SIMULATION OF A WEAPONS FIRE SIMULATOR MODELED AS AN OPTICAL COMMUNICATION CHANNEL

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SUMMARY

This paper presents a method of simulating various noise sources in a Weapons Fire Simulator System which has been modeled as an Optical Communications Channel. This Weapons Fire Simulator System is composed of laser transmitters mounted on weapons that fire blank cartridges, and laser receivers mounted on targets. The laser transmitter sends out "kill" beam pulses to the target whenever blank cartridges are fired. Detection of these pulses at the target signifies a "hit." The entire system along with the optical communication channel is simulated in a general-purpose computer program called SCEPTRE. This analysis package is an efficient means of modeling the communication channel characteristics and determining signal-to-noise ratios as functions of various electrical and physical parameters. Also the SCEPTRE program is a versatile tool for circuit noise calculations.[1] The main advantage is a single SCEPTRE run computes the total noise output from a large number of noise sources distributed throughout the circuit.

INTRODUCTION

The computer-aided design package SCEPTRE is used to simulate a portion of a Weapons Fire Simulator System.

SCEPTRE is an automatic circuit analysis program that solves for the transient and steady state response of large networks. SCEPTRE solves circuit equations from a description of circuit topology and component values. In addition, a defined parameter mode solves state equations which can describe any system. This approach models the receiver section. The communication channel is modeled using FORTRAN IV subroutines. SCEPTRE's circuit description is composed of elements, defined parameters, and functions. Element values can be defined by evoking FORTRAN IV subroutines. Subroutine parameters can be either circuit variables, defined parameters, or constants. The subroutine facility is used to specify noise sources and atmospheric effects on signal sources. Any of these parameters can be changed via the rerun feature.

A block diagram of the laser optical communication system representing the weapon fire simulator is shown in Figure 1. The laser transmitter emits a digital pulse code whenever the weapon is fired which includes weapon identifying data. The laser beam passes thru an optics system into the communication channel, the atmosphere. The channel characteristics include atmospheric turbulence, scattering, and absorption. These effects cause the laser beam to diverge, bend, attenuate, and scintillate. These effects are a function of the path length and specific meteorological conditions. The direct or indirect sunlight illuminating the laser detectors, cause a constant dc bias in the photodiodes generating shot noise. The signal amplifier generates shot and thermal noise. The output of the signal amplifier feeds digital processing circuitry.

The electrical noise sources in passive and active electronic components have been extensively examined for many years.[4,5] There is an increasing need for computer-aided noise analysis since calculations associated with noise in electronic circuits are often extremely tedious and complicated. In these calculations, noise is superimposed on the electronic circuit as a current or voltage source whose value follows the normal distribution probability curve with its mean value zero and standard deviation a function of various parameters.

The SCEPTRE program is a general circuit analysis program having many active device models available in its "library." One can add the noise sources into the existing SCEPTRE device models for calculations, or the user can supply his own model and do the same.

Noise Sources

The sources of noise encountered are shot noise, thermal noise, and excess noise. The magnitude of the shot noise, having a constant spectral density, can be calculated from physical parameters. We call this type of noise a white noise source. Shot noise is due to the fluctuations of the number of charge carriers flowing through a junction barrier in a solid state device. For a forward biased PN junction photodiode, the spectral density of the current fluctuation has an expression Si(f)=2eI where "e" is the electron charge in coulombs, and I is the dc current flowing through the photodiode. The thermal noise is caused by the random vibration of the charge carriers in a resistor due to thermal agitation. Over the practical frequency range of a circuit's operation, the thermal noise has a flat spectral density and is considered to be a white noise source. The excess noise most often encountered in electronic circuits is the 1/f type which has a spectral density of the form $S(f)=K/f^b$, where K is a constant and "b" has the value close to unity. The other type of excess noise found in semiconductors and photodiodes is burst noise. This noise consists typically of random pulses of variable length and equal height. Burst noise has a power spectral density varying with frequency in the form of $S(f)=K/f^a$ but with "a" approximately 2. Since both types of excess noise have spectral densities increasing as the frequency decreases, they are dominant noise components only in the low frequency region (below 10 KHz). This analysis deals with high frequencies masking the excess noise with shot and thermal noise. Assume excess noise is negligible and equal to zero for this paper.[2]

The noise sources in electronic circuits are normally represented in the form of voltage and current sources. The above noise sources are two types; one with the spectral density independent of frequency (called white noise), and the other with the spectral density varying with frequency (called colored noise).

Simulation of Noise Sources

Both white and colored noise sources can be simulated by insertion of FORTRAN IV subroutines into the SCEPTRE source deck. The SCEPTRE program is well known for its simplicity and capability for handling the input and output signals of a circuit with time as the independent variable. This capability of the program makes it especially efficient for circuit noise problems because all the noise sources in a circuit can be simulated with current or voltage noise sources which have the required spectral intensity. For this paper, the FORTRAN IV subroutine GAUSS which is available in the IBM/360 Scientific Subroutine Package was used to simulate the white noise sources. The simulation was achieved by using the normally or Gaussian distributed random numbers generated by the subroutine GAUSS as a voltage or current source in the circuit. To use this subroutine, the mean value and standard deviation of the distribution must be given in the program. Set the mean value of the noise to zero since we are interested only in the ac component of the noise. The standard deviation of the shot noise distribution can be determined via the following. Let the time interval between the neighboring randomly generated numbers be Δ and, if the number of the random points generated is large enough, the spectral intensity of the noise source will have an expression

$$Sv(f) = \begin{cases} Sw; 0 < f < \frac{1}{2\Delta} \\ 0;\ \text{elsewhere} \end{cases}$$

where Sw is the spectral intensity of the white noise source. For this analysis, only the positive frequency is considered. The mean square magnitude or the variance of this noise can be represented as

$$\overline{V^2} = 3.204 \times 10^{-19}\ If$$

The standard deviation is

$$\sigma = \sqrt{\overline{V^2}} = \sqrt{3.204 \times 10^{-19}\ If}$$

where I is the photo diode current generator JA, or JB thru JD in Figure 3. The time interval Δ is determined by the highest frequency of interest with the maximum frequency of interest being

$$f = \frac{1}{2\Delta}$$

For example; to generate a shot noise source which has a constant spectral intensity from dc up to 10 MHz,

$$\Delta = \frac{1}{2f} = \frac{1}{2 \times 10^7} = 50 \times 10^{-9}\ \text{sec}$$

should be used. It is important to note that all the noise sources simulated in this way are uncorrelated, since each photo diode has its own GAUSS subroutine, and contain all the noise power in the usable circuit bandwidth. These subroutines can be simultaneously inserted into the SCEPTRE program to compute the instantaneous values of the noise at the output of the circuit being simulated. From these values of noise, the noise power can be easily calculated by another FORTRAN IV subroutine that performs these calculations.

The thermal and shot noise in the signal amplifier are simulated by using the signal amplifier's measured output noise voltage. Divide this value by the amplifiers gain and use as the standard deviation for the normal distribution. The mean value is set to zero. Assume a noise bandwidth of 10 MHz, then

$$\Delta = \frac{1}{2f} = \frac{1}{2 \times 10^7} = 50 \times 10^{-9}\ \text{sec}$$

Transmitter and Receiver Efficiency Factors

These factors are due to the optics at the laser transmitter and receiver. The transmitter efficiency factors lower the effective laser output power. For a typical laser transmitter the transmitting efficiency is 22% with the receiver efficiency 30%. Thus, the equivalent laser power at the receiver's detectors is a function of the product of the transmitter and receiver efficiency factors.

Simulation of Atmospheric Effects

For the purpose of laser system design, atmospheric effects may be classified as attenuation and turbulence. For the design of a laser for an optical communication link, where the target or receiver is smaller than the laser beam, both attenuation and turbulence effects must be considered.[3] Attenuation in the atmosphere is caused by the mechanism of absorption and scattering. Most lasers have output wavelengths outside the absorption bands which are selected sharp bands throughout the electromagnetic spectrum. Scattering attenuation of a laser beam occurs when the photons in the laser beam are deflected by particles in the air. At shorter wavelengths, the air molecules will cause scattering attenuation, but at longer wavelengths, microscopic particles of dust and smoke are the primary scattering media. At 0.904 microns, attenuation is mostly due to particle scattering. Visibility is also a function of atmospheric attenuation and serves as a convenient parameter for specifying the attenuation. Turbulence effects are caused by refractive index inhomogeneities in the atmosphere and may result in deflection or spreading of the laser beam or in nonuniform energy distribution across the wavefront. All of these effects cause degradation of performance, resulting in reduced energy density on the target or receiver.

Atmospheric Attenuation

A FORTRAN IV subroutine calculates the percent transmission through the atmosphere of the laser beam based upon the path length, and wavelength. The transmission of the laser beam through the atmosphere is given by

$$T = e^{-\alpha R}$$

where α is the attenuation coefficient, and R the path length. This coefficient is a function of molecular scattering, particle scattering, and absorption. For a given wavelength, α is a sum of these factors. Visibility is defined as the range where a target of 100% contrast is seen as a target with its apparent contrast reduced to 2%. An accurate empirical relationship between α and the visibility accounting for the variation of α with wavelength is

$$\alpha = \frac{3.91}{Rv}\left(\frac{0.55}{\lambda}\right)^{g}$$

where "g" is a function of visibility (Rv) which varies according to the following

Rv(km)	g
0-6	$(Rv/5)^{1/3}$
6-9	(0.86+Rv/30)
9-12	(0.98+Rv/30)
12-100	(1.15+Rv/200)

Atmospheric Turbulence

The atmosphere is an inhomogeneous medium made up of regions of varying size in which the refractive index deviates from the mean value. When a laser beam passes through the atmosphere, these regions result in several effects. These effects are beam steering (the entire beam is deflected from its original path), spreading (the divergence of the beam is increased), and scintillation (phase changes across the wavefront result in constructive and destructive interference causing amplitude changes in the wavefront that vary in a randomly distributed Gaussian fashion).

Beam steering is assumed negligible, and beam divergence is a nonprobabilistic function for this analysis. Let the laser output power be PWR, XDIV the beam divergence in the X direction, and YDIV the beam divergence in the Y direction. The fraction of the transmitted energy at the receiver (PRW) is given below:[9]

$$A = (2.54 \times 10^{-2} + XDIV* R)/2$$

$$B = (2.54 \times 10^{-2} + YDIV* R)/2$$

$$EFA = e^{-\left(\frac{xd}{A}\right)^2} e^{-\left(\frac{yd}{B}\right)^2}$$

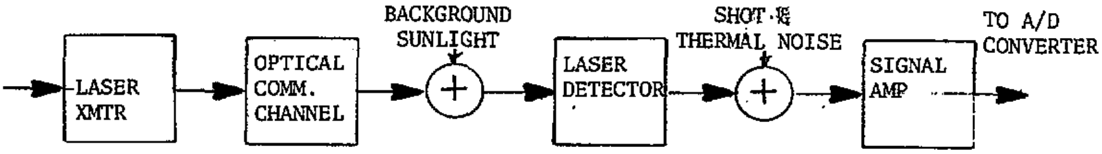
$$PRW = \frac{PWR\ (2.54 \times 10^{-2})^2\ EFA}{\pi\ (2.54)^2\ AB}$$

PWR = POWER * XET * XER
XET = Efficiency factor for transmitter
XER = Efficiency factor for receiver

where R is the path length, Xd the X distance from the laser beam center to the target center, and Yd the Y distance. PRW is the laser beam power at the detector after beam divergence and efficiency factors have been applied to the transmitter and receiver. PWR is the laser power output after efficiency factors have been applied. See Figure 2 for an illustration.[9]

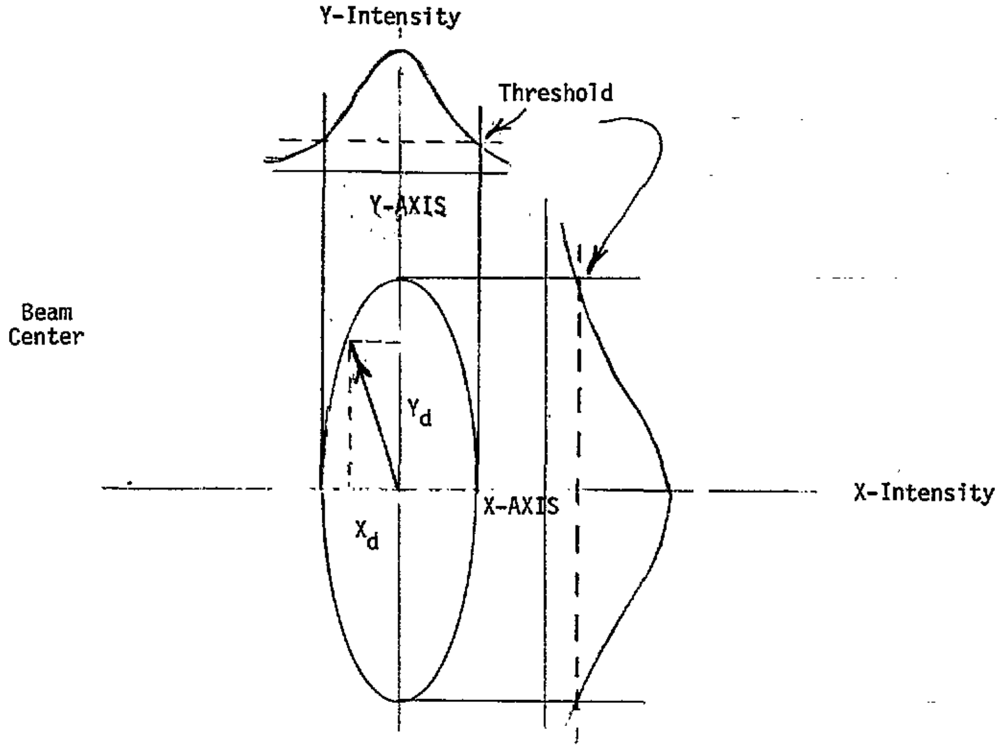
Scintillation Effects

A FORTRAN IV subroutine calculates the scintillation effect simulated by the subroutine GAUSS. Tatarski's work has shown that the intensities in a laser beam cross section are log normally distributed (have



Block diagram of weapon fire simulator viewed as an optical communication system

Figure 1.



Cross-sectional view of laser beam intensity distribution. The beam's elliptical cross section is defined by the threshold value, the peak power and the beam divergence of the transmitter.

Figure 2.

a normal distribution when plotted with the intensity on a logarithmic scale), with the variance of the GAUSSIAN distribution being

$$\sigma_t^2 = 1.23\ C_n^2\ K^{7/6}\ R^{11/6}$$

for an infinite plane wave case.[7] Here K is the wave number $2\pi/\lambda$ corresponding to the wavelength being propogated, Cn the turbulence structure constant of the atmosphere, and R the path length. The three classes of turbulence are:[6]

Weak turbulence	$Cn = 8 \times 10^{-9}\ m^{-1/3}$
Intermediate turbulence	$Cn = 4 \times 10^{-8}\ m^{-1/3}$
Strong turbulence	$Cn = 5 \times 10^{-7}\ m^{-1/3}$

During different times of day and seasons of the year, use different turbulence constants. During the winter season, use weak turbulence at sunrise and intermediate turbulence at noon; during the summer season, intermediate turbulence at sunrise and strong turbulence at noon.

One problem with the variance equation is that it predicts an infinite increase of energy variance with respect to path length, which is not the case. One must assume that σ_t will saturate at some level a function of both path length and σ_t^2. The corrected value of variance is

$$\sigma_a^2 = \ln\ (2 - \exp(-\sigma_t^2))$$

which saturates at 0.6931, the natural log of 2.[8] This equation is valid for a spherical wave but another correction is necessary for a plane wave. In our case, with the beam divergence high (> 3 milliradians) assume the laser is emitting a spherical wave with no correction necessary.

The mean value of the normal distribution that SCEPTRE generates is

mv=ln (PRW*200*10^{-9}*e$^{-\sigma a^2/2}$)
where 200X10^{-9}=laser pulse length

The frequency of the amplitude modulation due to scintillation is determined by eddy wind currents in the atmosphere. This movement of air normal to the path of propagation causes amplitude modulation of the scintillation pattern. The maximum frequency of this modulation is determined by the following equation

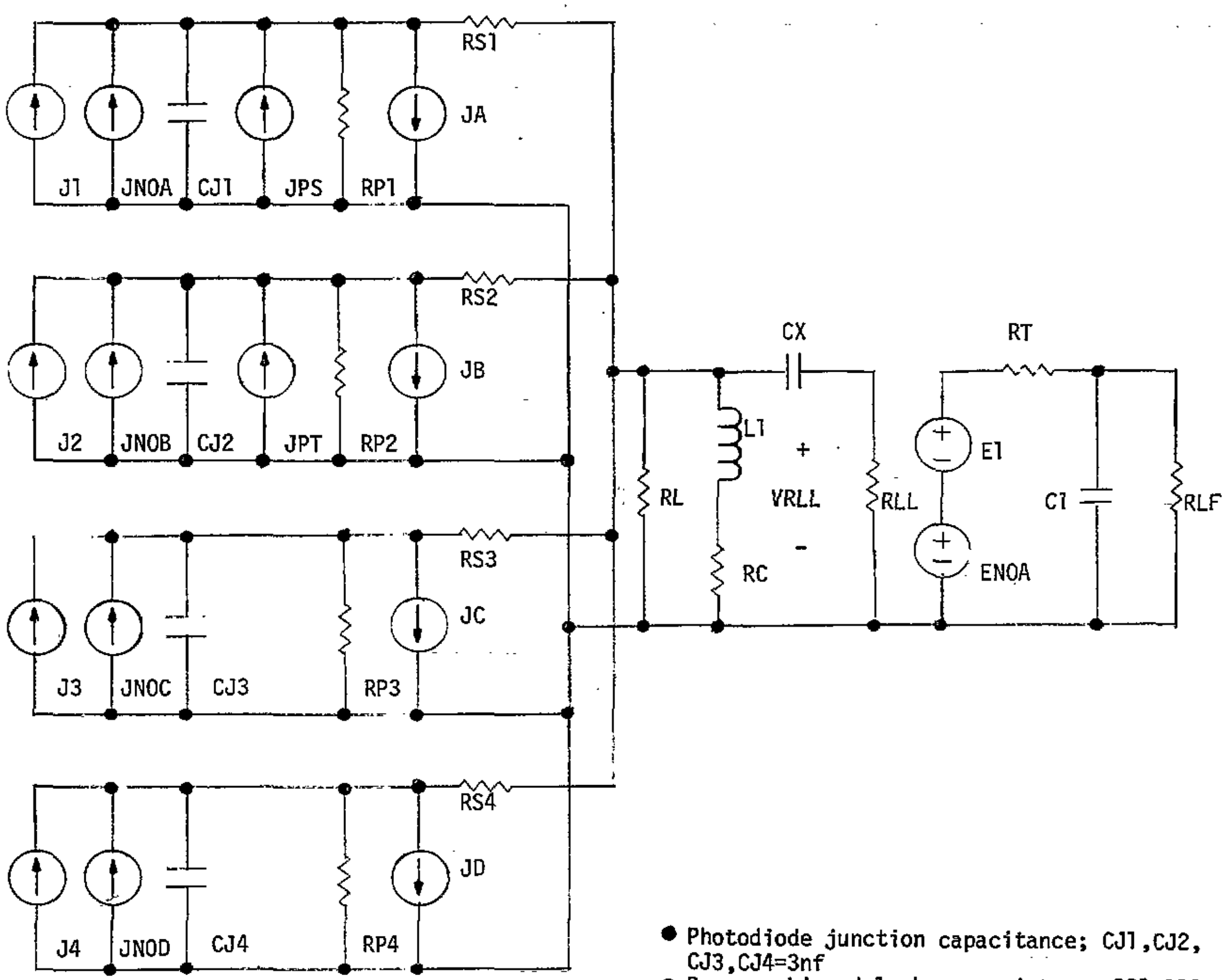
$$f = \frac{Vn}{(\lambda\ R)^{1/2}}$$

where Vn is the component of wind velocity normal to the line of sight, λ the wavelength, and R the path length. This maximum frequency is a measure of the rate that turbulence statistics change as the atmosphere moves across the laser beam path. This serves to establish the validity that each transmitted pulse is an independent event. For our analysis, the time interval between random number generation is 1/f, the rate at which new random numbers are generated by GAUSS during the SCEPTRE run.

Example

An example is given here illustrating the method of incorporating the simulated noise sources in the SCEPTRE program to compute the noise power at the circuit's output, a function of the parameters described above. The circuit to be analyzed consists of four solar cells in parallel driving a signal amplifier, see Figure 3. The circuitry loading the solar cells is ac coupled and loaded with an inductor to pass only the received pulses (ac component) of the signal. This is necessary when the detectors are in sunlight generating a dc bias. The shot noise in each solar cell is simulated with noise current generators JNOA thru JNOD, respectively. The dependent current generators JA thru JD simulate the diode effect occurring in the solar cells due to their silicon PN junction. J1 thru J4 simulate the dc bias introduced by the sunlight, CJ1 thru CJ4 the diode junction capacitances, RS1 thru RS4 the internal series bulk resistances, and RP1 thru RP4 the reverse bias series resistances. The signal amplifier is simulated by a voltage source and a resistor capacitor load limiting the bandwidth. Four different random number sequences are generated by four separate GAUSS routines giving completely uncorrelated shot noise results. The ENOA voltage source simulates the thermal and shot noise of the signal amplifier. JPS and JPT are the current sources simulating the currents due to the received laser pulses. For this analysis, assume a configuration with all four detectors in full sunlight, but only two of them receiving the laser pulses. Resistor RT simulates the output impedance of the signal amplifier with C1 and RLF a low-pass filter simulating the actual bandwidth of the amplifier. The RC time constant gives a cutoff frequency of approximately 1 MHz.

One computer run with SCEPTRE and the FORTRAN IV subroutines calculates the noise power at the output with JPS and JPT set equal to zero (no signal). Another computer run calculates the average peak signal by setting JNOA thru JNOD and ENOA to zero. These runs are compared and the signal to noise ratio determined. The various parameters discussed in this paper can be varied from run to run with the signal to noise ratio determined as a function of these parameters.



This is the equivalent circuit of four parallel solar cell photodiode outputs applied to an amplifier through a filter. The following is a description of the circuit parameters:

- Transmitter laser power; 5 watts
- Laser pulse width; 200 nanoseconds
- Laser signal current in photodiodes; JPS,JPT Due to scintillation, the laser signal has a statistical variation and for both JPS,JPT; mean value = m_y standard deviation = σ_a
- Current generated due to background illumination; J1,J2,J3,J4
- Current through PN junction of solar cell photodiode; JA,JB,JC,JD
- Shot noise current generated due to current through PN junction; JNOA,JNOB,JNOC,JNOD mean value of noise=o standard deviation=σ
- Photodiode junction capacitance; CJ1,CJ2, CJ3,CJ4=3nf
- Reverse biased leakage resistance;RP1,RP2, RP3,RP4=2KΩ
- Series resistance due to intrinsic bulk material of the photodiode and the circuit loads; RS1,RS2,RS3,RS4=14Ω
- Damping resistance for control of transient response: RL=1KΩ
- Inductance to reduce dc current through PN junction of photodiode; L1=3mh
- Resistance of inductance; RC=0.5Ω
- Coupling capacitor CX=.2μf
- Load resistance; RLL=200Ω
- Amplified signal voltage; E1=100VRLL
- Noise voltage in amplifier; ENOA mean value=o standard deviation=2.7volts
- Internal series resistance of amplifier; RT=1Ω
- Parallel capacitance and resistance used to simulate the amplifier bandwidth; C1=1μf RLF=200Ω

Figure 3.

For a 5-watt laser, the results of these runs are shown in Figure 4. Sun currents J1 through J4 are functions of the receiver optics, visibility, and orientation of the detectors with respect to the sun. Assume one orientation for all computer runs. The laser beam is attenuated by the transmitter and receiver efficiency factors, and subject to the atmospheric channel effects. The beam irradiates two of four detectors. The signal-to-noise ratios plotted represent peak current to rms noise current values. No consideration has been taken as to the effect of visibility on sun current.

Pulse detection occurs if the peak value of the signal current generated by the laser pulse exceeds a predetermined value or threshold. The threshold setting also determines how often a noise spike will be incorrectly interpreted as a pulse. The probability of this occurring is called the probability of a false alarm. The higher the threshold, the less likely a false alarm, but also less likely is the probability of a pulse being detected. Figure 5 shows the probability of detection, P_d, versus sun current, range, visibility and threshold level. The threshold to noise ratio, T/N, can be set to any desired value, and determines the probability of false alarm, Pfa.[3]

DISCUSSION

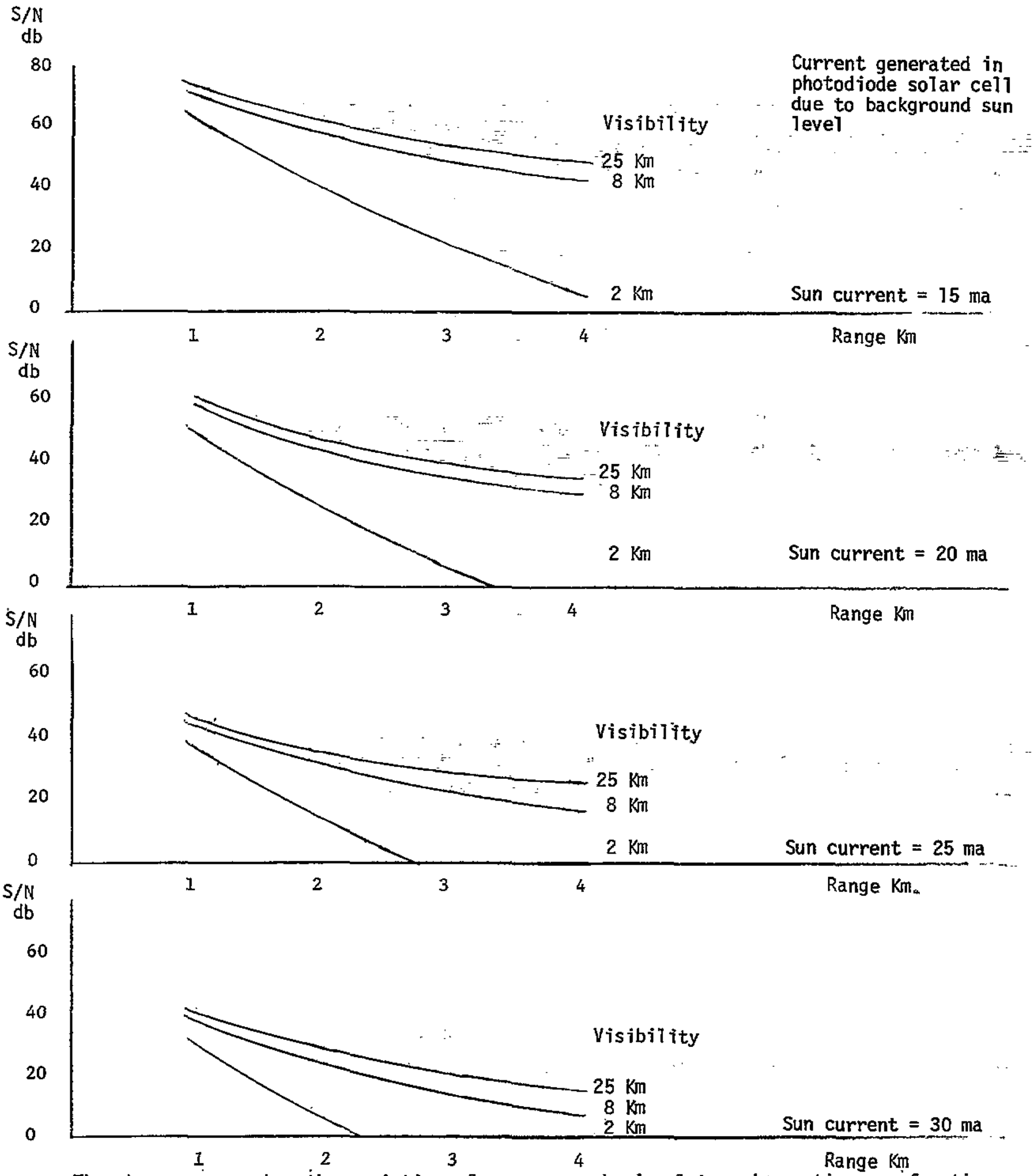
The circuit considered in this example was four parallel solar cells connected to an amplifier. The output of this amplifier is applied to a threshold detector and sent to a digital decoder. This paper was a study of only the communication channel and the detectors, hence, an ideal threshold detector has been assumed. The only system degradation considered is the scintillation of the atmosphere through which the signal traveled and the additive shot noise generated in the solar cell due to background sun light. A typical noise value was used for the single stage amplifier. For the usual applications of solar cells one would expect significantly higher values of sun generated current, but for this application this current is assumed limited by a passband optical filter centered upon the laser wavelength 0.904um.

Figure 4 shows the variation of the average signal-to-noise ratio for various amounts of sun current generated shot noise. An average signal value was obtained by calculating the amplifier peak signal output when a pulse from a 5 watt laser was transmitted through a scintillating, attenuating channel, and then averaging the peak values over a large number of separate pulses. Each detector was treated statistically independent for both the scintillation effects and the noise. The noise values were obtained by calculating the rms value of the amplifier output with no signal applied. The average signal-to-noise ratio remains very high even for lower visibility conditions. It is only under the most sever visibility condition at the longer ranges does the noise and scintillation give unacceptable signal to noise ratios. For the most part, the ratio is more than acceptable.

The graphs in Figure 5 illustrate how the probability of detection varies with range and visibility conditions. These graphs also reflect the high signal to noise ratio. The probability of detection remains at almost 100% except for the most adverse conditions. This high-detection probability would increase further if additional solar cells were illuminated by the same pulse. The additional cells must be spaced sufficiently far apart (usually greater than 8 cm) so that they can be treated as statistically independent. The probability of signal detection can be increased even more by the use of coding for single and/or multiple pulse error correction. Because of the very favorable signal-to-noise ratio, the threshold value can be set high which in turn makes a false alarm very unlikely.

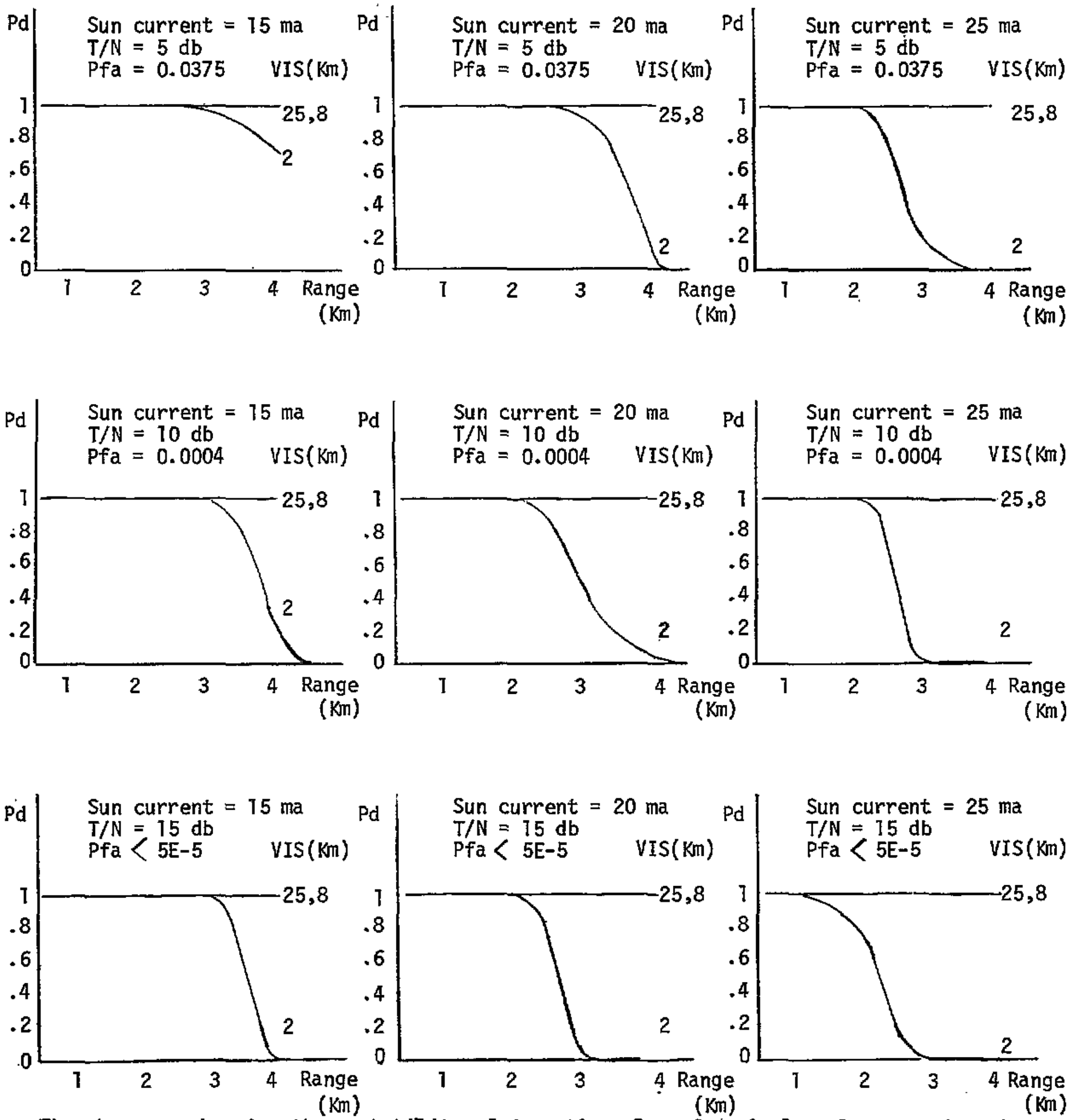
CONCLUSION

The SCEPTRE package provides the ability to describe analytically, through the use of FORTRAN IV subroutines, the effects of an atmospheric communication channel on laser transmitted signals. It also provides ease in the modeling of the laser signal detectors including the various types of noise which occur. The results of the simulation of the channel and the sensor electronics suggest that a number of inexpensive solar cells can be connected to a single pre-amplifier and still provide viable signal to noise characteristics.



The above curves show the variation of average peak signal to noise ratio as a function of visibility and range. For all the above cases the scintillation value was taken to be the worst case saturated value Ln 2, for a divergent laser beam.

Figure 4.



The above graphs give the probability of detection, P_d, of a single pulse as a function of range. Three visibility conditions are shown, the saturated scintillation condition is used for all cases. Reading from left to right, the sun background generated increases while the threshold to noise ratio is held constant. From top to bottom the sun current is fixed while the threshold to noise ratio is increased.

Figure 5.

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