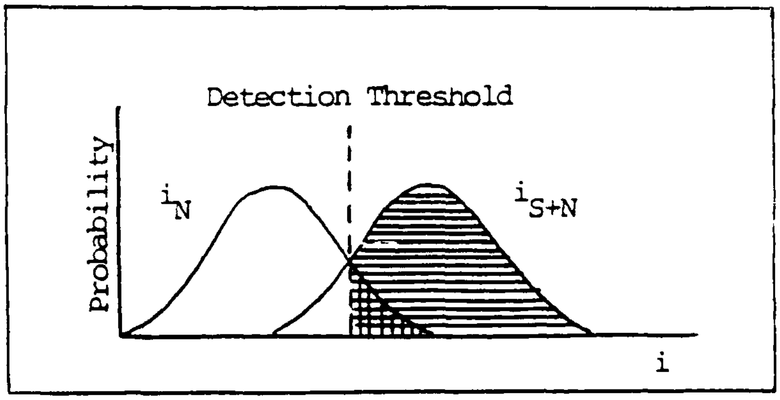

Fig. 1. Signal and Noise Distribution (7:7)

The probability of false alarm is the probability that a noise spike will exceed the threshold when no target is present and is vertically striped in Figure 1. The probability of detection corresponds to the area of the signal plus noise distribution which exceeds the threshold and is horizontally striped. The goal is to maximize the probability of detection and minimize the probability of false alarm. This can only be accomplished if one knows the distributions of the noise and the signal plus noise.

Approach

As stated before the problem is to identify, characterize, and determine the effect of the statistical variations of the signal and the noise on the detection capability of an IR system. In order to determine the effects of the signal and noise on target detection, a single element detection system searching a given area of coverage is examined. The detection systems performance is measured using a mathematical model, which is based on the relationships between the target/background variables and the sensor/signal processing variables. The variables include:

1. Spectral bandwidth,
2. Background characteristics,
3. Target characteristics,
4. Size of the Optics,
5. Detector characteristics,
6. Electrical bandwidth, and
7. False Alarm Rate.

Different input variables are used in the model to compare the effect of signal and noise sources on the system's probability of detecting a single target.

The first step in the approach is to identify the sources and characteristics of the signal and noise. System performance analysis is accomplished for those conditions where different probability distributions of noise or signal plus noise exist. Each case is examined separately, to determine the noise and signal plus noise distributions effect on probability of detection for a given signal to noise ratio.

Some cases or conditions are identified which could not be accurately represented with statistical descriptions or were beyond the scope of this study. These limitations of the study are identified and recommendations for possible approaches are presented.

Organization of Report

This report examines in detail how different sources of signal and noise affect the performance of an IR radiometer detection system. The signal and noise characteristics of the scene and IR system are identified in Chapter II. Next, a model is developed to show how the different sources of signal and noise effect system design. The model is described in Chapter III. Using the model, system performance data for different cases of noise and signal plus noise probability distributions are presented and analyzed in Chapter IV. Chapter V contains conclusions and recommendations for further analysis.

II. Signal and Noise Theory

Background

The main emphasis of this study is to examine the effects of different signal and noise distributions on the performance of an IR detection system. This chapter provides the necessary background to understand the origins of the relationships for describing the signal and the noise. The chapter begins by describing the conventions used in the derivations.

When using radiation detectors, the output of the detector can be either a voltage or a current. This study will assume the output is a current. The current has a mean value and fluctuates randomly about this mean value over a given time interval. There are two sources of the fluctuation in the current. The detection system is one source of noise (current fluctuations). Some of the noise is inherent to the detector and some of the noise is caused by the radiation from the scene. The noise of the preamplifier and signal processing electronics is assumed negligible. Figure 2 provides a diagram indicating the noise sources in the different types of detectors being studied in this report. In order to use decision theory in automatic target detection, it is necessary to have a quantitative description of the noise.

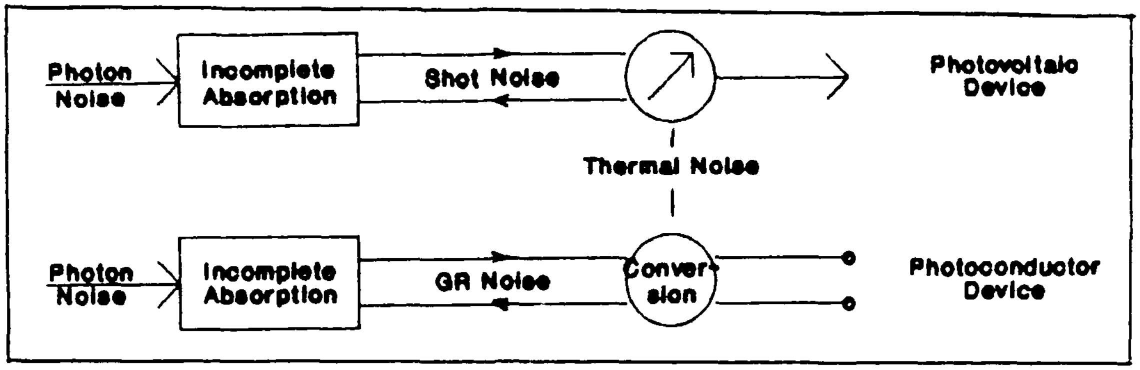

Fig. 2. Diagrams of Signal and Noise in the Detector

The statistics of the signal and the noise are determined from the processes causing the fluctuations. The magnitude of a random fluctuating quantity is described by its root mean square (rms) value. In this report, the mean or average value will also be used extensively. An average is either considered for a single system over a long period of time (time average) or considered at a single instant over a large number of identically prepared systems (ensemble average) (15:7). The time average and the ensemble average are equivalent for the fluctuations considered in this study.

If $N(t)$ is a fluctuating quantity and $\bar{N}$ is the mean value, then after a large number of trials τ seconds long, one will arrive at a mean value of $\bar{N}$ per τ. In each individual trial, n_x, a deviation from the mean will be observed:

$$\Delta n_1 = n_1 - \bar{N} \quad , \quad \Delta n_2 = n_2 - \bar{N} \quad , \quad \Delta n_3 = n_3 - \bar{N} \qquad (1)$$

The value of N(t) will on average be zero for a large number of observations. This is proved using the central limit theorem (9:414). Therefore, a more meaningful statement of the magnitude of the fluctuations is made by calculating the variance or mean square deviation. The mean square noise, σ_n^2, is defined as:

$$\sigma_n^2 = \overline{(n - \bar{N})^2} \quad (2)$$

Another means of describing the magnitude of the noise is the noise spectrum. The noise spectrum describes the distribution in terms of the frequency of the fluctuations in N(t). Let Y(f) be the Fourier Transform of N(t) for the period of τ:

$$Y(f) = \int_0^{\tau} N(t) \exp^{j2\pi ft} dt \quad (3)$$

Wiener and Khinchine used the Fourier Transform relationship to describe the noise spectrum, N(f) of the fluctuations in N(t) as:

$$N(f) = \lim_{\tau \to \infty} \frac{1}{2\tau} |Y(f)|^2 \quad (4)$$

(19:145)

The interrelationship between the mean square noise and the power spectrum is:

$$\sigma_n^2 = \int_0^{\infty} N(f)\, df \quad (5)$$

With these relationships in mind it is possible to derive the magnitude of signal and noise causing the fluctuating current.

The magnitude is important because it determines the amount of signal and noise in the system. This chapter will review the statistics and magnitude of thermal noise, shot noise, generation-recombination (GR) noise, and photon noise. Thermal, shot, and photon noise are found in photovoltaic detectors. Thermal, GR, and photon noise are found in photoconductive detectors. The statistics and magnitude of different target characteristics will also be discussed.

Johnson Noise

Johnson or thermal noise is caused by the thermal fluctuations of electrons in a resistive material. In a resistive volume, such as a detector, there is random thermal motion of the charge carriers which cause fluctuating charge gradients (25:256).

Johnson Noise Statistics. Johnson noise can be thought of as a form of blackbody radiation. The energy of each charge carrier follows a Fermi-Dirac distribution in a strict sense (21:349-350). However, because Johnson noise dominates during high temperature operation, the classical Boltzmann distribution is a good approximation. Since the total current is the sum of a very large number of current carriers, the central limit theorem can be used to predict that the Johnson noise current is a Gaussian process as shown below (4:185).

$$P(i) = (2\pi\overline{i_{JN}^2})^{-1/2} \exp^{-(i^2/2\overline{i_{JN}^2})} \qquad (6)$$

where

$P(i)$ = probability distribution of detector current
i = detector current (amperes)

$\overline{i_{JN}^2}$ = mean square Johnson noise current (amperes^2)

RMS Value. An approach to determine the magnitude of the Johnson noise is to represent the noisy detector by a Thevenin equivalent circuit consisting of a noise current generator in parallel with a noiseless conductance as shown in Figure 3.

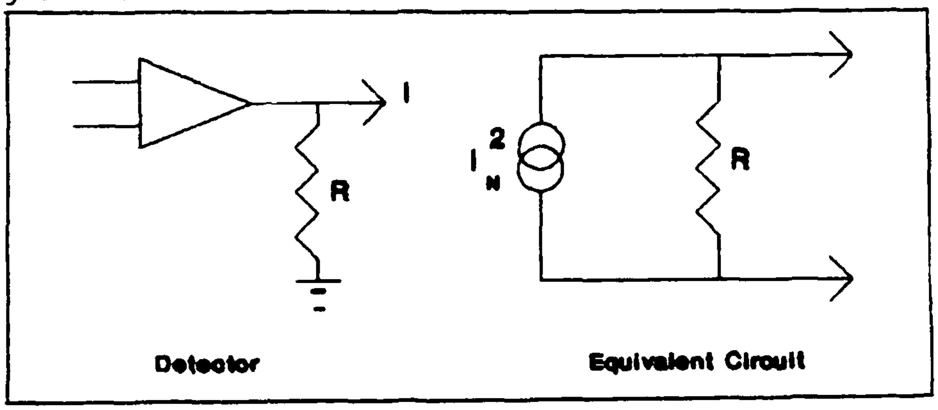

Fig. 3. Noisy Detector and Equivalent Circuit (25:259)

The impedances of the noise generator and conductance match so that maximum power transfer occurs between the two. Considering Johnson noise as a form of blackbody radiation, the mean energy of the charge carriers in the detector is given by the Planck radiation law:

$$\bar{E} = \frac{h\nu}{(e^{h\nu/kT} - 1)} \tag{7}$$

where

$\bar{E}$ = mean energy (J)
h = Planck's constant (J-sec)
ν = spectral frequency (Hz)
k = Boltzmann's constant (J/K)
T = detector temperature (K) (23:8)

The above relationship for mean energy can be simplified for ambient temperatures and low spectral frequencies and expressed as:

$$\bar{E} = kT \tag{8}$$

The power caused by the thermal fluctuations is equal to:

$$P = \bar{E}\Delta f = kT\Delta f \tag{9}$$

where

P = thermal power (W)
Δf = electrical frequency bandwidth (Hz) (25:257-258)

Since the resistor is matched to the noise generator only one-half of the noise current, $\bar{i}_{JN}$, will pass through the terminals (9:417). The power available at the resistor, R, is:

$$P = (\bar{i}_{JN}/2)^2 R = \overline{i_{JN}^{\,2}}\, R/4 \tag{10}$$

If the two powers are equated, one obtains the expression for the mean square Johnson noise current. The relationship is:

$$\overline{i_{JN}^{\,2}} = \frac{4kT\Delta f}{R} \tag{11}$$

Shot Noise

The shot noise is due to the discrete nature of photoelectron generation (6:40). Shot noise occurs in photovoltaic (photovacuum diode or photodiode) detectors. In a photovacuum diode detector, the photoelectrons are ejected from the surface of a photocathode. In a photodiode device, the photoelectrons are excited across an energy gap. In each process a potential energy must be overcome for a photoelectron to be excited (6:63,113). This excitation is caused either thermally or by incident photons.

Because the photodiode and photovacuum diode detector electron generation processes involve overcoming an energy gap, explaining the properties of the shot noise process is interrelated. In this report the derivation of shot noise for a photocathode will be examined. See references 3 and 6 for a similar derivation for the photodiode case. The electron generation process for a photocathode device, which causes detector output, is shown in Figure 4.

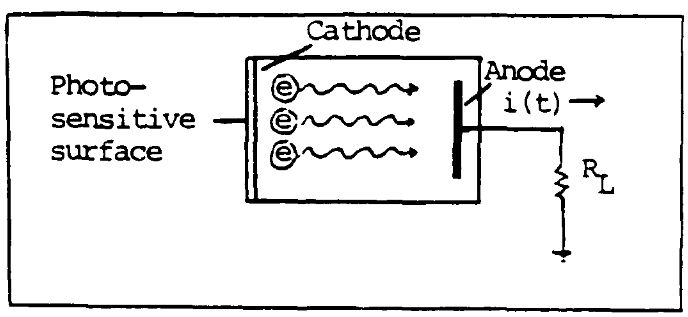

Fig. 4. Photocathode Signal Model

Electrons are released from the photocathode surface and travel to the anode surface. The electron motion produces a current at the detector output. This current is a superposition of the total collection of released electrons during a finite period of time (8:38). Electron emission from the cathode can be caused by IR radiation impinging upon the photocathode surface or by the thermionic emission of photoelectrons independent of incident IR radiation. The current produced by the thermionic emission is called the dark current. Since either the conversion of the IR radiation or the thermionic emission is probabilistic in nature, the detector output always evolves as a random process in time.

Shot Noise Statistics. The shot noise statistics need to be examined in terms of the thermionic emission and the emission induced by incident photons, which are assumed to have a constant rate of arrival.

Photon Induced. The most fundamental approach to understanding the random emission of electrons in a photocathode device is through quantum-electrodynamics. However, this approach is mathematically beyond the scope of this work. It has been shown that the simpler semi-classical approach is in agreement with the quantum approach (12:465). Three assumptions are made in the semi-classical approach to address the electron emission caused by IR radiation on the detector.

1. The probability of observing one photoevent in a time interval, τ, is linearly proportional to the incident optical power, P. In equation form this is:

$$P(1,W,\tau) = \frac{\eta P \tau}{h\nu} \tag{12}$$

where

W = incident energy (J) = $P \cdot \tau$
η = quantum efficiency

2. The probability of more than one photoevent occurring in such a time interval is very small compared to one or zero photoevents occurring.

3. The number of photoevents occurring in two non-overlapping intervals is statistically independent.

(12:466)

The above assumptions are inherent to a random experiment that has only two possible outcomes. The quantum efficiency of the detector determines the probability that a photoevent occurs. The random process caused by incident IR radiation is represented by the binomial distribution:

$$P(K,\tau) = \frac{n!}{K!(n-K)!} \eta^{K} (1-\eta)^{n-K} \tag{13}$$

where

$P(K,\tau)$= Probability of K photoevents in time τ
n = total number of incident photons in time τ
K = number of events in time τ

As n becomes large in such a way that $\eta \cdot n = \bar{N}$ is bounded, then the binomial distribution is approximated by the Poisson distribution (5:275-279):

$$P(K,\tau) = \frac{\overline{N}^K \exp^{-\overline{N}}}{K!} \tag{14}$$

This distribution is typically used for photoelectron counting conditions (10 to 100 incident photons), which will be discussed in chapter four of this report. When there are a large number of (greater than 100) incident photons in the time interval, τ, the distribution approaches the Gaussian distribution by the central limit theorem. The shot noise is represented by a Gaussian distribution with zero mean and the variance as defined below (16:110-118).

It is useful to express the Poisson distribution for the generation of electrons in terms of the average incident optical power, P. The average number of electrons emitted during the interval, τ, is represented by:

$$\overline{N} = \eta P\tau/h\nu \tag{15}$$

The Poisson distribution can now be expressed as:

$$P(K,\tau) = \frac{(\eta P\tau/h\nu)^K}{K!} \exp^{-(\eta P\tau/h\nu)} \tag{16}$$

<u>Thermally Induced</u>. In the photocathode, the number of electrons thermally excited is a function of the detectors particular work function. The Richardson-Dushman equation describes the amount of dark current, i_D, from the device:

$$i_D = 120AT^2 \exp^{-(\phi/kT)} \tag{17}$$

where

A = cathode surface area
T = device temperature
ϕ = device work function (3:153)

As in the case of thermal noise, the randomness of the dark current is a function of the electron's thermal energy and therefore follows the Boltzmann distribution in the high temperature case. If one assumes that many electrons are causing the dark current in the detector, then the central limit theorem can be applied to call the thermally induced shot noise a Gaussian process.

RMS value. A value for the magnitude of the fluctuations in detector current caused by shot noise can be derived using the statistical description developed previously and a somewhat qualitative approach. One needs to consider a low-pass filter coupled to the output of the detector. The filter is excited by the short current pulses associated with each electron (16:12). The filter will have an integration time, τ, which is the same as the time interval used in deriving the Poisson distribution. After a large number of trials, τ seconds long, one will arrive at an average value of $\bar{N}$ electrons emitted per τ. In each individual trial a deviation from the mean will be observed. For a Poisson distribution the variance is equal to $\bar{N}$ (19:30). In order to turn this average number of electrons into a current, one relates the amount of current measured during the time interval, τ, by:

$$i = nq/\tau \tag{18}$$

where

q = electronic charge (Coulombs)

The average current, I, is:

$$I = \bar{i} = \bar{N}q/\tau \tag{19}$$

The variance of the current averaged over many independent measurement times, all of length τ, is then:

$$\overline{i_{SN}^{\,2}} = \overline{(i - I)^2} = \frac{q^2}{\tau^2}\,\overline{(n - N)^2} = \frac{q^2}{\tau^2}\,\bar{N} \tag{20}$$

where

$\overline{i_{SN}^{\,2}}$ = mean square shot noise current (amperes^2)

This can be expressed in terms of the incident power, P:

$$\overline{i_{SN}^{\,2}} = \frac{\eta q^2 P}{\tau h\nu} \tag{21}$$

The variance of the noise current can also be expressed in terms of electrical bandwidth. If the width of each current pulse is much less than the sampling time τ, then we can consider the current to be a square pulse over τ. The effective bandwidth, Δf, for a matched filter and white Gaussian noise is:

$$\Delta f = 1/2\tau \tag{22}$$

See Appendix A for an explanation of the concept of a matched filter and the applicability of the above relationship. By substituting Eqs (19) and (22) into the mean square shot noise current expression Eq (21), an expression in terms of electrical frequency is obtained. The resultant mean square noise current is:

$$\overline{i_{SN}^{2}} = \frac{\eta q^{2} P \Delta f}{h\nu} = 2qI\Delta f \tag{23}$$

Therefore, the magnitude of the shot noise can be found by knowing the characteristics of the detector dark current and the incident signal or background radiation. The interactions of these noise sources will be examined in greater detail in the next chapter of this report.

The results obtained for the photovacuum device also correspond to the noise statistics and magnitude of a photodiode detector. The Richardson-Dushman equation is not applicable for determining the dark current magnitude. However, the noise distribution for the shot noise remains the same. An assumption made at the beginning of this section is that the signal and background are of constant power level. In some cases this may be true, however, the signal and/or background may be fluctuating which causes an added noise in the detection process. This noise source will be addressed under the section on photon noise.

Generation-Recombination Noise

Generation-recombination noise occurs in photoconductive devices. Photoconductivity occurs when the energy of an incident photon is high enough to cause the charge carrier to be transferred from one energy level to another in a semiconductor. The resulting electrons, holes, or both change the conductivity of the material. Excitation of electrons between an impurity level and the valence or conduction band is called extrinsic conductivity, while excitation of electrons from the valence band to the conduction band is called intrinsic photoconductivity (18:34-35).

The conductance of the detector is proportional to the spatial average of the carrier density. Therefore, fluctuations in the number of holes and electrons about their average values leads to fluctuations in the conductance. Under constant voltage operation there will be fluctuations in the detector's electrical current output (20:7051). An analysis of the noise produced by the carrier density fluctuations must take into account the following statistical aspects of the problem:

1. The rate at which incident photons strike the detector.
2. The quantum efficiency, η, which describes the probability, of electron photogeneration.
3. The lifetime of the electron in the conduction band.

(17:57)

The first characteristic will be covered under the section on photon noise, and therefore the assumption is made for this discussion that the incident radiation is constant. The second characteristic will be handled in the much the same manner as was done for shot noise. However, to simplify the analysis, the mean lifetime of the charge carriers in the conduction band are assumed to be constant (3:165). It is also assumed that only the motion of electrons contribute to the current flow (3:165). The analysis follows much the same procedure as was used for the shot noise.

GR Noise Statistics. As with shot noise, GR noise results from both thermally and optically excited free carriers.

Photon Induced. Addressing the optically excited carriers first and assuming the detector is cooled sufficiently, the probability of generation of exactly k electrons from n incident photons is a binomial distribution much like the shot noise case.

$$P(K,\tau) = \frac{n!}{K!(n-K)!}\eta^{K}(1-\eta)^{n-K} \tag{13}$$

where

n = total number of incident photons
K = number of charge carriers generated (18:106)

The variance of the binomial distribution is:

$$\sigma_n^2 = \eta(1-\eta)\bar{N} \tag{24}$$

where $\bar{N} = \eta \cdot n$

If the number of incident photons becomes large, then the Poisson distribution applies as before:

$$P(K,\tau) = \frac{\bar{N}^{K}\exp^{-\bar{N}}}{K!} \tag{14}$$

The recombination process occurs in much the same manner assuming constant carrier lifetime. Therefore the statistics involved with GR noise follow a Poisson process in the strict sense. However, for large number of incident photons (greater than 100) the distribution becomes Gaussian by the central limit theorem.

Thermally Induced. As in the case of the photovacuum diode, the number of charge carriers thermally excited into the conduction band is a function of the detectors particular characteristics. The two assumptions previously stated still apply and the randomness of the thermally generated charge carriers follows the Boltzmann distribution in the high temperature condition. The charge carriers will tend to recombine following the same distribution. Again applying the central limit theorem means that the thermally induced GR noise follows a Gaussian distribution.

RMS Value. A similar procedure used for the development of shot noise mean square deviation is used to determine the magnitude of the GR noise for a photoconductor. The shot noise relationship, Eq (22), is because the processes are similar in generation of charge carriers. The recombination process also involves fluctuations which are statistically as frequent as the fluctuations in ionization. Thus, the ideal photoconductor (assumed condition) has twice the noise power level of an ideal photodiode. There is also a gain factor, G, associated with the generation of electrons. This gain occurs because the lifetime of the generated electron can be longer than the transit time between the positive and negative electrodes of the photoconductor (23:746). The mean square value of the GR noise current is expressed as:

$$\overline{i_{GR}^{\,2}} = 4qGI\Delta f = \frac{4\eta G^2 q^2 P\Delta f}{h\nu} \qquad (25)$$

(3:166)

In actual photoconductors (intrinsic and extrinsic) there are more factors which should be taken into account when determining the rms value of the current noise. A strict approach includes determining the fluctuations in electron and hole carrier concentrations (3:169-176). Also, the effects of drift and diffusion will affect the probability of a fluctuation occurring and the time evolution of the fluctuation (20:7051). For the details of the semiconductor physics which completely describe the GR noise, the reader is referred to reference 3.

Photon Noise

The derivation for shot noise and GR noise assumes that the incident energy is a constant value. However, the incident intensity on the detector may be fluctuating and can cause photon noise. The resulting photon induced fluctuations in the detector output must be found from an ensemble average. A joint distribution is used to represent the compound consequence of both the uncertainties between the interaction of photons and matter and the fluctuations of the photons (12:469).

Photon Noise Statistics and RMS Value. It has been shown that the noise characteristics are approximately the same for both the shot and GR noise conditions. An example using the vacuum photodiode detector will be used to describe the photon noise. This derivation can then be expanded to the other detector types. The probability density of the number of photoelectrons, K, emitted when incident energy, W, is varying is given by:

$$P(K) = \int_{0}^{\infty} P(K,W,\tau)\ P(W)\ dW \tag{26}$$

where P(W) is the probability density function of the incident energy during the pulse. It should be noted, that in general the statistics of the above distribution will not be Poisson or Gaussian, even though the previous derivations of the shot noise and GR noise shows that $P(K,W,\tau)$ is Poisson (Gaussian in the limiting case) (11:1692).

In order to use the conditional probability distribution, the fluctuations of the incident energy needs to be known. Two examples will be examined and the resulting statistics and magnitude will be presented.

Constant Radiation. If one assumes that the incident energy on the detector is constant over both space and time, the average energy incident on the detector is expressed as:

$$W = P\tau \tag{27}$$

The probability distribution is:

$$P(W) = \delta(W - P\tau) \tag{28}$$

which implies that $W = P\tau$ with a probability of one.

The resulting conditional probability is:

$$P(K) = \frac{(\eta P\tau/h\nu)}{K!} \exp^{-(\eta P\tau/h\nu)} \tag{16}$$

which is expected for the constant incident energy condition. If the noise had been Gaussian, the photon noise would also have a Gaussian distribution. The magnitude of this noise will be calculated with the same equation used for shot noise (8:64-65).

<u>Fluctuating Radiation</u>. The next example is for fluctuating radiation. The energy is random and follows a negative exponential distribution which is expressed as:

$$P(W) = \frac{1}{W} \exp^{-(W/\overline{W})} \qquad W \geq 0 \tag{29}$$

The resulting distribution is found by solving for eq (26).

$$P(K) = \frac{1}{1 + (\eta P\tau/h\nu)} \left[\frac{(\eta P\tau/h\nu)}{1 + (\eta P\tau/h\nu)} \right]^K \tag{30}$$

The distribution in Eq (30) is referred to as the Bose-Einstein distribution. The variance of this distribution is approximately the same as in the shot noise case. In the strict sense it is modified by the Bose-Einstein statistics, however, operation in the infrared regime the causes the effects to be negligible (18:115). The probability distribution is Gaussian when there are a large number of (greater than 100) photons incident on the detector during the time interval, τ, for the photon noise case.

Signal Characteristics

The derivation of the statistics for the photon noise are directly applicable to describing the signal characteristics. The signal will either be fluctuating or constant. For the case of a constant signal coming from the target, the probability distribution of the signal plus noise should remain the same as the distribution of the noise. Gaussian noise is dominant in most IR applications. If the signal is constant the resulting signal plus noise distribution will be Gaussian.

A more interesting case occurs when the noise distribution is Gaussian but the peak signal current is described by the negative exponential statistics:

$$P(S) = \frac{1}{\bar{S}} \exp^{-(S/\bar{S})} \qquad S \geq 0 \qquad (31)$$

where

$\underline{S}$ = peak signal current (amperes)
S = average signal current (amperes)

This condition occurs when the detector is dominated by Gaussian noise and the signal is coming from a scintillating (fluctuating) target (22:1329). The resulting output current distribution for the signal plus noise case is shown below in integral form:

$$P(i,S) = \int_0^{\infty} (2\pi \overline{S}^2 \overline{i_N^2})^{-1/2} \exp^{-[(S/\overline{S}) + (i-S)^2/2\pi \overline{i_N^2}]} dS \qquad (32)$$

where

$P(i,S)$ = probability of output current, i, given peak signal current, S

$\overline{i_N^2}$ = mean square noise current

This distribution remains in integral form because there is not a simplified expression. However, it can be evaluated using numerical integration.

The characteristics of the signal and the noise discussed in this chapter will be applied to actual scenarios an IR system designer might encounter. The purpose is to show how the different statistics affect system performance. The next chapter details the model which will be used for evaluating IR search system performance.

III. IR System Detection Model

Introduction

A computer model, which simulates the IR detection process, is an ideal method for comparing the effects of different signal and noise statistics on an IR system's detection performance. This chapter explains the model used to predict IR detection performance. First, the structure of the model is presented in module form to highlight the major factors affecting an IR detection system design. Next, the assumptions and constraints of the model are discussed. The final section in this chapter presents the computer simulation using the IR detection model.

Model Structure

In this report, the IR target detection mission scenario consists of a single element detector searching a specified field of view, where a single target may or may not be present. The background and target are characterized by average temperature and emissivities.

Figure 5 is a flowchart which shows the process a system designer might take in developing an IR detection (non-imaging) system for the described scenario. There are four main subroutines to the model. These subroutines are used to find the instantaneous field of view (IFOV), the electrical bandwidth, the signal and noise currents, and the probability of detection. As in any system design, there is

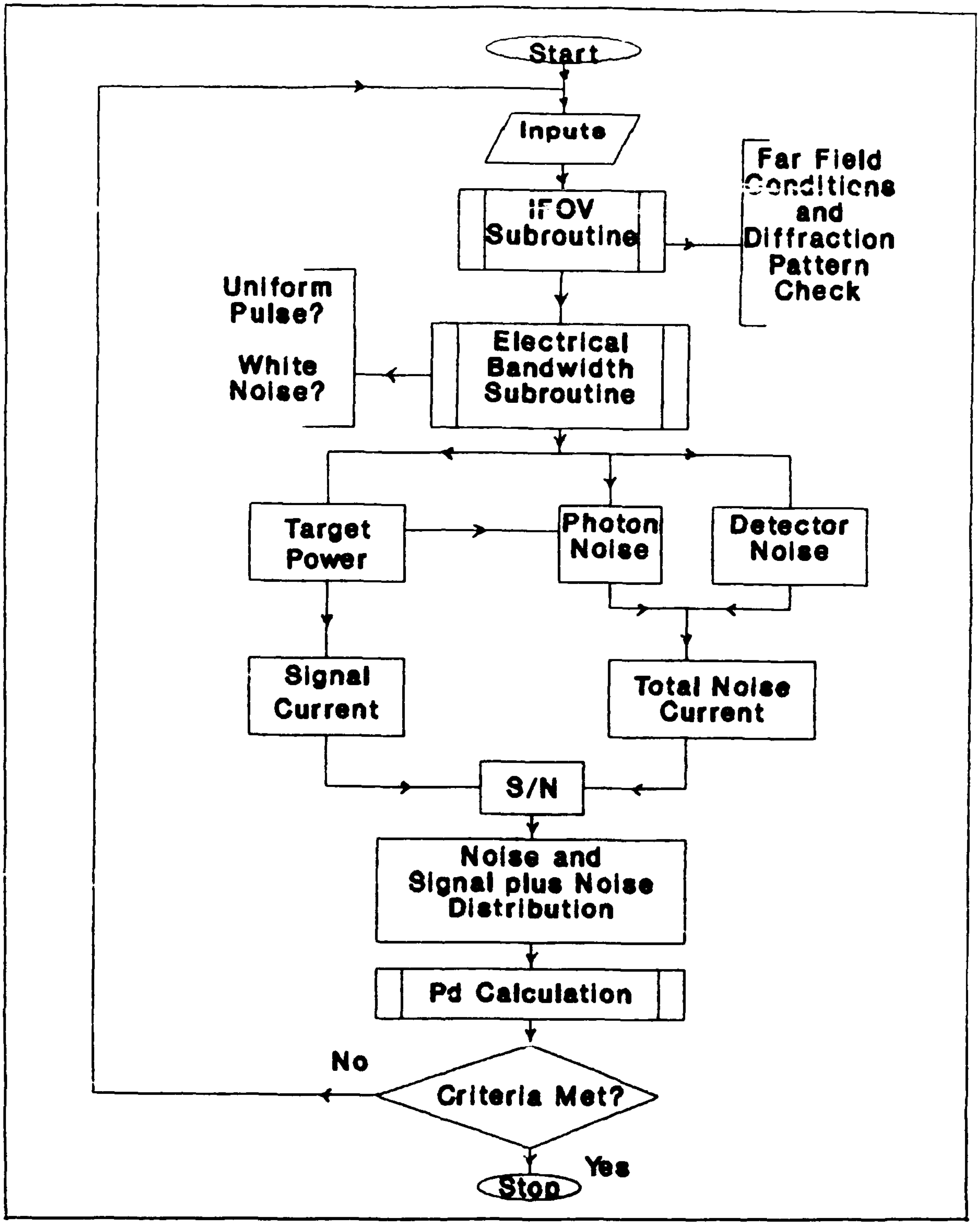

Fig. 5. Flowchart of IR System Design Model

an iterative process of meeting the desired performance capability within the constraints of technology. As seen in Figure 5, the subroutines appear linearly and the user is asked to redesign the system if the constraints or requirements are not met.

The first step in the model structure is to determine the IFOV for a given range. The IFOV has two purposes in the overall system design. First, the IFOV is used to determine the allowable dwell time. The larger the IFOV, the longer the dwell time possible for each IFOV. In turn, the allowable dwell time effects the noise effective electrical bandwidth of the filter for the detection system. The second purpose of finding the IFOV is to determine the area of the background the sensor views at any one time. This background area ultimately affects system noise. Two assumptions of the model are checked after finding the IFOV. First, the far field condition is checked to see if it is reasonable. Next, the area of the main peak of the diffraction pattern on the detector is also checked to make sure it is within the width of the detector. These conditions are discussed in the next section of this chapter.

The next subroutine determines the noise effective electrical bandwidth of the detector's filter. The signal to noise ratio of the current output of the detector is maximized by the use of a matched filter. The effective noise bandwidth is determined using the procedure discussed in Appendix A.

The next step in the model's structure is to determine the signal and noise currents entering the signal processing circuitry. The signal is a function of blackbody radiation and/or backscatter from an active source. The model assumes there are no active sources. Therefore, only blackbody (or graybody) radiation is considered. The peak signal from the target may be fluctuating about an average value, however, this only affects the signal plus noise statistics as discussed in Chapter II. The noise sources of interest are thermal noise, shot noise, GR noise, and photon noise depending on the type of detector (photovoltaic or photoconductive). The noise source's magnitudes are calculated separately and can be used to determine the dominant noise source. A system designer may use this information to reduce the noise in the detector output current.

Using the results for the signal and noise currents (magnitude and statistics) the probability of detection is calculated for the system design. The noise statistics from the previous calculations are used to determine a threshold for a specified false alarm rate. This threshold is used to determine the probability of detection given the signal plus noise statistics. If the resulting performance measurement does not meet the user's requirements, then the design process should be repeated for different input variables.

Assumptions and Constraints

The IR detection performance model in this study is not meant to be a comprehensive system design model. First, the mathematical model shows how the IR system parameters and scenario characteristics affect the signal and the noise. Second, the model shows how changes in signal and noise influence the predicted system performance. Ultimately, system performance will be discussed in terms of sensitivity to the signal and noise probability characteristics. The assumptions and constraints in the model provide the simplicity so that quick comparisons can be made for different systems and different operating environments. However, unless these assumptions and constraints are fully explained, the user may be misled about the usefulness of the model. The relationships used for the signal and noise characteristics are well documented (3:13-49). Other IR detection models use the same relationships for determining the signal to noise ratios (1:879-894). The model presented in this study relies on probability theory which is well documented (4:352-6). The equations used in the model-based computer program are documented in Appendix B. The constraints in using the equations in the computer simulation are presented below.

An initial constraint of the model is that atmospheric influences are not taken into account. The atmospheric conditions are important in terms of degraded system performance. Performance is decreased as range is increased depending on the atmospheric conditions. The resulting distribution of photons passing through the atmosphere to the detector is represented by a log-normal distribution (12:393-402). Therefore, atmospheric effects should be important to the system designer, because the resulting statistics of the signal and noise may change.

The model assumes a one element detector using staring or scanning for detection of a single target within a large search field. In the model used for an IR target detection system, it is assumed that the IFOV of the sensor is larger than the size of the target. Therefore, the background must be considered.

The target and sensor are assumed to have a specific geometry as shown in Figure 6.

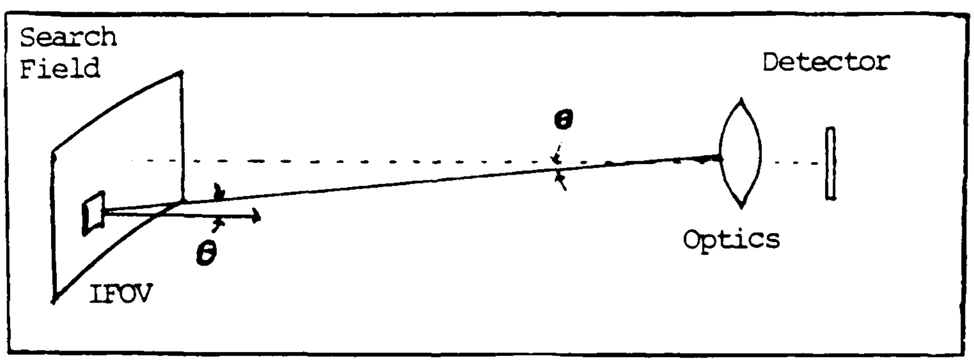

Fig. 6. Target and Sensor Geometry

As can be seen in Figure 6, the target and sensor are assumed to be on axis. In the relationships for power on the detector, (see Appendix B) the cosine θ term is assumed equal to one. However, the sensor will usually have to search a wide area to detect a target of interest. At an angle of 45 degrees the power from the IFOV will fall off by one fourth. The assumption of on-axis operation can easily be corrected by the user if appropriate.

The target is assumed to be in the far field of the detector. This assumption is usually reasonable because a detection system's goal is to detect a target at a long distance. The lens is assumed to be diffraction limited. Therefore, the effects of aberrations in the lens were neglected. These effects may affect the noise distribution in the system, if the aberrations affect the arrival of photons at the detector (12:400). Diffraction effects are also assumed to be negligible in the model. For this assumption to be accurate, the radius of the first half-power peak should be much less than the radius of the detector element.

In the model and the computer simulation, there are assumptions concerning the effective noise bandwidth of the filter used to maximize the signal to noise ratio. There are two assumptions in deriving the relationship for bandwidth as a function of dwell time. First, the optical input to the detector is assumed to be a rectangular pulse of width equal to the dwell time. The second assumption is that the noise in the detector electrical current is white

Gaussian noise. The model and noise theory presented in this report does not examine 1/f noise. The 1/f noise dominates at the lower electrical frequencies. Therefore, when selecting narrow electrical bandwidths, the white noise assumption is probably incorrect. Non-white is also likely when there is more than one source of noise. The method of handling the non-white noise case is discussed in Appendix A. The model used in this report ensures that the dwell time is at least ten times as long as the response time of the detector. There is a twofold reason for using this constraint. The frequency response of a detector is shown in Figure 7. The frequency response of the detector remains constant over a wide range of frequencies up to a cut-off frequency, f_c. The cut-off frequency is related to the rise time, T, by $f_c = 0.35/T$ (3:112). It is desirable to have a flat frequency response for both the noise and signal to assume a rectangular pulse input and white noise. These assumptions are met in the model by constraining the dwell

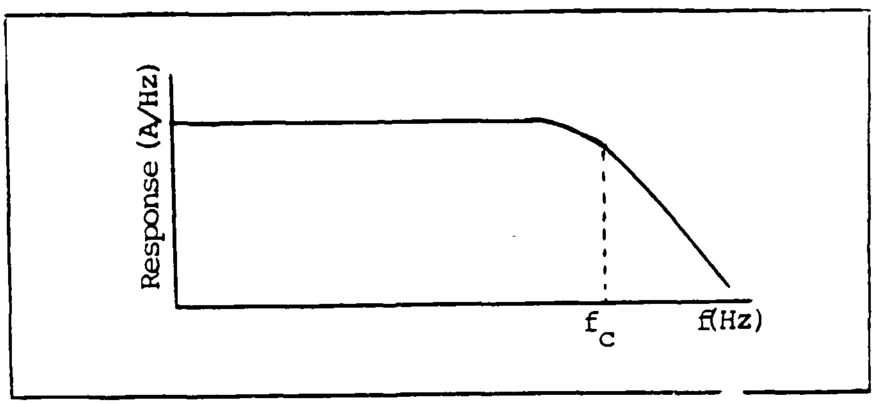

Fig. 7. Electrical Frequency Response of Detector (6:99)

time to greater than ten times the rise time of the detector (10:1583-1584). This insures the electrical bandwidth is less than the cut-off frequency of the detector. If a fast response detector or a long enough dwell time is possible, then the rectangular pulse input is a good assumption. Genoud and Seyrafi use a visibility factor to optimize the signal to noise ratio for cases where the dwell time is less than the response time of the detector (10:1583;18:322-323). However, this factor is not included in the model.

The final assumption is that the background emissivity and temperature can be represented by average values. In reality the sensor will be looking at a background that is non-uniform. Therefore, as the IFOV decreases (resolution increases) the aspect of clutter becomes more significant as a source of noise. The clutter effects will be assumed negligible in this model. Because the target is important for determining the signal to noise ratio, it is beneficial to know something more about the properties of the target. The temperature will again be assumed an average temperature, but it will be necessary to consider if the target has a fluctuating amplitude or can be considered constant in temperature (22:1330). Knowing the target characteristics will help determine the type of statistics which should be used in the probability of detection subroutine.

The model can be expanded for the multi-element case. The main effect is on either the IFOV and/or the electrical bandwidth, which ultimately effect the signal to noise ratio. Further, the multi-element sensor can be used as an imaging system if the resolution is good enough. The difference between imaging and detection is a function of the resolution. An imaging system has a higher quality of resolution so that the target fills more than one pixel (instantaneous field of view). An imaging system gives the user more information about the target and hence can also be used for target recognition. The effects of clutter must also be taken into account. Infrared imaging and recognition is beyond the scope of this study.

Computer Simulation of the Model

In order to utilize the model outlined in the previous section, a computer program was written for use on MathCAD 2.0 or 2.5. The computer program is discussed in the following material. The computer program is found in Appendix B and contains descriptions for the equations used in modeling an IR detection system.

The MathCAD program runs in a linear fashion and no loops are available in the program. Therefore, the user is only notified of assumptions not met by the input data.

The program begins by listing the inputs which the user can vary. The inputs are broken down into scenario dependent variables and sensor dependent variables. The

IFOV subroutine is performed next. After the IFOV is found, three conditions are checked. First, the IFOV is checked to see if it is greater than the area of the target. The program also checks the far field assumption and the assumption that the main peak of the diffraction pattern is within the radius of the detector. The program only checks these constraints. It does not add special factors to account for cases where the assumptions do not hold.

Next, the program determines the effective noise bandwidth. The first step is to find the maximum allowable dwell time on the target. The dwell time is a function of the area to be searched, the IFOV of the sensor, the velocity of the target, and the range to the target. The program uses the standard relationship between bandwidth and dwell time $\Delta f = 1/2\tau$. However, as mentioned in the constraints this condition only holds for a rectangular input pulse and white Gaussian noise.

The next subroutine in the program determines the signal and noise current. Standard relationships for blackbody radiance and detector theory are applied. The noise is calculated for Johnson noise, dark current noise and photon noise. The program can handle either photovoltaic or photoconductive detectors. A total noise current is calculated from the individual noise current results.

The probability of detection subroutine first determines the signal to noise ratio. It is up to the user to select the proper statistical routine for determining a threshold and probability of detection. There are three separate routines included in the documentation. These routines are for the constant signal in Gaussian noise case, the photoelectron-counting case, and the fluctuating signal in the Gaussian noise case. The output of the computer program is in terms of the probability of detection versus the S/N ratio and the probability of detection versus range. The next chapter of this report will examine the output of the computer model for three different scenarios.

IV. Signal and Noise Sensitivity Analysis

Introduction

Different sources of signal and noise affect the performance of an IR detection system. Typically, the S/N ratio is used to predict system performance. The higher the S/N ratio, the better an IR detection system will perform. Further analysis of the signal and noise characteristics in terms of statistical distributions provides a more accurate measurement of system performance. The analysis presented in this chapter compares the effects of different signal and noise distribution characteristics on the probability of detection performance. This chapter is broken down into three cases. The first case considers a constant signal from the target and Gaussian detector noise. The resulting signal plus noise distribution will also be Gaussian. The second case is concerned with a signal limited noise condition. The noise is dominated by the photon induced shot noise due to the incoming signal. The signal is considered to be constant. The distributions of the noise and signal plus noise are Poisson. The third case is concerned with a Gaussian noise source and a fluctuating signal from the target. The signal has a negative exponential distribution. The resulting signal plus noise distribution is the joint density in Eq (32) presented in Chapter II. Each of these cases is compared in terms of the probability of detection versus the S/N ratio of the IR detection system. The IR system model explained in chapter III is used to provide the data for analysis.

Constant Target Signal in Gaussian Noise Case

The first case to be examined is a detector receiving a constant signal in the presence of Gaussian noise. This condition is prevalent for many active and passive IR detection systems. The case applies to any incoherent detector whose electrical output noise is determined either by the circuit thermal noise, dark current shot (or GR) noise, or shot noise with a large number (greater than 100) of incident photons during the dwell time. The cases for Gaussian distributed noise coming from the detector are dominant in most system designs. The signal from the target is considered to be constant in this scenario. Therefore, the target is not causing scintillations (fluctuations) in the signal current either because of backscatter or because of inherent shape features. The resulting signal plus noise distribution is also Gaussian. Given this information about the probability distribution of the noise and the signal plus noise, the computer simulation was performed for a given IR detection system.

Typical scene and detector parameters were input into the MathCAD template. These inputs are shown in Appendix C. The range was varied between 60 and 108 km at 4 km intervals. False alarm rates of 1 and 10 per hour were used in the scenario. The resulting probability of detection versus S/N ratio is shown in Figure 8. As can be seen in Figure 8, the probability of detection approaches 100 percent rapidly as the S/N ratio increases. The results for varying the false alarm rate match the predicted performance; the probability of detection increases as probability of false alarm increases. Before analyzing the results any further, the other scenarios will be presented.

Photoelectron-Counting Case

In the case of signal- or background noise-limited detection, it may be necessary to perform the detection process by counting the number of individual pulses obtained during the measurement interval, τ. The photoelectron counting case usually holds for a small number of photoevents (less than 100) during the time interval, τ (16:118). The most likely scenario for these types of conditions are for a very low noise detector and a very cold background such as space. The most likely application is using a laser radar which reflects off a target but not off the background (11:1688). While these conditions are stringent, the photoelectron-counting case does provide interesting results for comparison to other scenarios. The inputs to the model are shown in Appendix C. It should be noted that the limiting case of the noise is caused by the signal. The noise in this case is photon induced shot noise. Because the signal is from the target is constant,

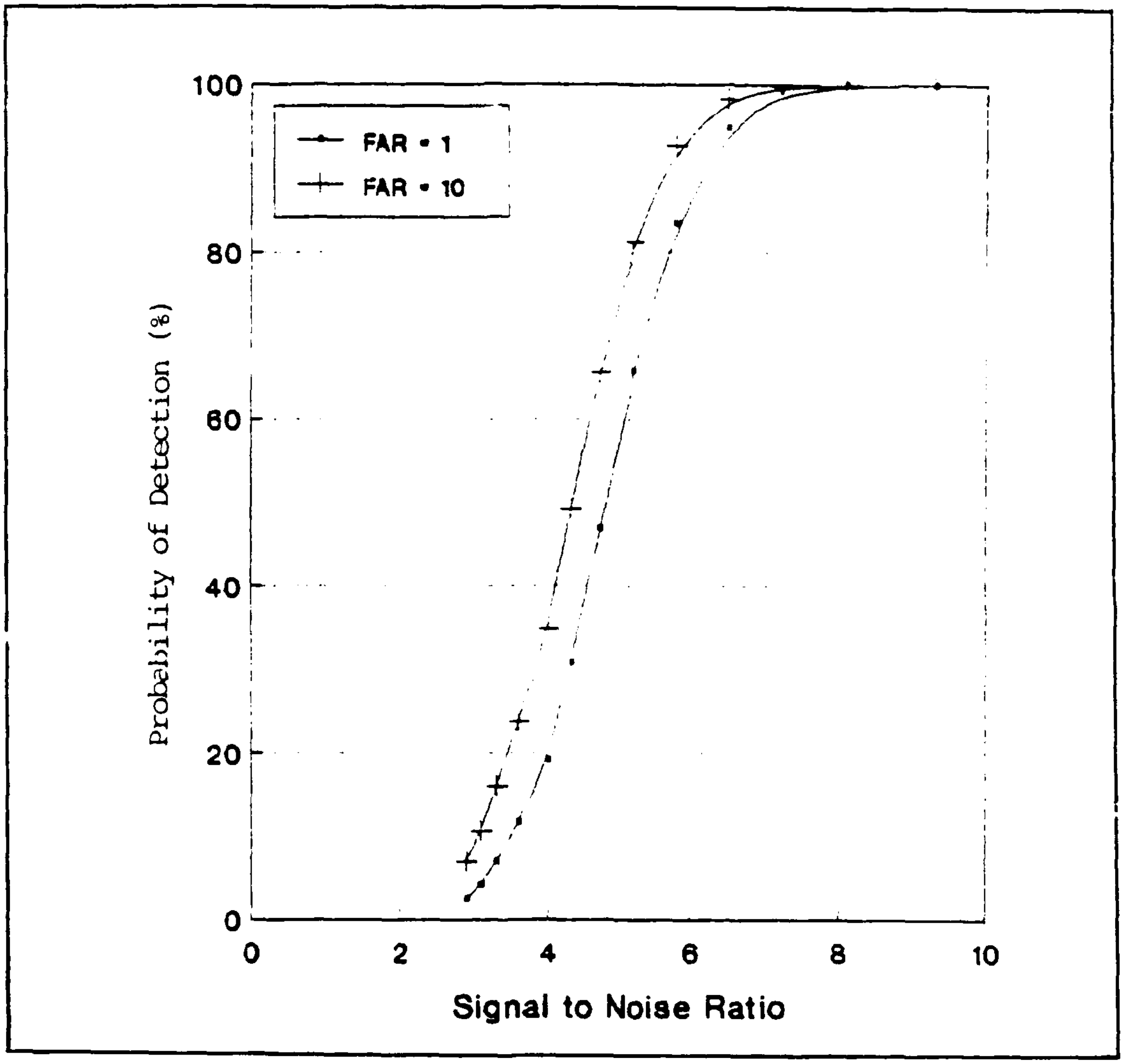

Fig. 8. Pd vs. S/N

(Constant Signal and Gaussian Noise Case)

FAR = False Alarm Rate

the noise and signal plus noise distribution are considered to be Poisson. Figure 9 shows the resulting probability of detection versus S/N ratio for this system design. As in the first case, the S/N ratio is varied by changing the range. The results show that the probability of detection again increases as the S/N ratio increases. These results will be compared to the other results in the last section of this chapter. Goodman's paper, "Some Effects of Target-Induced Scintillation on Optical Radar Performance," presents results for a scintillating target using photon noise statistics as developed in Chapter II (11:1688:1700). The reader is referred to this paper for a comparison of probability of detection between a scintillating target and a smooth or specular target.

<u>Fluctuating Target Signal in Gaussian Noise Case</u>

The final case considers a fluctuating target creating a signal with a negative exponential distribution. The signal plus noise probability distribution is represented by Eq (32). The noise is Gaussian and so the threshold is selected using the same relationship as the first case. The sensor and scenario inputs are the same as the constant target case and are presented in Appendix C. It is assumed that the same average power is emitted by the target even though its amplitude is fluctuating. Figure 10 shows the results for probability of detection versus S/N ratio. As in the previous examples, the range was varied to change the

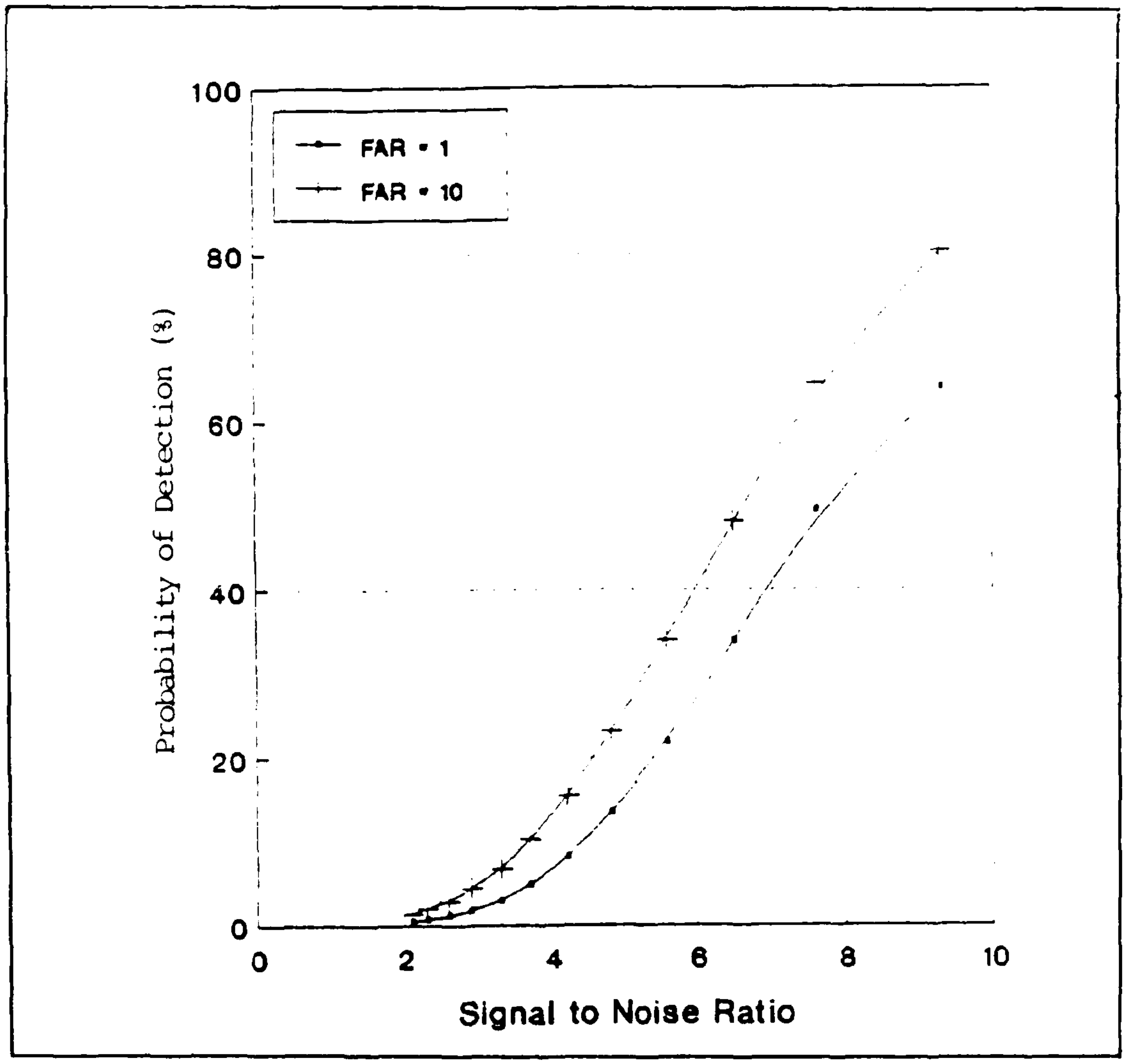

Fig. 9. Pd vs. S/N

(Photoelectron-Counting Case)

FAR = False Alarm Rate

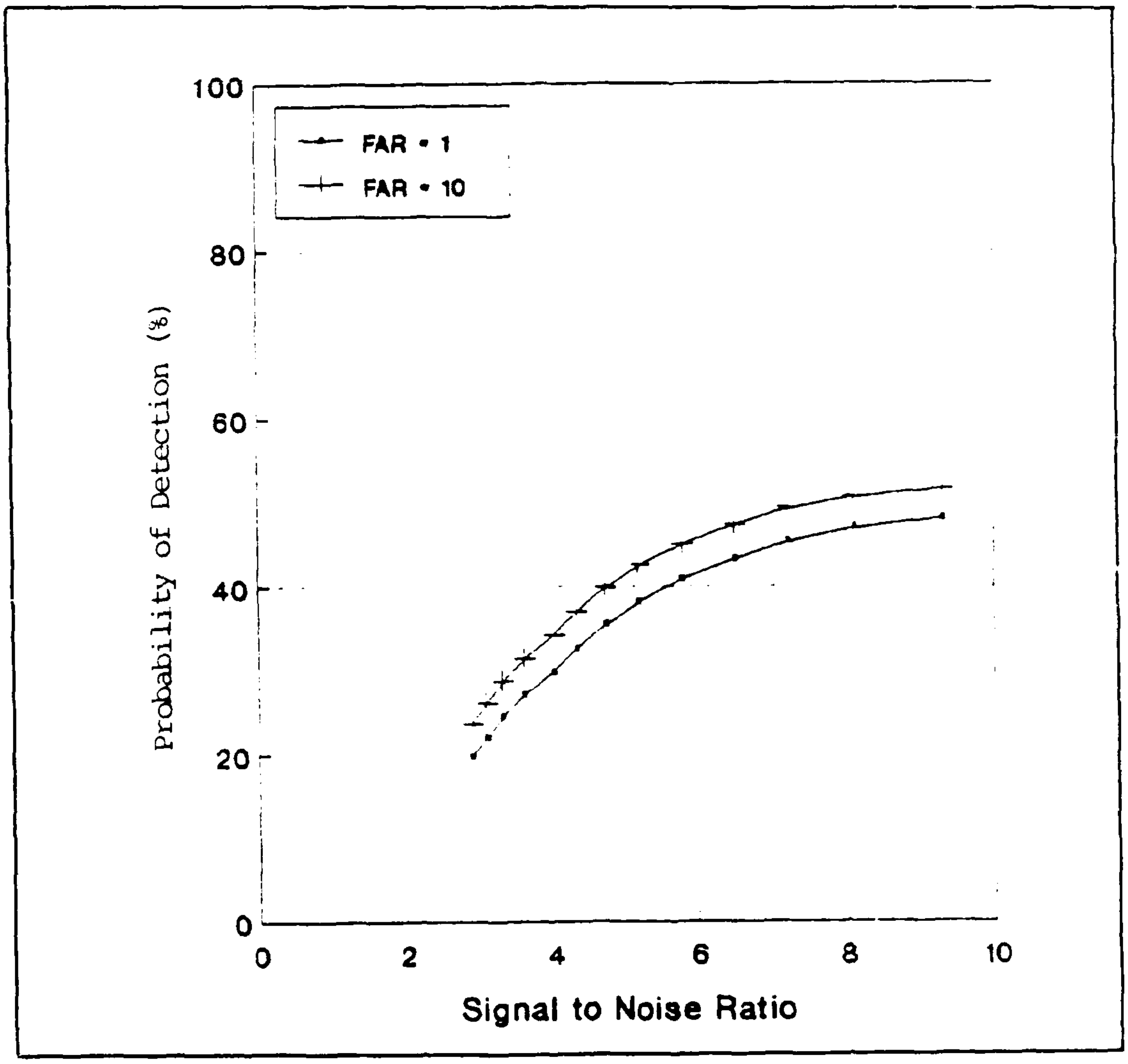

Fig. 10. Pd vs. S/N

(Fluctuating Target and Gaussian Noise Case)

FAR = False Alarm Rate

signal to noise ratio. Again the results show that the probability of detection increases as the signal to noise ratio increases. However, there are some noticeable differences from the first two cases. These differences will be explained in the next section.

Analysis of Results

Figure 11 is a composite graph of the three cases probability of detection versus signal to noise ratio for a false alarm rate equal to one per hour. As can be seen in this figure, there are similarities and differences in the probabilities of detection for each of the three cases. Each of the cases shows that the probability of detection increases with increasing signal to noise ratio. However, the graph also shows that the rates of increase are different for each case. This is a function of the signal plus noise distributions used in each case. The greatest rate of increase in probability of detection is in the Gaussian noise/constant signal case. However, the probability of detection also falls off fastest for this case, which can be a drawback if the design just meets performance requirements.

The photoelectron-counting case has a probability of detection curve in between the other two case. In fact, the constant signal versus fluctuating signal case represent the two extremes of system performance. A likely scenario is

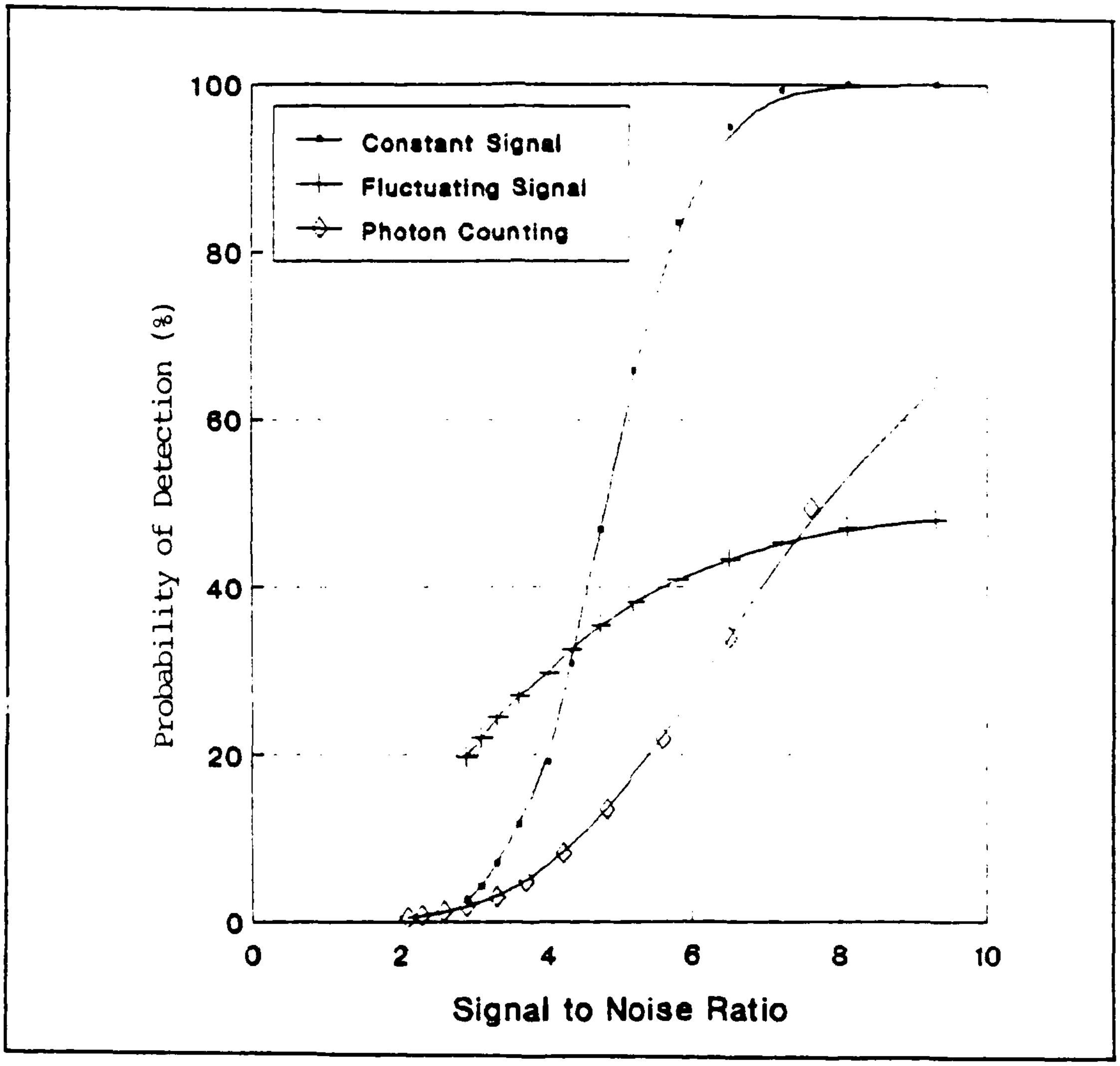

Fig. 11. Pd vs. S/N

(Comparison of Different Cases)

for the target signal to have varying degrees of fluctuation.

The fluctuating target signal case presents some interesting results. As can be seen the probability of detection does not approach 100 percent rapidly. Therefore, the system designer must provide a much higher signal to noise ratio to obtain a high probability of detection. The fluctuating signal results also show that for low S/N ratios a higher probability of detection is obtained. This is explained by Goodman and Stirling as being caused by the amplitude fluctuations. At low S/N ratios the fluctuations cause signal spikes which help the probability of detection. However, at high S/N ratios the converse is true and the probability of detection is less than the constant signal case.

The results show that different system performance is obtained depending on the signal and noise magnitude and statistics. The next chapter presents conclusions from this analysis and recommendations for further study.

V. Conclusions and Recommendations

Conclusions

Analytical models are always approximations to an actual system design because assumptions are made in developing the relationships between the scenario and the system. One assumption is that an IR system's detection performance can be measured in terms of its output S/N ratio. The S/N ratio describes the ratio of the magnitude of the signal to the magnitude of the noise. This study expanded on the signal to noise relationship by examining the statistical properties of the signal and the noise.

Different sources of the signal and noise were identified and the magnitude and statistical properties were characterized. The noise is usually characterized by a Gaussian probability distribution. If the signal or background photon limited noise case exists and there are less than 100 photons impinging on the detector during a given dwell time, then the noise is Poisson distributed (Bose-Einstein distribution for a fluctuating target or background). The signal plus noise distribution is also of interest to the system designer. If the signal is constant, then the probability distribution of the signal plus noise is the same as the distribution of the noise. However, if the signal is fluctuating, then a joint probability distribution exists. This distribution is a combination of negative exponential and Gaussian distributions and was represented by Eq (32) in the report.

Three different cases were examined to determine the effects of the signal and noise statistical properties on the performance of an IR detection system. The results show that an accurate system design model requires reliable representations of the signal to noise ratio as well as the actual distributions of the signal and noise.

Recommendations

The results presented in this study show how an IR detection system's signal and noise sources can be modeled. However, there were still numerous assumptions made in the report concerning the scenario and the type of detection system. Therefore, the accuracy of the analytical model used in this report can be improved if the model is expanded for a wider range of scenarios and system parameters. Areas where further work is necessary are identified below. Questions concerning effects on signal and noise characteristics are also provided.

1. **Atmospheric effects. What are the effects on the signal and noise in terms of magnitude and statistical distribution?**

2. **1/f noise. How** does 1/f noise affect the matched filter design and determination of effective noise bandwidth? What are the effects on signal and noise magnitudes and noise distribution?

3. Background clutter. What are the effects of background clutter on the mean amplitude of the noise current? How is the detection threshold level selected for a varying

mean noise current? Does the mean noise current have a statistical distribution associated with it?

4. Signal processing and amplifier noise. What are the effects of amplifier noise on the determination of noise effective bandwidth? What are the effects of signal processing noise on the selection of a detection threshold?

5. Scanning detection system. What are the effects of scanning on the signal and noise in terms of magnitude and probability distribution?

6. Focal plane arrays. What other noise sources must be addressed with the use of a focal plane array?

7. Laser source for active target detection. How does an active source change the characteristics of the signal (incoherent or coherent mode)?

8. IR imaging systems. Can a model be developed to predict the probability of target recognition given an IR imaging system and a known target recognizer (human or machine)? The same approach used to develop the target detection model is recommended, however, a model for the target recognition process would have to be developed in terms of signal and noise statistics.

One method for addressing the above recommendations is to identify and define all the variables in the scenario and IR system before developing the IR detection (or imaging) system analytical model. By identifying and defining the system and scenario up front, there is a greater probability that possible factors which may affect system performance will be addressed in the model. After the given scenario is modeled, then more variables can be added to the model to make the model more generic. The ultimate goal is to expand the model one piece at a time until all the important design considerations are identified for either an IR detection or imaging system.

Appendix A: Noise Effective Electrical Bandwidth

North developed a theory of optimum filters based on maximizing the signal to noise (S/N) ratio. The central result in North's theory is that for white Gaussian noise the S/N ratio is maximized by a filter whose impulse response has a form of the signal to be detected (26:1223). The term matched filter came from this theory. As an example of determining the effective noise electrical bandwidth, a constant received pulse over the time interval τ is assumed. The matched filter in this case has the amplitude versus frequency form of $(\sin \pi f\tau)/\pi f\tau$, where f is the electrical frequency. The effective noise bandwidth is defined as the area under a constant amplitude noise power spectrum (white noise condition) equal to the total area of the filter's power spectrum as shown in Figure 12 (19:146-8).

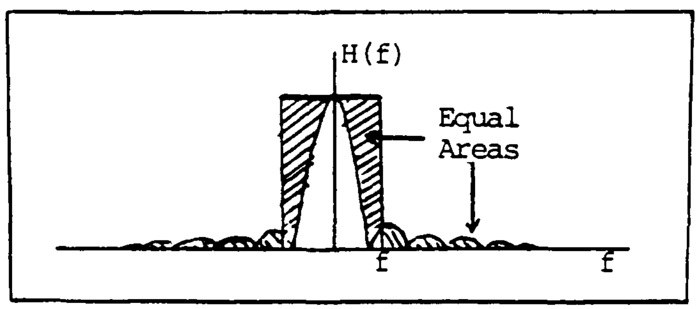

Fig. 12. Noise Effective Bandwidth

The relationship for noise effective bandwidth, Δf is:

$$\Delta f = \int_0^\infty |H(f)|^2 \, df \; / \; \max \, [H(f)] \qquad (33)$$

where H(f) is the filter transfer function.

By substituting for the matched filter's power spectral density for the white noise rectangular pulse case, the relationship between bandwidth and the time constant is:

$$\Delta f = \int_0^\infty (\sin \pi f \tau \; / \; \pi f \tau)^2 df = 1/2\tau \qquad (22)$$

This relationship gives the maximum signal to noise ratio assuming white Gaussian noise and a rectangular signal pulse. In actual system design, the noise spectrum of the detector may not be white and the signal energy coming from the detector may not be a rectangular pulse.

Using the above relationship between electrical bandwidth and dwell time may result in predicting a different signal to noise ratio than is actually achieved (2:1189). The solution to finding an optimum filter for non-white noise and/or non-rectangular signal requires knowledge of the signal energy and noise power spectrum characteristics. The optimum filter transfer function is:

$$H(f) = S^*(f)/N(f) \qquad (34)$$

where

$S^*(f)$ = complex conjugate of the signal energy spectrum
$N(f)$ = noise power spectrum (13:108)

The noise effective bandwidth of the matched filter is found by applying Eq (33).

Appendix B: MathCAD Computer Program

RADIOMETRIC SYSTEM DESIGN PROGRAM

This MathCAD program is to be used as a design aid for predicting the perfomance of a passive infrared search system. Performance will be measured in terms of probability of detection. Four subroutines are used to determine system performance. First, the IFOV is calculated. Then the electrical bandwidth is selected. Next, the signal and noise currents are determined. Finally, the S/N ratio and the probability of detection are calculated. The user inputs scenario and system characteristics below.

THE INPUTS TO THE MODEL ARE:	ENTER YOUR INPUTS HERE:
SCENARIO	
AZ, Azimuth Search Angle (deg)	$AZ := 90$
EL, Elevation Search Angle (deg)	$EL := 20$
R, Range (km)	$R := 100$
At, Area of Target (m^2)	$At := 1.5$
Tt, Temperature of Target (K)	$Tt := 450$
ϵt, Emissivity of Target	$\epsilon t := 1$
vt, Velocity of Target (m/s)	$vt := 300$
Tb, Temperature of Background (K)	$Tb := 300$
ϵb, Emissivity of Background	$\epsilon b := 1$
SENSOR	
Do, Diameter of Optics (cm)	$Do := 10$
f, Focal Length of Optics (cm)	$f := 10$
DT, Detector Type (1=photovoltaic) (2=photoconductor)	$DT := 1$
Ad, Area of Detector (cm^2)	$Ad := 1$
$\lambda 1$, Lower Spectral Wavelength (μm)	$\lambda 1 := 3$
$\lambda 2$, Upper Spectral Wavelength (μm)	$\lambda 2 := 5$
η, Quantum Efficiency	$\eta := .75$
Td, Temperature of Detector (K)	$Td := 77$
Rd, Detector Resistance (Ω)	$Rd := 1 \cdot 10^{6}$
G, Gain of Detector, (Photoconductor only)	$G := 1$
iD, Dark Current, (amperes)	$iD := 75 \cdot 10^{-9}$
τ, Response Time, (seconds)	$\tau := 2.5 \cdot 10^{-4}$
FAR, False Alarm Rate (#/hr)	$FAR := 5$

INSTANTANEOUS FIELD OF VIEW SUBROUTINE
(Determines Sensor Field of View)

The detector and optics combination is assumed to have a planar field of view.

The IFOV of the optics and the detector is calculated:

$$As(R) := \frac{Ad \cdot \left[R \cdot 10^{3}\right]^{2}}{f^{2}}$$

The IFOV is in terms of m^2

If the IFOV is smaller than the area of the target, then the power incident from the target is a function of the IFOV and not the area of the target.

$$At(R) := \mathrm{if}(At > As(R), As(R), At)$$

The far field assumption is checked:

$$FARFIELD(R) := \mathrm{if}\left[\left[R \cdot 10^{3}\right]^{2} > 100 \cdot At(R), \mathrm{if}\left[R \cdot 10^{3} > 100 \cdot Do, 1, 2\right], 2\right]$$

The peak of the diffration pattern is checked to see if it is within the area of the detector:

$$MAINPEAK := \mathrm{if}\left[\frac{2.44 \cdot f \cdot \lambda 1 \cdot 10^{-6}}{Do} < \frac{\sqrt{Ad}}{2}, 1, 2\right]$$

1 means **assumptions** hold.
2 means **assumptions** do not hold.

Assumption Checks:

FARFIELD(R) = 1
MAINPEAK = 1

BANDWIDTH SELECTION SUBROUTINE
(Determines electrical bandwidth
as a function of dwell time.)

To maximize the signal to noise ratio an electrical bandwidth is selected. The bandwidth is a function of the detector response time and the available dwell time.

The frame time is calculated for the given azimuth expanse and elevation expanse. The smaller of these two numbers is chosen as the frame time. This insures the target does not pass through the search area before the sensor is able to scan the search area (18:251-253).

$$rad := \frac{\pi}{180}$$ Degree to radian conversion

Azimuth frame time

$$tfa(R) := \frac{R \cdot 10^{3} \cdot AZ \cdot rad}{2 \cdot vt}$$

Elevation frame time

$$tfe(R) := \frac{R \cdot 10^{3} \cdot EL \cdot rad}{2 \cdot vt}$$

$tf(R) := if(tfe(R) < tfa(R), tfe(R), tfa(R))$ FRAME TIME

The dwell time is determined by dividing the frame time by the number of resolution elements. An overlap of four is included for complete coverage. (18:252)

$$td(R) := \frac{tf(R) \cdot As(R)}{16 \cdot \left[R \cdot 10^{3}\right]^{2} \cdot \tan\left[\frac{AZ}{2}\right] \cdot \tan\left[\frac{EL}{2}\right]}$$

DWELL TIME

$td(R) = 0.034623$ sec

The dwell time is compared to the detector response time. If the dwell time is less than 10 times the detector response time the bandwidth selection criteria do not hold (10:1583). The program will still calculate a bandwidth.

$tr(R) := if(td(R) > 10 \cdot \tau, td(R), 10 \cdot \tau)$

The bandwidth is:

$BW := if(td(R) \geq 10 \cdot \tau, 1, 2)$

$$B(R) := \frac{1}{2 \cdot tr(R)}$$

$BW = 1$ 1 assumption holds
2 doesn't hold

SELECTED BANDWIDTH $B(R) = 14.44127$ Hz

SIGNAL AND NOISE CURRENT SUBROUTINE
(Determines signal and noise current)

The signal and noise current are calculated using blackbody radiance theory and detector theory. The following constants are necessary:

$k \equiv 1.38 \cdot 10^{-23}$ W-sec/K $\qquad$ $h \equiv 6.626 \cdot 10^{-34}$ W-sec^2

$c \equiv 3 \cdot 10^{8}$ m/s $\qquad$ $q \equiv 1.6 \cdot 10^{-19}$ Coulombs

BLACKBODY RADIANCE EXPRESSION (3:54)

$$L(\lambda) := \int_{\lambda 1}^{\lambda 2} \frac{C1}{\lambda^{5} \cdot \left[\exp\left[\frac{C2}{\lambda \cdot T}\right] - 1\right]} d\lambda$$

C1 and C2 are constants:

$C1 \equiv 1.910 \cdot 10^{4}$ in W-μ^4 /cm^2-sr

$C2 \equiv 1.4388 \cdot 10^{4}$ in μ-K

POWER INCIDENT ON DETECTOR

$$Pd := To \cdot Ta \cdot \int_{As} \int_{Ar} \epsilon \cdot L(\lambda) \cdot \frac{(\cos\theta s)^{4}}{R^{2}} dAr\, dAs$$

Where To and Ta are transmission coefficients and assumed to be one. The far field condition sets the orientation angle θs to zero. Ar is the area of the optics and As is the area of the target or background. These remain constant over the integral.

The two previous expressions will be used to calculate the blackbody radiation power impinging on the detector from the target and the background.

The folowing expression is for peak signal current:

Signal Current $$s1 := \frac{\eta \cdot q \cdot Ps \cdot \lambda}{h \cdot c}$$

The signal current is a function of spectral wavelength, and an integration is performed over the spectral range.

Signal for Photovoltaic Detector:

$$s1(R) := \frac{\eta \cdot \pi \cdot Do^{2} \cdot \epsilon t \cdot At(R)}{4 \cdot \left[R \cdot 10^{3}\right]^{2}} \cdot \int_{\lambda 1}^{\lambda 2} \frac{q \cdot C3}{\lambda^{4} \cdot \left[\exp\left[\frac{C2}{\lambda \cdot Tt}\right] - 1\right]} \, d\lambda$$

$C3 \equiv 5.9915 \cdot 10^{22}$ replaces C1 and h*c^-1

Signal for Photoconductive Detector

$s2(R) := G \cdot s1(R)$

The following are the expressions for rms noise currents:

	PHOTOVOLTAIC DETECTOR	PHOTOCONDUCTIVE DETECTOR
Johnson Noise	$jn(R) := \frac{4 \cdot k \cdot Td \cdot B(R)}{Rd}$	"
Dark Current Shot Noise	$sn(R) := 2 \cdot q \cdot iD \cdot B(R)$	$grn(R) := 4 \cdot q \cdot G \cdot iD \cdot B(R)$

Photon Noise $$pn1 := \frac{2 \cdot \eta \cdot q^{2} \cdot (Ps + Pb) \cdot B \cdot \lambda}{h \cdot c}$$

Because the photon noise is a function of the spectral band it will need to be integrated with respect to the blackbody radiance.

Photon Noise for Photovoltaic Detector:

$$BBR := \int_{\lambda 1}^{\lambda 2} \frac{q \cdot C3}{\lambda^{4} \cdot \left[\exp\left[\frac{C2}{\lambda \cdot Tb} \right] - 1 \right]} \, d\lambda$$ Background Radiation

$$pn1(R) := 2 \cdot q \cdot B(R) \cdot \left[s1(R) + \left[\frac{\eta \cdot \pi \cdot Do^{2} \cdot \epsilon b \cdot (As(R) - At(R))}{4 \cdot \left[R \cdot 10^{3} \right]^{2}} \cdot BBR \right] \right]$$

Photon Noise for Photoconductive Detector:

$$pn2(R) := 2 \cdot G^{2} \cdot pn1(R)$$

Total Noise Current:

Photovoltaic:

$$n1(R) := \sqrt{jn(R) + sn(R) + pn1(R)}$$

Photoconductive:

$$n2(R) := \sqrt{jn(R) + grn(R) + pn2(R)}$$

If the detector is a photovoltaic type, use n1; if it is a photoconductive type, use n2 for the noise current.

n(R) := **if(DT < 2,n1(R)**,n2(R))

TOTAL NOISE CURRENT $n(R) = 4.266939 \cdot 10^{-11}$ amps

If the detector is a photovoltaic type, use s1; if it is a photoconductive type, use s2 for the signal current.

s(R) := if(DT < 2,s1(R),s2(R))

SIGNAL CURRENT $s(R) = 2.32861 \cdot 10^{-10}$ amps

PROBABILITY OF DETECTION SUBROUTINE
(Determines S/N and Pd)

This subroutine assumes the noise and signal plus noise have a Gaussian distribution. Probability theory is used to determine the probability of detection from the given false alarm rate.

$$snr(R) := \frac{s(R)}{n(R)}$$ Signal to noise ratio

The threshold is selected based on the given false alarm rate.

$n := 1$

A desired probability of false alarm is found given the false alarm rate.

$$Pf(R) := \frac{FAR}{7200 \cdot B(R)} \qquad TOL \equiv 10^{-12}$$

$$Pfa := \frac{1}{\sqrt{2 \cdot \pi \cdot n}} \cdot \int_{T}^{\infty} \exp\left[\frac{-i^2}{2 \cdot n^2}\right] di$$ The threshold, T, is selected by evaluating the Gaussian distribution to the left.

$$g(n) := .5 \cdot \left[1 - \text{erf}\left[\frac{n}{\sqrt{2}}\right]\right] - Pf(R)$$ The Gaussian is evaluated using the erf(x) on MathCAD.

$t(R) := \text{root}(g(n), n)$ The threshold is found by using the root function.

The probability of detection is found using the erf(x) and the known S/N and threshold for detection:

$$d(R) := .5 \cdot \left[1 - \text{erf}\left[\frac{t(R) - snr(R)}{\sqrt{2}}\right]\right]$$

RANGE	SIGNAL TO NOISE RATIO	PROBABILITY OF DETECTION
R = 100	snr(R) = 5.45733	d(R) = 0.940287

PROBABILITY OF DETECTION SUBROUTINE
(Determines S/N and Pd for Photoelectron Counting Case)

This subroutine assumes the noise and signal plus noise have a Poisson distribution. Probability theory is used to determine the probability of detection from the given false alarm rate.

$$snr(R) := \frac{s(R)}{n(R)}$$ Signal to noise ratio

The threshold is selected based on the given false alarm rate.

$n := 1$

A desired probability of false alarm is found given the false alarm rate.

$$pf(R) := \frac{FAR}{7200 \cdot B(R)} \qquad TOL \equiv 10^{-12}$$

A decision table is used to find the threshold for detection:

$$t := if\left[pf(R) > 10^{-1}, 2, if\left[pf(R) > 10^{-2}, 4, if\left[pf(R) > 10^{-3}, 5, 6\right]\right]\right]$$

$$t := if\left[pf(R) > 10^{-4}, t, if\left[pf(R) > 10^{-6}, 8, if\left[pf(R) > 10^{-7}, 9, 10\right]\right]\right]$$

$$t := if\left[pf(R) > 10^{-8}, t, if\left[pf(R) > 10^{-10}, 11, 12\right]\right]$$

The probability of detection is found using the Poisson distribution and the known S/N and threshold for detection:

$k := t, t + 1 \,..\, 20$

$$d(R) := \sum_{k} (snr(R) + n)^{k} \cdot \frac{\exp(-n - snr(R))}{k!}$$

PROBABILITY OF DETECTION SUBROUTINE
(Determines S/N and Pd for Gaussian Noise and Fluctuating Target)

This subroutine assumes the noise has a Gaussian distribution. The signal plus noise has the joint distribution given below. Probability theory is used to determine the probability of detection from the given false alarm rate.

$$snr(R) := \frac{s(R)}{n(R)}$$

Signal to noise ratio

The threshold is selected based on the given false alarm rate.

A desired probability of false alarm is found given the false alarm rate.

$$Pf(R) := \frac{FAR}{7200 \cdot B(R)} \qquad n := 1 \qquad TOL \equiv 10^{-12}$$

$$Pfa := \frac{1}{\sqrt{2 \cdot \pi \cdot n}} \cdot \int_{T}^{\infty} \exp\left[\frac{-i^{2}}{2 \cdot n^{2}}\right] di$$

The threshold, T, is selected by evaluating the Gaussian distribution to the left.

$$g(n) := .5 \cdot \left[1 - \operatorname{erf}\left[\frac{n}{\sqrt{2}}\right]\right] - Pf(R)$$

The Gaussian is evaluated using the erf(x) on MathCAD.

$$t(R) := root(g(n), n)$$

The threshold is found by using the root function.

The probability of detection is using the known S/N and threshold for detection:

$$f(R) := \int_{t(R)}^{100} \int_{0}^{100} \exp\left[\left[\frac{-w}{snr(R)}\right] + \left[\frac{-(i - w)^{2}}{2}\right]\right] dw\, di$$

$$d(R) := \frac{1}{\sqrt{2 \cdot \pi \cdot snr(R)}} \cdot f(R)$$

Probability of Detection

Appendix C: Scenario Inputs

(Constant Signal and Gaussian Noise)
(Fluctuating Signal and Gaussian Noise)

THE INPUTS TO THE MODEL ARE:	ENTER YOUR INPUTS HERE:
SCENARIO	
AZ, Azimuth Search Angle (deg)	AZ := 90
EL, Elevation Search Angle (deg)	EL := 20
R, Range (km)	R := 60,64 ..108
At, Area of Target (m^2)	At := 1.5
Tt, Temperature of Target (K)	Tt := 400
ϵt, Emissivity of Target	$\epsilon t := 1$
vt, Velocity of Target (m/s)	vt := 300
Tb, Temperature of Background (K)	Tb := 225
ϵb, Emissivity of Background	$\epsilon b := 1$
SENSOR	
Do, Diameter of Optics (cm)	Do := 10
f, Focal Length of Optics (cm)	f := 10
DT, Detector Type (1=photovoltaic) (2=photoconductor)	DT := 1
Ad, Area of Detector (cm^2)	Ad := 1
λ1, Lower Spectral Wavelength (μm)	$\lambda 1 := 3$
λ2, Upper Spectral Wavelength (μm)	$\lambda 2 := 5$
η, Quantum Efficiency	$\eta := .75$
Td, Temperature of Detector (K)	Td := 77
Rd, Detector Resistance (Ω)	$Rd := 1 \cdot 10^{6}$
G, Gain of Detector, (Photoconductor only)	G := 1
iD, Dark Current, (amperes)	$iD := 75 \cdot 10^{-9}$
τ, Response Time, (seconds)	$\tau := 2.5 \cdot 10^{-4}$
FAR, False Alarm Rate (#/hr)	FAR := 10

(Photoelectron Counting Case Inputs)

THE INPUTS TO THE MODEL ARE:	ENTER YOUR INPUTS HERE:
SCENARIO	
AZ, Azimuth Search Angle (deg)	$AZ := 90$
EL, Elevation Search Angle (deg)	$EL := 20$
R, Range (km)	$R := 10, 12 \,..\, 40$
At, Area of Target (m^2)	$At := 1.5$
Tt, Temperature of Target (K)	$Tt := 350$
ϵt, Emissivity of Target	$\epsilon t := 1$
vt, Velocity of Target (m/s)	$vt := 300$
Tb, Temperature of Background (K)	$Tb := 50$
ϵb, Emissivity of Background	$\epsilon b := 1$
SENSOR	
Do, Diameter of Optics (cm)	$Do := 10$
f, Focal Length of Optics (cm)	$f := 10$
DT, Detector Type (1=photovoltaic) (2=photoconductor)	$DT := 1$
Ad, Area of Detector (cm^2)	
$\lambda 1$, Lower Spectral Wavelength (μm)	$\lambda 1 := 3 \cdot 10^{-4}$
$\lambda 2$, Upper Spectral Wavelength (μm)	$\lambda 2 := 5$
η, Quantum Efficiency	$\eta := .75$
Td, Temperature of Detector (K)	$Td := 77$
Rd, Detector Resistance (Ω)	$Rd := 1 \cdot 10^{9}$
G, Gain of Detector, (Photoconductor only)	$G := 1$
iD, Dark Current, (amperes)	$iD := 75 \cdot 10^{-11}$
τ, Response Time, (seconds)	$\tau := 15 \cdot 10^{-9}$
FAR, False Alarm Rate (#/hr)	$FAR := 5$

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19.

The purpose of this study was to determine the effect of the statistical properties of the signal and the noise on an IR system's detection performance. Noise sources identified and characterized include Johnson noise, shot noise, generation-recombination noise, and photon noise. The signal was characterized as either constant or fluctuating.

A computer model was used to evaluate system detection performance for various combinations of signal type and noise distribution. Results were presented in terms of probability of detection versus signal to noise ratio. Analysis of the results suggest that an IR system's detection performance cannot be measured in terms of signal to noise ratio alone. The system designer needs to take into account the statistical properties of the signal and the noise to accurately predict system performance with an IR detection model.