OPTIMUM DETECTION OF LASER SIGNAL THROUGH TURBULENT ATMOSPHERE

A THESIS
submitted in fulfilment of the
requirements for the award of the Degree
of
DOCTOR OF PHILOSOPHY
in
ELECTRONICS & COMMUNICATION ENGINEERING

By
NILAMBER MALAVIYA

DEPARTMENT OF ELECTRONICS AND
COMMUNICATION ENGINEERING
UNIVERSITY OF ROORKEE
ROORKEE (INDIA)
April 1975

C E R T I F I C A T E

Certified that the thesis entitled " OPTIMUM DETECTION OF LASER SIGNAL THROUGH TURBULENT ATMOSPHERE" which is being submitted by Mr. Nilamber Malaviya in fulfilment of the requirements for the award of the Degree of Doctor of Philosophy in Electronics and Communication Engineering of the University of Roorkee is a record of the student's own work carried out by him under my supervision and guidance. The matter embodied in this thesis has not been submitted for the award of any other degree.

This is further to certify that Mr. Malaviya has worked for a period of four years from March 1971 to March 1975 , for preparing the thesis at this University.

A. K. Kamal.

(A. K. KAMAL)
Professor and Head ,
Department of Electronics and
Communication Engineering,
University of Roorkee, Roorkee
India.

Roorkee
April 22, 1975.

A C K N O W L E D G E M E N T S

I would like to express a profound sense of gratitude to my thesis supervisor, Dr. A. K. KAMAL, Professor and Head, Department of Electronics and Communication Engineering, University of Roorkee, Roorkee for the liberal guidance, wisdom and encouragement which I have received from him on my hands so spontaneously and lavishly throughout the period of this thesis work.

I will long cherish the continual patient help of Dr. Kamal, his inspired teaching, generous counsel, and constant encouragement, which I had from him time to time. In particular, I can never forget the moral support and warm appreciations which I had from him, when, at one time, I was in a desperate and pensive mood during the progress of this work. For this I want to record his greatest and special debt.

Thanks are due to Mr. M.C. Agarwal for his help in Computer Programming.

Also, to all others who have helped me directly or indirectly - my sincere thanks .

Also I am thankful to Mr. M.P.Goel for typing the manuscript.

TABLE OF CONTENTS

Contents (Contd..)

--

CAPTION OF FIGURES

GLOSSARY

D	- transmitting aperture
λ	- wavelength
d_B	- beam diameter
ℓ	- inhomogeneity dimension
$D_\phi(\bar{r})$	- structure function for phase
$D_t(\bar{r})$	- structure function for propagation time
p_v	- water vapour pressure
$\bar{n}$	- refractive index
P_a	- pressure of atmosphere
$n_o(\bar{r})$	- mean value of refractive index
$n_1(\bar{r})$	- random variation of refractive index about mean
ν	- kinematic viscosity
R_e	- Reynold number
V	- characteristic velocity scale
L_c	- characteristic length
t_c	- characteristic period
R_{cr}	- critical Reynold number
$\Delta\theta_c$	- beam deflection
Δn	- gradual index change
L_{cz}	- correlation distance parallel to the direction of propagation
L_{cT}	- correlation distance transverse to the direction of propagation
L_p	- path length
$\Delta\theta_{ms}$	- mean deflection
δI	- change in intensity

ρ_ℓ	-	distance between observing point for measuring phase fluctuations
ph	-	phase angle
Ψ	-	random variable describing phase fluctuations
Ψ_i	-	root mean square log amplitude fluctuations
$\Gamma_\Psi(\rho_\ell)$	-	cross correlation function
$\gamma_{12}(\rho_\ell)$	-	coherence function
L_c	-	correlation length
τ_c	-	correlation time
k_w	-	wave number
A	-	amplitude of the turbulence distorted wave
A_o	-	amplitude in the absence of turbulence
C_n^2	-	structure constant
ℓ_o	-	size of the smallest eddy
L_o	-	size of the largest eddy
$V(z)$	-	wind velocity at an altitude z
$I(t)$	-	incident instantaneous intensity
I_S	-	current resulting from detector information carrying signal
I_b	-	current resulting from undesired background radiation
I_d	-	dark current
t_{ot}	-	observation time
σ_t^2	-	variance of the detector thermal noise current
k	-	normalizing constant

N_o	- spectral density of white Gaussian noise
$p(n)$	- density for background radiation noise
$p(\varphi)$	- density of the phase variation
α	- spread of the density
$I_o(\alpha)$	- Bessel function at the first kind
τ	- delay time
$p(G)$	- density of gain variations
μ	- average value of gain variations
ω	- signal frequency

ABSTRACT

[MALAVIYA, NILAMBER "OPTIMUM DETECTION OF LASER SIGNAL THROUGH TURBULENT ATMOSPHERE"
Ph.D.Thesis,Department of Electronics and Communication Engineering, University of Roorkee,Roorkee India March 1975.
Guide: and Supervisor - Dr. A. K. KAMAL, Professor and Head of Electronics and Communication Engineering Department, University of Roorkee, Roorkee, India.]

The invention of laser in 1960, triggered the imagination of a large number of communication engineers to develop a sophisticated communication system for handling huge amount of information. Considerable amount of work has been done towards inventing new forms of modulation and detection techniques with such coherent sources. It is now possible to establish in practice real communication systems involving extremely large band widths. These efficient optical communication systems have the added advantage of high achievable directivity, increased antenna gain and higher data rates.

Laser communication systems operate at carrier frequencies in the interval of 10^{13}Hz to 10^{15}Hz. The attributes of large information band width and narrow transmitted beams of laser systems compared to radio frequency communication system are simply a result of high frequency of optical waves, narrow spectral width and coherence.

For laser communication, the channel or medium of transmission may be earth's atmosphere, closed optical waveguide, or vacuum. For short distance transmission any sort of guiding technique may be employed, but for long and medium distances, transmission through atmosphere becomes inevitable.

The propagation characteristics of atmosphere have been the subject of investigation for several decades particularly at radio frequency. The advent of laser spurred renewed activities in the optical and infrared region of the spectrum. The hope for use of lasers for communication through atmosphere was hampered some what due to the adverse role played by atmospheric effects as reported by Subramanian [155]. Propagation through turbulent atmospheric channel has been reviewed by Strohbehn [152], Lawrence and Strohbehn [101], Brookner [17][18], Kennedy and Karp [89]. There are a number of propagation effects due to the random spatially and temporally varying refractive index. The ultimate atmospheric limitation on propagation at optical frequencies can be established by applying communication theory ideas to adequate statistical models of atmospheric channel. In the turbulent case one is faced with a slowly varying fading channel with amplitude variations having log-normal distribution [89] and the phase variations for which the probability distribution has been assumed as [164] .

$$p(\varphi) = \frac{\exp(\alpha \cos \varphi)}{2\pi I_o(\alpha)} , \quad -\pi \leq \varphi \leq \pi$$

The function $I_o(\alpha)$ is the Bessel's function of the first kind. α is regarded as a parameter that controls the spread of the density.

The transmitter sends a signal whose intensity is modulated with one of a set of M-possible intensities each T second long. One can associate a signal energy component m_k for the k^{th} intensity. During an interval of T second, one of the M equal energy signal is known to be transmitted. During transmission through the atmosphere multipathing occurs due to inhomogeneities of turbulence. The signal is perturbed by background radiation noise, which is assumed to be white, stationary, Gaussian and statistically independent of the channel perturbations. The receiver determines with minimum probability of error as to which signal was transmitted. It does this by appropriately processing the received signal S. This operation consists of computing the a-posteriori probability of the M received signal and choosing the one with the largest probability.

An upper bound on average probability of error of multiphoton count laser system has been derived. The signal has been assumed to be disturbed by background radiation noise alone. It has also been mentioned that the probability of error bound can be used to attain any required standard of performance in terms of the allowable error.

Analytical expressions have been derived for the a-posteriori probability of detecting M-possible signals, with multipathing and perturbed by random variations in phase and gain. Receiver structures are proposed which can implement the analytical expression giving the a-posteriori probability. Decision is given in terms of that signal which gives the maximum a-posteriori probability. The physical realizations of the proposed receivers are also discussed.

CHAPTER I

INTRODUCTION TO THESIS

1.1 INTRODUCTION

In common with most areas of modern day technology, the field of communication has expanded explosively in the past decades. Today there is a greater need for reliable, rapid and efficient means of communication over larger distances. Significant advances in communication system performance and economy have come about by virtue of technological progress in the form of new devices such as solar batteries, information storage and retrieval devices, lasers and space vehicles for satellite repeaters. Modern communication systems incorporating these and other devices may include a number of links that employ different transmission media such as underground or submarine cables, microwave radio relays, tropo-scatter path and communication satellites, each with a different analog or digital modulation method and each with its particular type of transmission equipments.

Noise impairment during transmission, various kinds of non-linearities, unavoidable attention and phase deviation over the transmission band, random time fluctuations in the channel transmittance and mutual interference are some of the problems encountered.

One of the aims in a communication system is to provide high quality of transmittance. It is necessary to avoid excessive disturbance from noise inherent in transmission medium and also noise or interference from other sources. Besides noise, it is also necessary to consider disturbances that originate in a variety of unavoidable imperfections in the channel. These channel imperfections and the resultant transmission impairments are usually of greater concern than additive random noise in communication system.

At present different techniques are available for transmitting a large volume of message over a long distance. The oldest of these is the co-axial cable system, which still carries a large proportion of the communication traffic. Amplifying equipments are located every five or six kilometers apart depending on the amount of traffic. Another method which is in use is by means of microwave-radio relay towers spaced few kilometers apart. A third long distance technique called wave guide, has also been perfected but is not yet in wide-spread use. The fourth long distance technique involves the use of satellites. Broadband communication by satellite operating within the microwave radio bands are possible.

The announcement of laser in 1960 [107] and subsequent work on intense coherent optical sources [59] ,stimulated the work towards laser communication as another suitable technique for long distance transmission. The basis for this is the simple fact that the capacity of a communication channel is proportional to the width of its band of frequencies. Thus a communication system utilizing electromagnetic waves in the visible region of spectrum, where enormously wide bands of frequencies are available, should inprinciple be capable of carrying many times the amount of information carried by lower frequency radio wave systems.

Laser communication may be divided into four categories [139]:

(a) Terrestrial short range path through the atmosphere.

(b) Closed pipe system

(c) Near space communication for relaying high data rates.

(d) Deep space communication from the outer planet.

The division into four classes depends upon the path length, data regimes, line-of-sight requirements for laser links and weather effects. Each class has its own particular problems and solutions. The short wave length of laser makes enormous antenna gains possible even with physically small apertures. Even narrow band laser signals are capable of carrying thousands of time more information than microwave radio signals.

The importance of directivity factor can be noted by stating that the beam width of an electromagnetic signal is given by the diffraction limit as $\theta = \frac{1.27\ \lambda}{D}$, where λ is the wave length and D is the transmitting aperture. Since λ is 10^3 to 10^4 times smaller at optical wavelengths than at microwaves, D may be 10 cms to achieve bandwidths less than 10 μ radian. The power required for transmission due to directionality factor is much less at laser wavelength than that at microwaves as given by the ratio

$$\left[\frac{\lambda_L/D_L}{\lambda_M/D_M}\right]^2$$

, where the subscripts L and M refer to laser and microwave wavelength respectively. In a laser communication system with 30 psec. pulses, a bandwidth of approximately 30 GHz is easily obtainable. At a laser wavelength of approximately 3×10^{14} Hz, 30 GHz is 10^{-4} of the optical carrier frequency. One thousand such channels along the same path would only increase the bandwidth utilized to 10% of the carrier frequency. Yet, 30 GHz being used in some experiments, far exceeds the total microwave spectrum. Further, the directionality factor of the laser would easily allow overlapping of spectrum for different links without interference problems.

There are large number of photodetectors and detection techniques available for use in a laser communication systems [3] [41] [104] [111] [136] [145] [156] [168] . The correct choice of a particular detection technique and photodector depends mainly on the wavelength of operation, the information bandwidth of the signal and the sensitivity desired for the demodulation of weak signals.

The history of receiving devices in the optical and infrared region goes back to nineteenth century. Although photon effect had already been observed, the detectors developed in this period were of thermal effect type. The operation of thermal detectors depends on the heating produced by the incident radiation. Essentially, thermal detectors measure the rate at which incident energy is absorbed. In contrast with the thermal detectors, the so called photon detectors measure the rate at which quanta are absorbed. Phototubes, photo-multipliers and photo-conductive semi-conductors are examples of photon detectors. In receiving systems, thermal detectors are not preferred because of their inherently slow response. Proper design of demodulator systems for optical signals requires specially designed photo-detectors that are efficient and fast. The major requirements imposed on photo detectors and detection systems for laser communication applications, thus include [140] :

(i) Large response to incident signals

(ii) Sufficient instantaneous bandwidth to accommodate the information bandwidth of incoming signal and

(iii) Minimum of noise added by demodulation process.

Attention must not only be given to the choice of the optimum detector but also to the other system parameters such as desired field of view, optical band width, possible relative motion between transmitter and receiver and interference due to sun and other radiation. Photo detectors in a laser communication system which convert the intensity of the carrier into electrical signals are usually square law detectors which respond to the intensity of light averaged over a number of optical cycles. This is because the speed of response is determined by the carrier transport and relaxation process within the photodetector. These processes do not have sufficiently short time constants to reproduce field variations which occur at optical frequencies. The main consideration in the selection of a photodetector for a laser communication receiver is the relative output levels of the detector due to laser carrier and due to noise. Number of criteria for optical detector performance exist. Among all the detectors possessing sufficient bandwidth and acceptable physical characteristics, the detector to be chosen should have:

(i) highest quantum efficiency

(ii) lowest noise equivalent power

Thus the correct choice of a particular detection technique and photodetector will depend on wavelength of operation, the information bandwidth of signal and on the sensitivity required for the demodulation of weak signals.

A laser signal propagating through the earth's atmosphere is attenuated due to absorption of radiation by atmospheric constituents and is subjected to scattering by particles in the atmosphere. Signal is also severely affected by the turbulence in the atmosphere. It is convenient to consider the turbulent medium to be composed of discrete blobs, each of which is homogeneous but of different refractive index than its neighbours. An inhomogeneity dimension is associated with each blob. The smallest and the largest inhomogeneities are characterized by the dimension ℓ_o and L_o respectively. The effect of atmospheric turbulence depends upon the relative sizes of the beam diameter d_B and the inhomogeneity dimension ℓ [35] . If $d_B \ll \ell$, the major effect of turbulence is to deflect the beam as a whole. At long ranges the beam appears to execute a two dimensional random walk in the receiver plane. For $d_B \approx \ell$, the inhomogeneities act as lenses which focus or defocus all or part of the beam, imparting a grannular structure to beam cross-section. If $d_B \gg \ell$, small portions of the beam are independently diffracted the beam phase fronts are badly distorted. For communication from a deep space transmitter to an earth receiver $d_B \approx \ell$. The principal turbulent effects are then beam spreading, beam scintillation and spatial coherence degradation. In the opposite case, that is, for an earth transmitter and deep space receiver $d_B \ll \ell$. Under these conditions, image dancing and beam steering are the predominant effects of atmospheric turbulence [35] .

Although optical systems are severely influenced by various properties of atmosphere, techniques have been developed which may over come many of these effects. A number of optical communication systems have been experimentally investigated in the laboratory and at lower atmosphere.

The physical basis for various effects of atmosphere turbulence on laser system is briefly discussed by Davis [35]. As to specific application, the signal-to-noise ratio for an AM signal passing through the turbulent atmosphere is derived in terms of this ratio. The effect of power fluctuations on the probability of detection for laser radar is discussed in general.

Detailed reviews of the components, techniques and atmospheric channel descriptions are available.[17][18][19][101][152]. There are three main factors that affect the channel time spread for clear weather conditions. These factors are [18]:

(i) multipathing due to atmospheric inhomogeneities,

(ii) dispersion due to variations in index of refraction with frequency and

(iii) the channel molecular absorption due to absorbing gases and water vapour.

Multipathing results from the scattering by atmospheric inhomogeneities. A measure of multipathing in the channel is obtained from the spatial statistics of the phase of signal wave front. In particular, it is obtained from the structure function of the phase of the signal observed. Let ϕ_i be the phase of the signal arriving at any point i on the receiver. Also let, the position of the point i be designated by the vector $\bar{r}_i$. Then for locally homogeneous and locally isotropic turbulence, the structure function for the phase of the signal observed at points 1 and 2 on the receiver is given by:

$$D_\phi(\bar{r}_2 - \bar{r}_1) = D_\phi(\bar{r}) = \left[\overline{(\phi_2 - \phi_1)^2}\right] \quad \ldots(1.1\text{-}1)$$

Let the propagation time for the ith path be $t(\bar{r}_i)$. The structure function for the propagation time at the receiver is given by :

$$D_t(\bar{r}) = \left[\left\{\overline{t(r_2) - t(r_1)}\right\}^2\right] \quad \ldots(1.1\text{-}2)$$

The above structure function provides a measure of the channel time spread.

The ultimate atmospheric limitation on communication laser frequencies can be established by applying communication theory ideas to adequate statistical models of atmospheric channel. For the Gaussian fading dispersive radio channels discussed by Kennedy [92], it has been shown that with proper signals and reception techniques the incoherence attributable to Doppler spread or time spread does not reduce the channel capacity. A very complicated receiver is required to realize the full potential of the channel. The optimum receiver for a classical Gaussian field is obtained in the same way as for Gaussian processes. The well known results of Price [126] and Kennedy [91] can be used. Many results have been obtained in connection with Sonar and Seismometric application as reported by Gaarder [56] , Schweppe [146] and Capon [25] and with optical application by Harger [64] and Kennedy [90] .

The radar detection case with log-normal fading has been considered by Heidbreder and Mitchell [70] and Fried and Schmeltzer [50] in the case of one sensor and assuming a suboptimum receiver structure. Much work has been done in constructing and evaluating the performance of various optical receivers based on direct detection, local heterodyning or transmitted reference systems by such workers as Goldstein et al [63] , Miller and Tilloston [112] , Ross [139] , Cooper [33] , Brookner et al [20] and Denton and Kinsel [42] .

In the present work, receiver models are proposed for the case when there are random phase and random gain variations due to atmosphere turbulence. Expressions are derived for the a-posteriori probabilities for the two cases in the presence of additive background noise. Also, an upper bound on the average probability of error of multiphoton count laser system has been derived.

1.2 ORGANIZATION OF THE THESIS

The work embodied in this thesis has been arranged in the following manner.

Chapter II begins with a brief idea about the turbulent atmosphere. This explains the various significant effects of the atmosphere on the communication system. Discussion is also given of the available results on the adverse role played by atmospheric turbulence at laser wavelengths.

Chapter III is concerned with the problem of determining the performance that can be achieved with a photon count laser detection system. Here one is concerned with a photon counter at the receiver and the ensuing photo-electron statistics that results when M-ary laser beam is incident on photoemissive surface of the detector. An expression has been derived for the upper bound on the probability of error. The results are presented in terms of the ratio of received signal energy to noise power and information rate. A discussion is also given of the results so obtained.

Chapter IV is devoted to find the structure and performance of optimum receivers for reception in a turbulent atmosphere. Constraints imposed on the communication systems, background radiation noise and its statistical descriptions are given. An attempt has been made to explain multipathing, random variations in phase and random variations in gain and affects caused thereby. Thus the received signal depends on the transmitted message, the effects of the propagation medium and the additive background radiation noise. The job of the proposed receiver is to process the received signal in such a way so as to reproduce the signal as faithfully as possible.

A summary of the contributions made in this thesis is given in Chapter V. Suggestions for further research work in this area have been incorporated.

CHAPTER II

ATMOSPHERIC LIMITATIONS FOR LASER DETECTION

2.1 INTRODUCTION

The medium or channel through which the laser beam travels has a significant effect on the communication system characteristics. For laser communication the medium of transmission may be earth's atmosphere, closed optical waveguides, lens system or vacuum. For short distance transmission any sort of guiding technique may be employed, which to some extent precludes any undesirable effects due to atmosphere. For long and medium distances transmission through atmosphere becomes unevitable [112] [135]. The atmosphere acts as an attenuating channel for transmission in the millimeter and microwave range, but it may degrade the performance of a laser communication system completely [5] [16] [17] [18] [19] [20] [33] [67].

A laser signal propagating through the earth's atmosphere is attenuated due to absorption of radiation by atmospheric constituents and is subjected to scattering by particles in the atmosphere. Part of the sunlight incident upon the earth's surface is absorbed which causes the surface air layer of warm air to become less dense and rises to mix turbulently with the surrounding cooler air. Air temperature thus varies from point to point in atmosphere in a random manner.

The temperature fluctuations are a function of altitude and wind speed [158] . The index of refraction of air is dependent on its temperature. When a laser beam traverses a region in which there is a temperature change in the air, the beam is totally or partially deviated depending upon the relative size of the beam and temperature inhomogeneity. This leads to random amplitude and phase variations of laser carrier.

At any instant of time atmosphere is not perfectly homogeneous and turbulent free throughout the path of transmission. Temperature, pressure, density, refractive index and wind velocity show fluctuations about their mean value and atmosphere is said to be turbulent [141] [144] . Although the above physical parameters tend to distort the wavefront of the nominally coherent optical radiation, however, the refractive index inhomogeneities contribute the maximum distortion thereby producing the turbulence, [141] [144] [156] [162] [171] [172] .

A simple model of turbulent atmosphere, however, can be described in terms of a distribution of spherical inhomogeneities of refractive index called eddies. The largest eddy size can be considered as the outer scale of turbulence, while the smallest eddy size is taken to be microscale or inner scale of turbulence. The values of the outer scale and the inner scale depend upon the height above the ground, both increasing with altitude.

Refractive index of the atmosphere is a function of both temperature and humidity of the air and is given by [158] :

$$(n-1) = 10^{-6} \times \frac{79}{T} (p_a + \frac{4800}{T} \rho_v) \quad \dots (2.1-1)$$

where

n - refractive index

T - temperature of the air

ρ_v - water vapour pressure

p_a - pressure of the atmosphere

The refractive index fluctuations are, as a result, dependent upon temperature and humidity variations which result from turbulent mixing of blobs of various dimensions. The effect of temperature and humidity fields in determining the refractive index variation has been studied [158] . It is often convenient to write the refractive index $n(\bar{r})$ at any point in space as

$$n(\bar{r}) = n_o(\bar{r}) + n_1(\bar{r}) \quad \dots (2.1-2)$$

where

$n_o(\bar{r})$ - mean value of the refractive index

$n_1(\bar{r})$ - random variation about its mean.

For turbulence considerations, the behaviour of $n_1(\bar{r})$ is of prime importance. The refractive index variations can be statistically described by a quantity called structure function, which has been discussed in detail by Tatarski [158] .

2.2 KOLMOGOROV'S THEORY OF TURBULENT FLOW

Statistical theories of turbulent flow were advanced in the year 1941 when Kolmogorov and Obukhov established the laws, which characterize the basic properties of the microstructure of turbulent flow at very large Reynold numbers.

Consider an initially laminar flow of a viscous fluid. This flow can be characterized by the value of kinematic viscosity ν , the characteristic velocity scale V and the characteristic length L_ℓ . The laminar flow is stable only in the case when the Reynold number $R_e = \frac{VL_\ell}{\nu}$ does not exceed a certain critical value R_{cr}. As the number R_e is increased, the motion becomes unstable. Suppose a velocity fluctuation v'_ℓ occurs in a region of size ℓ. The characteristic period $t_c = \ell / v'_\ell$ corresponding to this fluctuation specifies the order of magnitude of the time required for the occurrence of the fluctuation. The energy of the given fluctuation is proportional to v'^2_ℓ . Thus, when the velocity fluctuation under consideration occurs, the amount of energy per unit time is given by $v'^2_\ell / t_c \rightleftharpoons v'^3_\ell / \ell$. The energy dissipated as heat per unit mass per unit time is of the order of magnitude $\varepsilon = \frac{\nu \, v'^2_\ell}{\ell^2}$. If the velocity fluctuation is to exist, it is necessary that the inequality given by Eqn (2.2-1) holds, that is,

$$v_{\ell}'^{3} / \ell \quad > \quad \nu \, v_{\ell}'^{2} / \ell^{2} \qquad \ldots (2.2\text{-}1)$$

or
$$v_{\ell}'^{3} / \ell \;\Big/\; \nu \, v_{\ell}'^{2} / \ell^{2} > 1$$

or
$$\ell \, v_{\ell}' / \nu \quad = R_e > 1 \qquad \ldots (2.2\text{-}2)$$

R_e given by Eqn (2.2-2) is the inner Reynold number denoting the fluctuations corresponding to the size.

Let us assume that the number R_e is gradually increased, the laminar motion loses instability and velocity of fluctuations v_{ℓ}' occur. If the initial Reynold number $v_{\ell}' \ell / \nu$ was only a little longer than R_{cr}, then the fluctuations which arise have small velocities. This means that the first order velocity fluctuations, which arise, loose stability themselves and can transfer energy to new second order fluctuations. As the number R_e is increased further, the second order fluctuations become unstable and so on. Let the geometrical dimension of the smallest fluctuation be ℓ_o and let their velocity be v_o. For all the velocity fluctuations with size $\ell > \ell_o$, the inner number R_e is large. It follows from this that their direct energy dissipation is small compared to the energy which they receive from larger perturbations. Thus their fluctuations transfer almost all the energy they receive, to small perturbations. Consequently the quantity $v_{\ell}'^{3} / \ell$ which represents the energy per unit mass received per unit time by eddies of nth order from eddies of (n-1) th order and transferred by them to the eddies of the (n+1)th order, is constant for almost all the sizes. In the smallest velocity perturbations with size ℓ_o, this energy is converted into heat. The rate of dissipation of energy into heat is determined by the local velocity gradients in these smallest perturbations which is of the order of $\varepsilon \approx \frac{\nu v_o^2}{\ell_o^2}$. Thus for velocity fluctuations of all scales, we have,

$$v_\ell'^3 / \ell \approx \varepsilon$$

$$\text{or} \quad v_\ell' = (\varepsilon \ell)^{1/3} \qquad \ldots (2.2\text{-}3)$$

For all scales the size of the fluctuations depends on the energy dissipation rate ε. For smallest inhomogeneity

$$\left.\begin{aligned} v_o &\approx (\varepsilon_o \ell_o)^{1/3} \\ \frac{\nu v_o^2}{\ell_o^2} &\approx \varepsilon \end{aligned}\right\} \qquad \ldots (2.2\text{-}4)$$

From these equations one gets,

$$\left.\begin{aligned} \ell_o &\approx v_o^3 / \varepsilon \\ v_o &\approx \sqrt[4]{\nu \varepsilon} \end{aligned}\right\} \qquad \ldots (2.2\text{-}5)$$

The quantity ℓ_o can also be expressed in terms of the dimensions of largest eddy as

$$\left.\begin{aligned} \ell_o &= \frac{L}{(R_e)^{3/4}} \\ v_o &= \frac{V_L}{(R_e)^{1/4}} \end{aligned}\right\} \qquad \ldots(2.2\text{-}6)$$

Thus larger the Reynold number of the flow as a whole, the smaller the size of the velocity inhomogeneity which can arise.

2.3 ATTENUATION AND SCATTERING

Optical transmission through the clear atmosphere has been investigated both theoretically and experimentally by many workers [5] [17] [18] [23] [28] [33] [35] [71] [72] [101] [108] [109] [119] [120] [131] [153] [155] [162] [171] [172] .

These workers have reported that the constituents of the atmosphere form one of the limitations for optical transmission. These constituents can be classified in three categories.

(i) Particulate matter such as dust and aerosols

(ii) Precipitation manifesting itself in the form of haze, fog, rain and snow.

(iii) Absorbing gases such as carbon dioxide and water vapour.

The effect of particulate matter on optical radiation is to scatter energy away from the original direction of propagation. Precipitation in the form of droplets produces significant scattering, the precise amount depending upon the size of the droplets with respect to wavelength of radiation. It should be recalled that the water droplet may vary in size from a fraction of a micron, as in the case of aerosol and haze , to several centimeters as in the case of hail. The atmosphere also contains many gases having narrow and broad band absorption spectra, some of which coincide with laser wavelengths. Laser propagation is consequently difficult due to attenuation of the beam.

In the clear atmosphere, scattering and diffraction caused by inhomogeneities are of great importance, although the constituents of the atmosphere produce much more scattering and attenuation [102] [101] [108]. The attenuation and scattering of laser beam by rain, fog and snow have also been studied [28][29] . A simple picture of difference in attenuation of waves by fog and rain has been substantiated by theory and experiment. The relatively low attenuation by rain is, in part, the result of forward scattering. The scattering patterns of fog drops have little directivity compared with laser beams themselves therefore the forward scattering correction for the fog attenuation of narrow laser beams is small. If the beam width of the incident laser beam is comparable with the width of the scattering patterns of precipitation particles, the forward scattering will reduce the scattering loss significantly.

When the scattering of the precipitation particle is added to the original attenuated beam, a broadened beam is observed at the receiving plane. Measurements show that various degrees of beam broadening occur when a 0.63 μ laser beam propagates through precipitation . Beam broadening resulting from rain is more pronounced than that of snow and fog. Beam broadening measurements during clear weather do not differ much from those taken during snow fall. However, during the snow storm, the amount of beam broadening and attenuation is large [29] .

When a laser beam is incident on a turbulent medium then due to the turbulent mixing of various layers scattering of the beam occurs. The mean density of the energy scattered in a given direction has been calculated by Tatarski. The scattered energy comes out to be the sum of two spherical waves whose amplitude and phases depend on the refractive index fluctuations inside the given volume [158] .

Thus atmosphere has a pronounced effect on coherent light, even during fair weather. Useful optical transmission system which use the atmosphere as the transmission medium will require some useful techniques to achieve high reliability.

2.4 PHYSICAL CHARACTERISTICS

The turbulent atmosphere is an inhomogeneous medium in which the refractive index is a function of position and time. It is also described as to consist of large number of regions with varying dimensions called eddies, over which the refractive index deviates from the average. When a laser beam passes through such a medium, it interacts with the eddies, producing random variations in amplitude and phase of the signal. This randomness causes variety of effects which degrade the directivity and coherence property of laser radiation. A major effect is to deflect the beam randomly and it may miss the collecting aperture totally. The coherence degradation leads to beam broadening. In addition, the beam dancing due to beam deflection and image blurring or the intensity scintillation of the received image due to coherence degradation form the various effects encountered. Davis [35] discussed the physical basis for various effects of atmosphere turbulence on laser systems and summarised the Tatarski's results. The most important conclusion is that Tatarski's results for amplitude and phase fluctuations are not applicable to laser beam of arbitrary diameter, but provides an adequate approximation when the beam diameter is at least a factor of two greater than the lateral correlation length for amplitude fluctuations which is true in many applications. Hodara [71] derived from elementary principles, simple expressions giving order of magnitude for various effects of atmospheric turbulence on lasers. The various deleterious effects have been considered by several authors [2][27][70][71] [72][75] and are summarized below :

2.4.1 Beam Steering

The entire beam may be deviated from the line of sight giving rise to a loss of power at the receiver aperture, when the receiver is in the far field of transmitter.

2.4.2 Beam Dancing

Due to the time varying refractive index, there is a steady drift of the centre of the received beam. In addition to this drift there is a change in the angle of arrival of the beam. Thus the received wavefront becomes tilted related to the line-of-sight axis. The displacement of the image with time is called the beam dancing.

2.4.3 Beam Broadening

Small angle scattering by the inhomogeneities spreads the signal energy over a larger region. In case when the size of the beam is large compared to the turbulence scale size, the beam can be considered as consisting of many ray tubes, individually small compared to the scale size. Each of these tubes, is displaced from the unperturbed position in an uncorrelated manner and beam broadening results. Scattering by dust particles, aerosols, precipitation and turbulence all constitute the beam broadening.

2.4.4 Image Blurring

Destruction of the phase coherence across the beam leads to a blurring of the image. The interference between different parts of the beam take place in a time varying manner. The amount of blurring is proportional to the loss of coherence of the wavefront.

2.4.5 Random Beam Scanning

Time variation of refractive index gradient bring about beam scanning. Hodara [71] has derived expressions using geometrical optics approach. Beam deflection at a point is given as:

$$\Delta\theta_c = \Delta_n \frac{L_{cz}}{L_{cT}} \qquad \text{... (2.4-1)}$$

where

Δ_n - gradual index change,

L_{cz} - correlation distances parallel to the direction of propagation.

L_{cT} - correlation distances transverse to the direction of propagation.

The mean square temporal angular variation within a coherence interval is

$$\overline{\Delta\,\theta_c^2} = \overline{\Delta_c^2} \left(\frac{L_{cz}}{L_{cT}} \right)^2 \qquad \text{... (2.4-2)}$$

Over a path length L_p , the beam traverses L_p / L_{cz} coherence intervals. Because the deflections are uncorrelated from one interval to the other, they add upon a mean square basis and the total mean square deflection

$$\langle \Delta \theta_{MS}^2 \rangle = \frac{L_p}{L_{cz}} \overline{\Delta \theta_c^2}$$

$$= \overline{\Delta n^2} \frac{L_{cz} L_p}{L_{cT}^2} \qquad \ldots(2.4\text{-}3)$$

2.4.6 Random Phase Change

Phase changes may take place at random in the direction of propagation or perpendicular to it. The phase variations over the collecting aperture imposes limitations upon the maximum permissible amplitude modulation rate M_R

$$M_R \ll \frac{2\pi c}{\sqrt{2L_p L_c \overline{n^2}} \sqrt{1 - \exp(-D^2/L_c^2)}} \qquad \ldots(2.4\text{-}4)$$

D - collecting aperture diameter

2.4.7 Random Cross-section Change

A more serious limitation is caused by random changes in beam cross-section. The change in beam cross-section sets a lower permissible limit to the modulation depth w_m. The signal-to-noise ratio is given as

$$\frac{P_s}{P_N} = \frac{w_m^2}{2\left|\frac{\delta I}{I_o}\right|} \qquad \ldots(2.4\text{-}5)$$

where

I_o - initial undistorted intensity and

δI - change in the intensity.

The maximum tolerable value of w_m is one which satisfies the inequality

$$\left[\frac{2(P_s/P_N)}{(L/L_c)^3\ \overline{\Delta n^2}}\right]^{1/2} \leqslant w_m \leqslant 1 \qquad \ldots(2.4\text{-}6)$$

2.4.8 Phase and Frequency Fluctuations

Hodara [72] investigated the effects of atmospheric turbulence on the phase and frequency of optical waves. Turbulence induces random variations in optical path length along the various rays that make up the wave front. It results in phase fluctuations across the beam as well as along the beam. The former degrades the spatial coherence across the wave front, twisting it and bending it in random fashion. The latter reduces temporal coherence along each ray causing random frequency modulation. The spatial phase instability is described by comparing the phases of wave-fronts at two neighbouring observation points spaced ρ_ℓ apart in a plane perpendicular to the mean direction of the arrival of the beam. At these two points the phases are

$$\left.\begin{aligned} Ph_1 &= w_o t + \Psi_1 \\ Ph_2 &= w_o t + \Psi_2 \end{aligned}\right\} \qquad \ldots(2.4\text{-}7)$$

Ψ_1 and Ψ_2 are random variables describing phase fluctuations with zero mean and $< \Delta \Psi^2 >$ variance.

There are three quantities which are found to be useful to describe phase instabilities

The cross-correlation function

$$\Gamma_{\Psi}(\rho_{\ell}) = \langle \Psi_1 \quad \Psi_2 \rangle \qquad \ldots (2.4\text{-}8)$$

Structure function

$$D_{\Psi}(\rho_{\ell}) = \langle (\Psi_1 - \Psi_2)^2 \rangle \qquad \ldots (2.4\text{-}9)$$

Coherence function

$$\gamma_{12}(\rho_{\ell}) = \langle \exp \left[i(\Psi_1 - \Psi_2) \right] \rangle \ldots (2.4\text{-}10)$$

2.4.9 Frequency Instability

It has been pointed out that it is easy to measure the rate of change of phase in terms of frequency. Refractive index fluctuations along the path cause random variations in the arrival time of the successive wave fronts. The mean square frequency deviation is given as

$$\Delta f_r^2 = \frac{L_p L_c}{\gamma_o^2} \quad \frac{\langle \Delta n^2 \rangle}{\tau_c^2} \qquad \ldots (2.4\text{-}11)$$

where

L_p - path length

L_c - correlation length

τ_c - correlation time

2.4.10 Polarization and Angle of Arrival Fluctuation

Atmospheric turbulence produces fluctuations in polarization of laser beam. The initial polarization can be resolved into component E_{1x} in the plane of incidence and E_{1y} parallel to interface, then,

$$\tan Ph = \frac{E_{1y}}{E_{1x}} \qquad \ldots (2.4.12)$$

gives the initial angular direction of polarization. After refraction through the interface the transmitted components have different values E_{2x} and E_{2y} corresponding to a change in polarization given by

$$\tan (Ph + \Delta Ph) = \frac{E_{2y}}{E_{2x}} \qquad ...(2.4-13)$$

If a beam is propagating along a z-direction and at any point the correlation distance are L_{cz} and L_{cT}, parallel and transverse to the direction of propagation, then the random polarization variation is given as

$$\Delta Ph^2 = \sqrt{\frac{\Delta n^2}{2}} \; \frac{L_{cz}^2}{L_{cT}^2} \left[\frac{L}{L_{cz}} \right] \qquad ...(2.4-14)$$

This shows that mean square deviation in polarization angle is proportional to the mean square refractive index change.

2.5 ATMOSPHERIC SCINTILLATIONS

An infinite plane wave travelling through a turbulent atmosphere is subject to severe perturbations of its phase and intensity due to various physical effects caused by turbulence [39] [40] [43] [51] [53] [54] [93] [94] [119] [120] [159].

A convenient way of describing the intensity fluctuation is in terms of the fluctuations of the logarithm of amplitude. One is concerned with the covariance of the log amplitude measured at two points on a plane perpendicular to the nominal direction of propagation. The results concerning the log-amplitude covariance for propagation of an infinite plane wave were derived by Tataraski [158] . The root mean square log-amplitude fluctuation Ψ_i and r.m.s intensity fluctuation σ for a plane manochromatic wave propagating through the atmosphere may be approximated for small signal fluctuation by

$$\Psi_i^2 = \log (A/A_o)^2$$

$$= 0.31\ C_n^2\ K_w^{7/6}\ L_p^{11/6} \qquad \ldots(2.5\text{-}1)$$

$$\sigma^2 = 4\Psi_i^2 \qquad \ldots(2.5\text{-}2)$$

where,

- A - amplitude of the turbulence distorted electromagnetic wave
- A_o - amplitude in the absence of turbulence
- L_p - path length traversed
- K_w - wave number

Fried et al [52] made measurements of the scintillation of a laser beam after propagating over a 8 km path near the ground. Measurements were made of the statistics of scintillation for various collector sizes and under varied environmental conditions. They obtained accurate measurement of the refrac tive index structure constant, under variety of conditions. For laser beam propagation the collector aperture should be much less than the correlation distance. In a ground to ground optical communication it is necessary to reduce scintillation to prevent carrier fading and consequent loss of information Fried and Schmeltzer [50] analysed the effects of scintillation on an optical data channel and presented the numerical results. Fried [51] examined theoretically the effect of atmospheric distortion of an optical wavefront on the performance of an optical heterodyne detection system. The point of interest is the way in which the distortion of the wavefront and intensity variations affect the detector performance, particularly the average signal to noise ratio.

2.6 STRUCTURE FUNCTION AND LOG AMPLITUDE COVARIANCE

The statistical theory of optical propagation in a randomly inhomogeneous medium has been given in terms of the logarithm of the amplitude of irradiance by Tataraski [158] . The refractive index variations along a path of propagation modulate the intensity in a multiplicative manner. The variations induced in each subrange of the path then combine multiplicatively such that the effect of the atmosphere in each subrange is independent of the initial degree of coherence. These refractive index variations modulate the logarithm of the intensity and the amplitude in an additive manner, that is, the observed variation of the log-amplitude is the sum of the many random perturbations induced at various places along the path of propagation. As a consequence of the central limit theorem, the variations of the log-amplitude should follow a normal distribution.

During sunrise and sunset, temperature gradients close to the ground gradually change due to preferential heating or cooling of the air with respect to the ground and cause a steady drift in the mean value of refractive index. Thus the process is no longer stationary. Tataraski [158] called such processes as random process with stationary increments and said that a more adequate characterization of atmospheric turbulence for such processes is structure function defined as the mean square difference between index fluctuations at two points.

It has been shown by dimensional analysis that the structure function is given by the relation

$$D_n = C_n^2 \, r^{2/3} \qquad \ldots(2.6\text{-}1)$$

in the interval between inner and outer scale of turbulence, within the inner scale of turbulence, structure function is given as

$$D_n = C_n^2 \, \ell_o^{2/3} \, (r/\ell_o)^2 \qquad \ldots(2.6\text{-}2)$$

The approximate value of structure constant is given as

$$C_n^2 \approx \frac{\langle 1.9 \ \Delta n^2 \rangle}{L_o^{2/3}} \qquad \ldots(2.6\text{-}3)$$

Fried [52] developed the techniques for measurements of turbulence induced effects on optical propagation as a basis for remote probing of atmosphere. The optical strength of turbulence is measured by refractive index structure constant $C_n^2(z)$. At present there is very little data available on the value of optical strength as a function of altitude.

A relationship exists between the spatial covariance of scintillation and the distribution along the path of propagation of the optical strength of turbulence. The former is measured by the conventional log-amplitude covariance and the latter by the refractive index. The two quantities are related by an integral equation as

$$C_{\ell}(\rho) = K_w^{7/6} \int_0^{\infty} z^{5/6} C_n^2(z) F\left(\frac{K_w \rho^2}{4z}\right) dz \qquad \ldots(2.6\text{-}6)$$

where $F\left(\frac{K_w \rho^2}{4z}\right)$ is a function which is represented in a series form. An analytical expression is also known [90] for the function of log-amplitude covariance to include its temporal and spatial dependence. The spatial-temporal log-amplitude covariance is given by

$$C_{\ell}(\rho, t_s) = K_w^{7/6} \int_0^{\infty} z^{5/6} C_n^2(z) F\left[\frac{K_w}{4z}\left\{\rho - V(z)t_s\right\}^2\right] dz \qquad \ldots(2.6\text{-}7)$$

where V(z) is wind velocity at an altitude z.

From Eqn (2.6-6) and Eqn(2.6-7) the values of the structure constant at various altitudes and the values of spatial-temporal log-amplitude covariance can be found. Fig. 2-1 and Fig. 2-2 indicate the variations mentioned above. The covariance data can be used to determine the expected signal-to-noise ratio [85] .

CHAPTER - III

M-ARY LASER DETECTION IN BACKGROUND RADIATION NOISE

3.1 INTRODUCTION

The reception of signal in noise presents problems of critical importance in the theory of communication, since noise of varying degrees always obscures the desired signal or message. Because the observation period during which the signal may be recovered is necessarily limited and because of the inherently statistical character of signal and interference, information is lost and recovery incomplete. Of course, reception of signals under such conditions can usually be carried out in a variety of ways, but very few of these possess optimum properties.

The performance of communication systems employing M-ary signalling alphabet in a noisy environment is of paramount importance. Their high capability of information transfer, one of M- possibilities, makes them attractive to any potential user of such a communication. At the same time, the immunity to noise and the required bandwidth and symbol duration of the signals of M-ary communication system must be answered before a decision on its desirability is made. The equipment complexity, the sensitivity of the M-ary system to network tolerances and to unexpected changes in noise statistics must be ascertained.

In the past, analysis of binary communication and detection, both for phase coherent and phase incoherent has received wide attention [6] [8] [13] [22] [23] [24] [26] [31] [65] [68] [114] [115] [116] [125] [127] [137] .

The derivation of error probabilities and channel capacity under fading conditions, random multipath and non white noise has also been given [11] [12] [14] [15] [34] [44] [45] [57] [61] [62] [69] [79] [100] [108] [134] [123] [124] [138] [154] [157] [160] .

For M-ary communication, a number of results of orthogonal signals are available. Some approximate results for the error probabilities have been derived by various authors [1] [10] [66] [78] [97] [117] [118] [128] [129] [130] [147] [149] [150] [170] [161] [173].

The problem of optimum reception of binary Gaussian signal and M-ary Gaussian signal in Gaussian noise in terms of the observable waveforms has been considered and a scheme for deciding among M alternative mean and covariance with minimum probability of error has been given by Kadota [81] [82] [83] .

To cope with the large communication traffic over various distances on overland routes, greater signal band widths are required. For large bandwidth, the use of laser beam to communicate information is becoming increasingly important. In a laser communication one is concerned with a photon counter at the receiver and the ensuing photo electron statistics that results when a laser beam is incident on a photoemissive surface of the counter.

A knowledge of the output statistics of a quantum detector is necessary for the application of the techniques of optimum detection and estimation theory. In the physical theory of coherence these statistics are a means by which the light incident on the detector can be studied. In both the cases, a useful statistics, which is relatively easy to evaluate is the probability of detecting events or counts in the given interval of time. In an idealized detector, the conditional probability of k counts in a given time interval, with known incident radiation, can be shown to obey Poisson law, with the time average intensity of the field as rate parameter. There have been a lot of controversy regarding the detector statistics. The assumption of Poisson statistics is valid for dark current and background illumination of thermal origin and for signals from a thermal source such a luminiscent diode at small signal level encountered in a communication receiver. Photon statistics and communication under Poisson regime and communication with lasers has been of interest to many workers [4] [7] [33] [36] [77] [38] [46] [47] [48] [58] [80] [86] [87] [88] [98] [99] [110] [132] [133] [148] [163] . Usually signals from lasers do not exhibit exactly Poisson distribution. However, for signals from a single mode or a mode locked multimode laser with coherence time long compared with the duration of the signal pulse and operating well above threshold, the Poisson statistics is valid.

In what follows, after giving a brief idea about photon statistics and background radiation noise, a detailed study for the detection of a set of all possible M-ary coded system each using large average photon statistics has been carried out. An expression has been derived for the upper bound on error probability averaged over this set of systems.

3.2 PHOTON STATISTICS

The description of the photo-electron statistics emitted from a material stimulated by sources has been treated both semi-classically and strictly quantum mechanically. The semi-classical treatment amounts to treating the light incident on a photo-emissive surface classically and using first order perturbation theory to account for photo-emission from the surface matter. For a number of situations, the two approaches yield similar results. Mandel [105] [106] has shown that the probability of photo-emission of electrons in the interval t to $t+\tau$ for any time t is

$$p(n,t,\tau) = \frac{1}{\lfloor n} \left[\eta\, U(t,\tau)\right]^{n} \exp\left[-\eta\, U(t,\tau)\right] \qquad \ldots(3.2\text{-}1)$$

where,

$$U(t,\tau) = \int_{\tau}^{T+\tau} I(t')\, dt' \qquad \ldots(3.2\text{-}2)$$

$I(t)$ - instantaneous incident intensity

This result is obtained by solving the problem of an electric field interacting with a photo-emissive surface using perturbation theory. The probability of emission of a single electron in the time Δt is

$$p(1,t,\tau)\,\Delta t = \eta\, I\,(t)\,\Delta t \qquad \ldots(3.2\text{-}3)$$

where,

η - quantum efficiency of the detector

The average mean count recorded in time τ is

$$\bar{n} = \eta\, U\,(t,\tau) \qquad \ldots(3.2\text{-}4)$$

and the average variance recorded in time τ is

$$\overline{\sigma_n^2} = n + \eta^2\, \overline{(\Delta U)^2} \qquad \ldots(3.2\text{-}5)$$

here,

$$\overline{(\Delta U)^2} = \overline{U^2(t,\tau)} - \overline{U(t,\tau)}^2$$

$\bar{n}$ in Eqn (3.2-5) represents the fluctuation associated with particles obeying a Poisson distribution and the second term in Eqn (3.2-5) can be interpretted as a photon-bunching effect called the excess noise.

When the output of the laser is a mixture of many modes plus noise, the distribution can be difficult to find. The extension of semi-classical techniques to a source that is a mixture of multimode signal plus noise has been attempted by Hodara and others.

In optical receiving system, photodetectors convert the observed optical radiation into electrical output signals. Output is modelled as a sequence of electron counts and the optical photoelectrons obey Poisson statistics. The occurrence of event over an observed interval Δt is said to obey Poisson process if the probability of exactly k events occurring is given by

$$p(k) = \frac{(n\Delta t)^k \, e^{-n\Delta t}}{\underline{|k}} \qquad \ldots(3.2\text{-}6)$$

The parameter n is the average rate of occurrence and is called the intensity of the process. If the event occurs in a sequence of interval Δt , in which density may vary from one interval to next, but is constant over each interval, then it is a discrete time varying process. In photo detection each event corresponds to the emission of an electron which occurs upon arrival of a photon, each photon having a fixed energy. The level is therefore proportional to average energy received per interval, while the intensity n is proportional to the average power.

When the average number of arrival during the observing time is large, the fluctuations approach a Gaussian distribution about the mean with $\sigma = \sqrt{n}$. The emission photoelectron statistics from an idealized photoemissive surface when laser light impinges on it, has been examined. Both experimental and theoretical treatments have been given by various authors. In practical communication systems, the received radiation, which has propagated through a random medium may loose its coherence. In addition, the receiver photo-emissive surface may not be uniform. Thus the condition maintained in the laboratory when verifying theoretical work may not be reproducible in a practical communication system.

3.3 NOISE CONSIDERATIONS

Optical receiver performance is often limited by background radiation from the sun, moon, planet , stars and sky. These radiations impair the laser signal thereby increasing the detector shot noise level.

Background noise is analysed by modelling the receiver photodetector output as a Poisson process with a rate parameter proportional to the detected optical power P. With P in watts, the average detected current I in amperes is found to be

$$I = \frac{\eta q}{h\nu} \qquad \ldots(3.3\text{-}1)$$

where,

η - is the detector quantum efficiency

ν - is the frequency of the incident optical radiation in hertz.

The mean square fluctuation about the average current I has the value 2q I B, where B is the electrical bandwidth of the photodetector in hertz. This variation is often represented as a noise current whose r.m.s value is $\sqrt{2qIB}$. The current I is composed of three component currents: the current I_s resulting from detector information carrying signal P_s , the current I_b resulting from undesired background P_b and dark current I_d . Hence,

$$I = I_s + I_b + I_d$$

$$= \frac{\eta q}{h\nu} (P_s + P_b) + I_d \qquad \ldots(3.3\text{-}2)$$

This equation shows that the noise current fluctuations occur even when the dark current I_d and background current I_b are negligible compared to the signal current I_s. This is the case of noise in signal or self noise. Of course, background noise and dark current add to these self noise fluctuations in every laser communication system and thus it becomes desirable to minimize their contribution. The mean number of photon in a single quantum state is

$$\overline{n_s} = \frac{1}{e^{h\nu/kT} - 1} \qquad \ldots(3.3\text{-}3)$$

In order to arrive at the amount of fluctuation in the radiation itself, one must consider the fluctuation in each quantum state.

The mean square fluctuation in the photon case is given as,

$$\overline{n_s^2} = \frac{e^{h\nu/KT}}{(e^{h\nu/KT} - 1)^2}$$

$$= \overline{n_s} \, (1 + \overline{n_s}) \qquad \ldots(3.3\text{-}4)$$

The noise energy in a signal will be at least $h\nu$, the average background noise competing with the signal may be much less than $h\nu$ if average number of background photons are much less than the number of signal photons. Since this means that in the same time frame in which one signal photon is received, on the average, much less than one background photon will be received.

Discrimination against background noise can be made by choosing a detector with high quantum efficiency. The background noise can be minimised by :

(i) Reducing the input optical spectrum to that of the transmitted spectrum by means of an optical filter.

(ii) Reducing the field of view to the minimum possible for system operation.

(iii) Reducing the post detection bandwidth to the minimum that will pass information.

In short one can say that the best detector to discriminate against the background noise is the detector with the highest quantum efficiency and the best detector to discriminate against internal noise is the detector with the lowest noise equivalent power.

3.4 CHARACTERIZATION OF PHOTON COUNT DETECTION SYSTEM

In the laser communication system, as has been previously mentioned, one is concerned with a photon counter at the receiver and the ensuing photo-electron statistics that results when the M-ary laser beam is incident on a photo-emissive surface of the detector. The model of such a communication system is shown in Fig. 3.1.

The transmitter sends a signal whose intensity is modulated with one of a set of M-possible intensities each T second long. The received signal is corrupted by background radiation noise. The output of the photo-detector at the receiver is a time varying process of electron counts. The receiver observes the counting process over the time interval (0,t) and decides which of the M-possible intensities is received. The information signal may take any one of the M possible forms $\{m_i\}$ where $i = 0,1,2,\ldots,M-1$ with the sequence of discrete digits it is possible to characterize the transmission capability required to communicate the source output to a distant terminal. In the simplest case, one can have a source that produces statistically independent binary digits, each of which is equally likely at a uniform rate of I bits / second. During any interval of time T, this source generates a sequence of IT binary digits. The transmitter alphabet consists of L photon count levels $(a_1, a_2, \ldots, a_L)$ each having the dimension r.

The output of the transmitter will thus be a different T second long multiphoton count signal. This output is designated as,

$$\{P_i\} = (P_{i1}, P_{i2}, \ldots, P_{ir}) \qquad \ldots(3.4\text{-}1)$$
$$i = 0,1,2,\ldots,M-1$$

The output of the photodetector consists of a vector set of the photo electron counts

$$\{Q_i\} = (q_{i1}, q_{i2}, \ldots, q_{ir}) \qquad \ldots(3.4\text{-}2)$$
$$i = 0,1,2,\ldots,M-1$$

Each of the q_i's consist of two components, one is the average count which is the result of the signal current while the other is caused by the thermal and shot noise produced in the photodetector. If the efficiency of the detector is η, then the vector set $\{V_i\}$ of the average component is given as

$$\{V_i\} = (\eta\, p_{i1}, \eta\, p_{i2}, \ldots, \eta\, p_{ir}) \qquad \ldots(3.4\text{-}3)$$
$$i = 0,1,2,\ldots, M-1$$

$$= (V_{i1}, V_{i2}, \ldots, V_{ir}) \qquad \ldots(3.4\text{-}4)$$
$$i = 0,1,2,\ldots,M-1$$

The vector set of noise photo-electrons is given as

$$\{N_i\} = (n_{i1}, n_{i2}, \ldots, n_{ir}) \qquad \ldots(3.4\text{-}5)$$
$$i = 0,1,2,\ldots,M-1$$

3.5 PROBABILITY OF ERROR BOUND

In this section the objective is to derive an expression for the average error probability bound for the entire ensembles of possible signals of the transmitter output. This will help in making a judicious choice of particular signal to meet any given performance criterion. It is assumed in analysis to follow that the photon count represented even by the lowest alphabet letter is large and the maximum distance between the alphabet letters is very small. Alphabets are also assumed to be equispaced.

The probability density of receiving Q_i counts is given by the Gaussian distribution since the photon counts are assumed to be large [122][131] . Therefore

$$f(Q_i / V_i) = \frac{1}{(2\pi V)^{r/2}} \exp \left[-(Q_i - V_i)^2 / 2V \right] \quad \ldots(3.5\text{-}1)$$

where,

$$V = V_1 + \sigma_t^2 \cdot \frac{t_{ot}^2}{C_e}$$

$$V_1 = \frac{1}{L} \sum_{j=1}^{L} b_j$$

$$b_j = \eta\, a_j \ , \qquad j = 1,2,\ldots,L$$

σ_t^2 = variance of the detector thermal noise current.

t_{ot} - observation time

C_e - charge of electron

To reduce the error, the average signal photo electron count at the receiver has been taken as V_1, the arithmatic average of various letters of the received alphabets. The optimum detector observes the entire sequence and decides in favour of that m_i which maximizes the a-posteriori probability, that is, the receiver sets the optimum value of m_i as $\hat{m} = m_k$, if $f(m_i)f(Q_i / V_i)$ is maximum for $i = k$, where $i = 0,1,2,\ldots,M-1 \cdot f(m_i)$ is the a-priori probability of the transmitted message. Since the logarithm of a function is a monotonic function therefore, the maximization of the a-posteriori probability given above is equivalent to the maximization of

$$\log \left[f(m_i) \; f(Q_i / V_i) \right] \qquad \ldots(3.5\text{-}2)$$

Substituting Eqn (3.5-1) in Eqn (3.5-2) it follows that the maximization of Eqn (3.5-2) is equivalent to the minimization of

$$(Q_i - V_i)^2 - 2V \log \left[f(m_i) \right] \qquad \ldots(3.5\text{-}3)$$

This decision rule can be implemented either by a bank of correlators or matched filter.

Since the average number of photo-electrons during the observing time is large, the fluctuations approach a Gaussian distribution given by [131]

$$f(N_i) = \frac{1}{(2\pi V)^{r/2}} \exp \left[- |N_i|^2 \Big/ 2V \right] \ldots(3.5\text{-}4)$$

Let $f(E/V_k)$ denote the probability of error when the transmitted signal is m_k. An approximation to $f(E/V_k)$ for any set of M equally likely signals in additive Gaussian noise is obtained by noting that an error occurs when V_i is transmitted, if and only if, the received data is closer to at least one signal V_k , $k \neq i$, If E_{ki} is used to denote the event that the receiver decides in favour of V_i when V_k is transmitted , then

$$f(E/V_k) = f(E_{ko} \cup E_{k1} \cup \ldots \cup E_{kM-1})$$

Now since the probability of a finite union of events is bounded above by the sum of probabilities of the constituent event

$$\therefore \quad f(E/V_k) \leqslant \sum_{\substack{i=0 \\ i \neq k}}^{M-1} f(E_{ki})$$

$$= \sum_{\substack{i=0 \\ i \neq k}}^{M-1} Q\left[\frac{(V_i - V_k)}{\sqrt{4V}}\right] \qquad \ldots(3.5\text{-}5)$$

where,

$$Q(x) = \frac{1}{2\pi} \int_x^{\infty} e^{-t^2/2} \, dt$$

The average value of the probability $f(E_{ki})$ is given as

$$\overline{f(E_{ki})} = \sum_{\substack{\text{for all} \\ \text{photon} \\ \text{count}}} f(V_i)\, f(E_{ki}) \qquad \ldots(3.5\text{-}6)$$

and

$$\overline{f(E/V_k)} = \sum_{\substack{i=0 \\ i \neq k}}^{M-1} \left[\sum_{\substack{\text{for all} \\ \text{photon} \\ \text{count}}} f(V_i)\, f(E_{ki}) \right]$$

$$= \sum_{\substack{i=0 \\ i \neq k}}^{M-1} \overline{f(E_{ki})} \qquad \ldots(3.5\text{-}7)$$

It is well known from the theory of Q-function that

$$Q(x) < \exp\left[-x^2/2\right] \qquad \ldots(3.5\text{-}8)$$

$$\therefore \quad f(E_{ki}) = Q\left[\frac{V_i - V_k}{\sqrt{4V}}\right]$$

$$< \exp\left[-\frac{(V_i - V_k)^2}{8V}\right]$$

$$= \exp\left[-\frac{1}{8V}\sum_{\ell=1}^{r}(V_{i\ell} - V_{k\ell})^2\right]$$

$$= \prod_{\ell=1}^{r} \exp\left[-\frac{1}{8V}(V_{i\ell} - V_{k\ell})^2\right] \qquad \ldots(3.5\text{-}9)$$

where $V_{i\ell}$ and $V_{k\ell}$ are the components of V_i and V_k respectively. The average value of $f(E_{ki})$ will be

$$\overline{f(E_{ki})} < E\left[\prod_{\ell=1}^{r} \exp\left[-\frac{1}{8V}(V_{i\ell} - V_{k\ell})^2\right]\right] \qquad \ldots(3.5\text{-}10)$$

Let the distance between the S^{th} alphabet and u^{th} alphabet be

$$d_{Su} = (b_s - b_u)$$

$$s,u = 1,2,\ldots, L$$

Further let,

$$V_{i\ell} = b_s \text{ and } V_{k\ell} = b_u \text{ , then}$$

$$(V_{i\ell} - V_{k\ell})^2 = d_{su}^2 \qquad \ldots(3.5\text{-}11)$$

over the ensemble of photon signals, the probability of the joint event $(V_{i\ell} = b_s , V_{k\ell} = b_u)$ is $f_s f_u$, independent of the coordinate ℓ , therefore,

$$f\left[d_{su}^2\right] = f\left[(V_{i\ell} - V_{k\ell})^2\right] = f_s f_u \qquad \ldots(3.5\text{-}12)$$

independent of all i and k.

The statistical independence of $(V_{i\ell} - V_{k\ell})^2$ permits the simplification of Eqn (3.5-10) by using the fact that the expected value of a product of statistically independent random variables is product of their expected values. Therefore, Eqn (3.5-10) can be written as

$$\overline{f(E_{ki})} < \prod_{\ell=1}^{r} E\left[\exp\left[-\frac{1}{8V}(V_{i\ell} - V_{k\ell})^2\right]\right] \qquad \ldots(3.5\text{-}13)$$

From Eqn (3.5-12)

$$E\left[\exp\left[-\frac{1}{8V}(V_{i\ell} - V_{k\ell})^2\right]\right]$$

$$= \sum_{s=1}^{L}\sum_{u=1}^{L} f\left[(V_{i\ell} - V_{k\ell})^2 = d_{su}^2\right] \exp\left[-d_{su}^2 / 8V\right]$$

$$= \sum_{s=1}^{L} \sum_{u=1}^{L} f_s \, f_u \exp \left(-d_{su}^2 / 8V\right) \qquad \ldots(3.5\text{-}14)$$

Let,

$$I_o = -\log \left[\sum_{s=1}^{L} \sum_{u=1}^{L} f_s f_u \exp \left(-d_{su}^2 / 8V\right) \right] \qquad \ldots(3.5\text{-}15)$$

$$\therefore \quad \overline{f(E_{ki})} < \prod_{\ell=1}^{r} \sum_{s=1}^{L} \sum_{u=1}^{L} f_s f_u \exp \left[-d_{su}^2 / 8V\right]$$

$$= \prod_{\ell=1}^{r} 2^{-I_o}$$

$$= 2^{-rI_o}$$

$$\therefore \quad \overline{f(E_{ki})} < 2^{-rI_o} \qquad \ldots(3.5\text{-}16)$$

Since the bound given by Eqn (3.5-16) is valid for all values of i and k

$$\overline{f(E_{ki})} = \overline{f(E)} \qquad \ldots(3.5\text{-}17)$$

If I_r is the transmission rate in bits per dimension, then $M = 2^{rI_r}$. Therefore using Eqn (3.5-7), (3.5-16) and (3.5-17)

$$\overline{f(E)} < 2^{-r(I_o - I_r)} \qquad \ldots(3.5\text{-}18)$$

Eqn (3.5-18) shows that as long as the transmission rate I_r is less than the factor I_o, the average probability of error can be made arbitrarily small by taking the dimension **r** sufficiently large. In the special case when all the alphabet symbols are equally likely, then Eq. (3.5-15) gives

$$I_o = -\log_2 \frac{1}{L^2} \sum_{s=1}^{L} \sum_{u=1}^{L} \exp\,(d_{su}^2 / 8V) \qquad \ldots(3.5\text{-}19)$$

d_{su} can be expressed as

$$d_{su} = \frac{b_L - b_1}{L-1}\,(s-u)$$

If

$$b_1 = 0.99\, b_L$$

$$d_{su} = \frac{0.01}{L-1}\,(s-u) \qquad \ldots(3.5\text{-}20)$$

With Eqn (3.5-20) in Eqn (3.5-19) it is seen that I_o can be expressed as a function of b_L^2 / V - a measure of peak received signal energy divided by the noise power. Values of I_o have been calculated for different values of b_L^2 / V with the help of IBM 1620 computer and results obtained are shown in Fig. 3.2 . The computer program and results are shown in Appendix II. From Fig. 3.2 and Eqn (3.5-19) it is evident that maximum value of I_o is

$$(I_o)_{max} = \log_2^L \quad \text{bits / dimension}$$

and the exponentially decaying nature of average probability of error given by Eqn (3.5-18) now holds for larger information rates per dimension.

3.6 COMMENTS

It can be concluded that for a laser communication system the probability of error achievable with optimum a-posteriori probability computing receiver satisfies the simple bound given by Eqn (3.5-18) with $M = 2^{rI_r}$ and I_o a function of signal energy to noise power ratio as given by Fig. 3.2.

With the help of the bound given by Eqn (3.5-18) it may be possible to attain any required standard of performance in terms of the allowable probability of error. Reliability has always been considered during system design . However, as systems have become increasingly complex, the reliability problem has become more acute. A major objec tive of system reliability analysis is to investigate the means by which a reliability requirement or goal can be achieved in the best possible way. This means a thorough analysis of the relationship of reliability with the other important parameters of the system. In the previous section, the average probability of error for large average photon statistics has been derived. More complete knowledge of the achievable error performance provided by I_o is embodied in a function called reliability function [84] as is discussed in Appendix I.

The reliability equation shows that reliability depends on number of parameters, such as average number of signal photon, average number of noise photons, information rate and the channel capacity. For the laser communication system to be more reliable, the average number of noise photons should be less. This can be made small by avoiding the background radiation. Therefore in the system, there should be proper arrangement to nullify the effect of background radiation which can be done by the use of proper optical filters.

CHAPTER IV

OPTIMUM RECEIVER STRUCTURE FOR LASER SIGNAL PERTURBED BY ATMOSPHERIC TURBULENCE

4.1 INTRODUCTION

The performance and structure of a receiver in a communication system depends on the form of signal used to transmit messages and on the nature of random noise that accompanies the signal . The tools of probability and statistics are used to design receivers which discriminate noise corrupted signals from noise only or which distinguish between different signals in the presence of noise. By an optimum receiver is meant a receiver which best satisfies a given criteria under a given set of assumptions. The principal approaches of optimizing the reception of signal contaminated with noise has been considered by various authors. One of the criteria for optimum reception is the maximization of signal-to-noise ratio This was one of the earliest criteria investigated. Previously, band-pass filtering techniques were developed to effect discrimination between a desired signal and an interferring signal with adjacent but non-overlapping spectra. Matched filter theory is one of the important results of this criterion.

Another approach to the optimum reception problem that has received considerable attention is based on the methods of statistical interference. The application of statistical decision theory to problems in communication is being actively pursued. Despite the power of the method, certain limitations restrict its range of application. These limitations result from requirements on the system model that can never be completely satisfied in practice. One limitation is concerned with the cost assignments. A more important limitation stems from the need for a-priori information concerning both the signal and noise processes.

It has been found that the receiving process can be described as a transformation from a set of a-priori probabilities to a set of a-posteriori probabilities for every possible transmitted message. It can be explained by means of an ideal observer that calculates the a-posteriori probabilities of all possible message from the received wave form and present this information to another observer at the receiving end, in suitable form. Since the received waveform usually contains more information than that required to compute the a-posteriori probabilities, the total receiver must eliminate undesired information. Undesired information in this context refers to extraneous noise interference as well as information not pertinent to the desired output. Once the ideal observer presents the available information in the form of an a-posteriori distribution, the observed may select the most probable message as the one with the greatest posterior probability.

Let $X_1, X_2, \ldots, X_n$ constitute a complete set of possible transmitted signals,with a priori probability $p(X_i)$ associated with the signal X_i, Let $y_1, y_2, \ldots, y_n$ represent the possible received wave form.If X_i is transmitted and y_k is received, y_k may not be identified with X_i because of noise. After the waveform y_k has been received, the state of knowledge of the observer is altered. In the case of noise free transmisssion medium, one signal in the set is unmistakably singled out, that is,its probability of occurrence has increased to unity. The probabilities of occurrence of all other signals in the set simultaneously decreases to zero in this case.

If, however, waveform y_k is contaminated by noise there is a doubt concerning the exact identity of the transmitted message or signal. This is particularly true when two or more signals in the set are similar to one another. In this case the situation after reception can be represented by a set of a-posteriori probabilities which describe the probabilities that the received waveform y_k contains signal X_i. The a-posteriori probability that signal X_i is present in y_k is described by the conditional probability $p(X_i/y_k)$ that is, the probability of X_i given that y_k is received. Thus, in the a-posteriori theory of reception, a posteriori probability and probability densities provide a complete description of the results of the receiving process. In order to attack a problem by using statistical methods, certain information must be available before hand. One should know, more particularly, the statistics of noise and, if possible, also the statistics of the signal. The less one can assume known concerning these, the more difficult is the solution in general. A clear statement should be available concerning the number of alternatives among which the decision must be made. In addition to this, another datum is required for the problem, namely, a criterion of excellence by which the performance of a reception system can be rated and with respect to which the optimization can be carried out. Once the criterion is selected, the optimum system is in principle determined. It is important, however, to understand the strength and the limitations of this theoretical approach. In practice , performance specifications are rarely explicit enough, to fix the optimum system uniquely . More often, the designer must himself supply a definition of best for the situation at hand, which is sufficiently precise to determine a unique system and which at the same time accurately reflects the given design constraints.

Optimum design depends on the nature of signal and noise statistics, and it is usually assumed that some knowledge of these is available. However , in practice reliable estimates of these distribution, are not easy to obtain. So optimum performance may be defined and determined in situations where the signal probabilities are unknown, or only partially known.

The theory of posterior reception has been applied to a laser communication system using photon counting detection to obtain optimum receivers in the case of signal perturbed by background radiation noise and by random variations in phase and gain due to atmospheric turbulence.

In the subsequent sections, after the precise characterization of the additive noise, the randomly varying parameters and the transmitter, an analytical expression has been derived for the a-posteriori probability of detecting the M-possible signals and then to give a decision in favour of that signal which gives the maximum a-posteriori probability,. The receiver structures are also proposed.

4.2 ADDITIVE NOISE CHARACTERIZATION

Optical receiver performance is often limited by background radiation from the sun, moon, planets, stars and sky. Background radiation impairs laser signal detection by increasing the detector noise level. The origin and magnitude of the several kinds of background noise, including background radiation sources viewed directly, radiation reflected from background objects and radiation scattered by the atmosphere into the receiver field of view has been discussed at large. Also the effect of background radiation noise on the performance of optical system has also been dealt with by various authors.

Reception with the sun as a direct background is usually not feasible because of its high brightness. The sky presents a background radiance due to scattering of incident radiation and due to emission by atmospheric particles as a result of absorption of incident radiation. At night, incident sky radiation, is due to star light, galactic light, air glow and scattered light from these sources.

Background radiation from the moon and planets consists of reflected sunlight and self emission, by the bodies. The reflected radiation spectrum is the same as the sun's spectrum, but the radiation intensity is reduced by the absorption of the body. The spectral distribution of radiation reflected from the moon and the planet is similar to that of the sun differing primarily in magnitude. This magnitude is determined by the distance traversed by the radiation, the ratio of the total reflected radiation to the total incident radiation properties of the reflecting bodies and its orientation with respect to the sun and the receiver.

The background radiation noise is assumed to be additive noise, the samples of which are statistically independent. This assumption ensures the maximum randomness.

Also, let it be that each sample of the additive noise has the same mean square value so that the squared samples contribute to the total energy of the noise. If all the samples are assumed to have Gaussian distribution with zero mean, then the entropy will be maximum. Such type of additive noise is stationary white Gaussian noise as given by Woodwards [169] . The probability distribution is given as :

$$p(n) = k \exp \left[- \frac{1}{N_o} \int_0^T n^2(t)\,dt \right] \qquad \ldots(4.2\text{-}1)$$

This has a constant power spectral density N_o over the bandwidth sufficiently wide to cover the transmission band. In Eqn (4.2-1) T represents the length of the noise data and k is the normalizing constant of the density. This noise is further assumed to be independent of signal and channel disturbances.

4.3 CHARACTERIZATION OF RANDOMLY VARYING PARAMETER

The preceding section has dealt with the statistical characterization of the background radiation noise which accompanies the signal. However, this is not the only undesirable feature which affects the signal parameters. When a laser beam traverses through the atmosphere, then it comes across the inhomogeneities in the atmosphere which are called eddies . These eddies are of various sizes. The message signal after having encountered with the inhomogenieties takes number of transmission paths. Each path has a different path length and transmission delay, but for one particular path the length and delay may be assumed to be fixed. Because of the difference in path length and transmission delay, the transmittance of the signal varies. The variation in transmittance gives rise to distortion of received signals, with resultant transmission impairments of various kinds. The transmittance variations give rise to distortion and intersymbol interference so that the error probability is increased.

In the turbulent case one is faced with a slowly varying fading channel which differs from the often considered Gaussian fading channel because the amplitude variations have a log-normal rather than Rayleigh distribution.

The liability to deep signal fades and resultant excessive transmission impairments can be significantly reduced by various methods which depend on resultant probability distribution of the combined signal-to-noise ratios.

In order to describe the random phase variations, its probability density should be such as to specify the variations in a generalized form. This density can be given as

$$p(\varphi) = \frac{\exp(\alpha \cos \varphi)}{2 \pi I_o(\alpha)} , \quad -\pi \leq \varphi \leq \pi \qquad \ldots(4.3\text{-}1)$$

where,

α - spread of density

$I_o(\alpha)$ - Bessel function of first kind.

Eqn (4.3-1) gives a family of densities, members of which depend on the values of α . This family of probability density for phase angle has been described and plotted by Vantrees [164] , and as mentioned by him was first used by Viterbi [165].

The probability density for the random gain variation can be specified by taking into consideration the fact that in the case of turbulence the multipathing severely affects the gain of the received signal [16] . The multipathing causes the gain in the signal to fade in time. As indicated by Brookner [16] , this type of gain variations of the signal have log-normal distribution given as

$$p(G) = \frac{1}{\sigma G \sqrt{2\pi}} \exp \left[\frac{(\log G - \mu)^2}{2 \sigma^2} \right] \qquad \ldots(4.3\text{-}2)$$

where,

μ - average value of gain

σ^2 - variance of the random gain

4.4 TRANSMITTER CHARACTERIZATION

The transmitter sends a signal whose intensity is modulated with one of a set of M-possible intensities each T-second long. One can associate a signal energy component m_k for the k^{th} intensity. Thus the transmitter sends a set of M-message signal $m_1, m_2, \ldots, m_k, \ldots, m_M$. During an interval of T-sec., one of the M equal energy signal is known to be transmitted. If signal m_k is generated, then the information which is transmitted into the channel is given as $m_k \cos \omega t$. The output of the channel will be x_k under the hypothesis than m_k was transmitted. The signal x_k is perturbed by additive noise which is due to back ground radiation. The additive noise is assumed to be white Gaussian noise n(t) with a constant spectral density N_o.

Due to the atmospheric inhomogeneities in the turbulent atmosphere, the transmitted signal takes a number of paths which is called multipathing. Due to this multipathing there is time delay in receiving the signal. Each path has got different path lengths, different transmission delays, gain and phase but for one particular path these parameters namely path length, delay, gain and phase may be assumed to be fixed. Let G_i, φ_i and τ_i be the gain, phase and delay for this i^{th} random path. At any instant of time, the state of the multipath is characterized by the vectors :

$$\left.\begin{aligned} \bar{G} &= G_1, G_2, \ldots G_i, \ldots, G_n \\ \bar{\varphi} &= \varphi_1, \varphi_2, \ldots \varphi_i, \ldots, \varphi_n \\ \bar{\tau} &= \tau_1, \tau_2, \ldots \tau_i, \ldots, \tau_n \end{aligned}\right\} \quad \ldots(4.4\text{-}1)$$

The variation in each parameter is random. Thus $\bar{G}$, $\bar{\varphi}$ and $\bar{\tau}$ are random variables each of which can be represented by a probability density function. The multipath channel is represented as ($\bar{G}$, $\bar{\varphi}$, $\bar{\tau}$) where the symbols $\bar{G}$, $\bar{\varphi}$ and $\bar{\tau}$ are defined by the equation (4.4-1). Thus the output of the channel is given as,

$$x_k = \sum_{i=1}^{n} G_i m_k(t - \tau_i) \cos(\omega t + \varphi_i) \quad \ldots(4.4\text{-}2)$$

During transmission, the signal is perturbed by the random variations in phase and gain, which has also been taken into account in the subsequent section for the computation of the optimum receiver structures.

4.5 ANALYSIS FOR a-posteriori PROBABILITY AND THE RECEIVER STRUCTURE

The transmitted signal x_k is perturbed by background radiation noise n(t) which is assumed to be an additive noise. The resultant signal S is the observed data for that particular transmission. Thus the observed data is given by the equation

$$S = x_k + n(t) \quad \ldots(4.5\text{-}1)$$

The probability of receiving the signal S when x_k was transmitted under the channel condition $(\bar{G}, \bar{\varphi}, \bar{\tau})$ is denoted as $p_k(S/\bar{G},\bar{\varphi},\bar{\tau})$. From Eqn (4.5-1), one can infer that this probability will be the same as receiving the noise data $n(t)$ when the signal x_k was transmitted. This is mathematically expressed as,

$$p_k(S/\bar{G},\bar{\varphi},\bar{\tau}) = p_k\left[n(t)\right] = p_k\left[S - x_k\right] \qquad \ldots(4.5\text{-}2)$$

Using Eqn (4.2-1)

$$p_k(S/\bar{G},\bar{\varphi},\bar{\tau}) = k \exp\left[-\frac{1}{N_o}\int_0^T (S-x_k)^2\,dt\right]$$

$$= k \exp\left[-\frac{1}{N_o}\int_0^T (S^2+x_k^2-2x_kS)\,dt\right]$$

$$= k \exp\left[-\frac{1}{N_o}\left[\int_0^T S^2dt + \int_0^T x_k^2dt - 2\int_0^T x_kSdt\right]\right] \qquad \ldots(4.5\text{-}3)$$

Since the received waveform S is known, the integral $\int_0^T S^2dt$ is constant. Further, if the energy in each transmitted signal x_k is chosen the same for all the nessages , then $\int_0^T x_k^2\,dt$ is also constant. Also, the noise power density N_o can be measured prior to reception of S. Therefore, the first two terms in the exponent of Eqn (4.5-3) are constant and the equation can be written as :

$$p_k(S/\bar{G},\bar{\varphi},\bar{\tau}) = K(S,x_k) \exp\left[\frac{2}{N_o}\int_0^T x_k\, S\, dt\right] \quad \ldots(4.5\text{-}4)$$

where,

$$K(S,x_k) = k \exp\left[-\frac{1}{N_o}\left[\int_0^T S^2 dt + \int_0^T x_k^2\, dt\right]\right] \quad \ldots(4.5\text{-}5)$$

Substituting (4.3-1) in Eqn (4.5-4)

$$p_k(S/\bar{G},\bar{\varphi},\bar{\tau}) = K(S,x_k) \exp\left[\frac{2S}{N_o}\int_0^T \sum_{i=1}^{n} G_i\, m_k(t-\tau_i)\cos(\omega t+\varphi_i)\, dt\right]$$

$$\ldots(4.5\text{-}6)$$

$$= K(S,x_k) \prod_{i=1}^{n} \exp\left[\frac{2SG_i}{N_o}\int_0^T m_k(t-\tau_i)\cos(\omega t+\varphi_i)\, dt\right]$$

$$= K(S,x_k) \prod_{i=1}^{n} \exp\left[G_i Z_{ki}\right] \quad \ldots(4.5\text{-}7)$$

where,

$$Z_{ki} = \frac{2}{N_o}\int_0^T S\, m_k(t-\tau_i)\cos(\omega t+\varphi_i)\, dt \quad \ldots(4.5\text{-}8)$$

It is found, however, that in addition the uncertainty caused by additive, noise, an additional uncertainty created by the randomness of signal parameters due to the turbulence effects. In this section the signal parameter of particular interest is the phase and gain of the signal. The phase φ is a random variable and consequently a density function may be associated with this random variable. Instead of choosing a particular density one can specify a family densities indexed by a single parameter. Such type of density function is given by :

$$p(\varphi) = \frac{\exp(\alpha \cos \varphi)}{2\pi I_o(\alpha)} \qquad -\pi \leqslant \varphi \leqslant \pi \qquad \ldots(4.5\text{-}9)$$

The function $I_o(\alpha)$ is a modified Bessel function of the first kind which is included so that the density will integrate to unity. α can be regarded as a parameter that controls the spread of density Eqn (4.5-7) can be written as

$$p_k(S/\bar{G},\bar{\varphi},\bar{\tau})$$

$$= K(S,x_k) \prod_{i=1}^{n} \exp\left[\frac{2G_i}{N_o}\int_0^T S\, m_k(t-\tau_i)\cos(\omega t+\varphi_i)\,dt\right]$$

$$= K(S,x_k) \prod_{i=1}^{n} \exp\left[\frac{2G_i}{N_o}\int_0^T S\, m_k(t-\tau_i)(\cos\omega t \cos\varphi_i - -\sin\omega t \sin\varphi_i)\,dt\right]$$

$$= K(S,x_k) \prod_{i=1}^{n} \exp\left[\frac{2G_i}{N_o}\int_0^T S\, m_k(t-\tau_i)\cos\omega t \cos\varphi_i\,dt - \frac{2G_i}{N_o}\int_0^T S\, m_k(t-\tau_i)\sin\omega t \sin\varphi_i\,dt\right]$$

$$= K(S,x_k) \prod_{i=1}^{n} \exp\left[\frac{2G_i}{N_o}\left[X_{ki}\cos\varphi_i - Y_{ki}\sin\varphi_i\right]\right] \qquad \ldots(4.5\text{-}10)$$

where,

$$\left.\begin{aligned} X_{ki} &= \int_0^T S\, m_k(t - \tau_i) \cos \omega t \, dt \\ Y_{ki} &= \int_0^T S\, m_k(t - \tau_i) \sin \omega t \, dt \end{aligned}\right\} \quad \ldots(4.5\text{-}11)$$

Further let,

$$\left.\begin{aligned} X_{ki} &= M_{ki} \cos \theta_{ki} \\ Y_{ki} &= M_{ki} \sin \theta_{ki} \end{aligned}\right\} \quad \ldots(4.5\text{-}12)$$

Eqn (4.5-10) can be written as

$$p_k(S/\bar{G},\bar{\varphi},\bar{\tau})$$

$$= K(S,x_k) \prod_{i=1}^{n} \exp\left[\frac{2G_i}{N_o} M_{ki} \cos(\theta_{ki} + \varphi_i)\right] \quad \ldots(4.5\text{-}13)$$

This shows that the probability of receiving the signal S under the known channel conditions of gain, phase and delay time, is given in terms of the product of exponentials for different paths.

With the phase variation φ having the density function given by Eqn (4.5-9), the probability of the observed data S under the two known channel conditions gain and delay time is given as,

$p_k(S/\bar{G},\bar{\tau})$

$$= \int_{-\pi}^{\pi} K(S,x_k) \prod_{i=1}^{n} \exp\left[\frac{2G_i}{N_o} M_{ki} \cos(\theta_{ki}+\varphi_i)\right] \frac{\exp(\alpha\cos\varphi_i)}{2\pi\, I_o(\alpha)} d\varphi_i$$

$$= \frac{K(S,x_k)}{2\pi I_o(\alpha)} \int_{-\pi}^{\pi} \prod_{i=1}^{n} \exp\left[\frac{2G_i}{N_o} M_{ki} \cos(\theta_{ki}+\varphi_i)+\alpha \cos\varphi_i\right] d\varphi_i$$

$$= \prod_{i=1}^{n} \frac{K(S,x_k)}{2\pi\, I_o(\alpha)} \int_{-\pi}^{\pi} \exp\left[\left(\frac{2G_i}{N_o} M_{ki} \cos\theta_{ki}+\alpha\right) \cos\varphi_i - \left(\frac{2G_i}{N_o} M_{ki} \sin\theta_{ki} \sin\varphi_i\right)\right] d\varphi_i$$

...(4.5-14)

Integral in Eqn (4.5-14) is a standard integral whose solution is given in terms of the Bessel function. Thus Eqn (4.5-14) reduces to

$p_k(S/\bar{G},\bar{\tau})$

$$= \prod_{i=1}^{n} \frac{K(S,x_k)}{2\pi I_o(\alpha)} I_o\left[\left[\left(\alpha+ \frac{2G_i}{N_o} M_{ki} \cos\theta_{ki}\right)^2 + \left(\frac{2G_i}{N_o} M_{ki} \sin\theta_{ki}\right)^2\right]^{1/2}\right]$$

...(4.5-15)

Eqn (4.5-15) gives an expression for the a-posteriori probability of the received data when the signal is perturbed by random phase variations during the transmission. The hardware implementation of this is physically realizable as shown in Fig. 4.1 . From the figure it is clear that the receiver operates on the received data for each transmission so as to compute the set of a-posteriori probability and then decides in favour of that symbol which is most probable a-posteriori. The received symbol is cross-correlated with the delayed symbol $m_1(t-\tau_1)$ and with cos ωt , which is passed through an integrater. The output of the integrater is multiplied with $\frac{2G_1}{N_0}$ and passed through an adder which adds the spread of the density α. This sum is then squared in a squarer. The received symbol is also cross-correlated with the delayed symbol $m_1(t-\tau_1)$ and sin ωt , passed through an integrator, and a multiplier in which it is multiplied by $\frac{2G_1}{N_0}$. The output of this is squared in a squarer. It is to be noted here that in this case when the symbol is cross-correlated with sin ωt the spread of the density α is not added. Now the output of the squarers of the cosine correlator and sine correlator is added together, the square root of which is passed through a circuit which performs the operation of calculating the Bessel function of the first kind. This process is repeated for the symbol m_1 at different paths which are having their own gain change, phase change and the change in delay time. Thus if there are n multipath, we get n different combinations of cosine and sine correlators and multipliers etc. The n different outputs $I_o(.)$ are multiplied together in a multiplier. The output of the multiplier is passed through a circuit which gives the product of the output of the previous multiplier with $\frac{K(S,x_k)}{2\pi\, I_o(\alpha)}$. $K(S,x_k)$ is obtained by S and x_k as shown in Fig. 4.1. S and x_k are squared seperately and each passed through an integrator. The integrated output from both the case is added and the sum is passed through a multiplier which gives its product with $-\frac{1}{N_o}$. This product is passed through a circuit which performs the operation of k exp (.) to give the output $K(S,x_k)$.

As given above the product of $\frac{K(S,x_k)}{2\pi\, I_o(\alpha)}$ and the multiplier output gives the value of the a-posteriori probability $p_1(S/\bar{G},\bar{\tau})$ for one value of M. The whole process described above is repeated for different values of the original symbol in which k varies from 1,2,...,M . This gives the a-posteriori probability $p_k(S/\bar{G},\bar{\tau})$. Ultimately the maximum of these a-posteriori probabilities gives the desired value.

Now the case of random change in the gain will be considered. The distribution for the random gain G_i is given by the log normal distribution density function which is given as

$$p(G_i) = \frac{1}{G_i \sigma \sqrt{2\pi}} \exp\left[- \frac{(\log G_i - \mu)^2}{2\sigma^2} \right]$$

where μ is average value and σ^2 is the variance of the random gain. With gain variations G_i, having the density function given above the probability of the observed data S, under the two known channel conditions - phase and delay time is given as

$$p_k(S/\bar{\varphi},\bar{\tau})$$

$$= \int_0^{\infty} k(S,x_k) \prod_{i=1}^{n} \exp\left[\frac{2SG_i}{N_o} \int_0^T m_k(t-\tau_i) \cos(\omega t+\varphi_i)\,dt \right] p(G_i)\,dG_i$$

$$= \prod_{i=1}^{n} K(S,x_k) \int_0^{\infty} \exp\left[\frac{2SG_i}{N_o} \int_0^T m_k(t-\tau_i) \cos(\omega t+\varphi_i)\,dt \right] p(G_i)\,dG_i$$

...(4.5-19)

Eqn.(4.5-19) can be further written using Eqn.(4.3-2) as

$$p_k(S/\bar{\varphi},\bar{\tau})$$

$$= \prod_{i=1}^{n} \frac{K(S,x_k)}{\sigma\sqrt{2\pi}} \int_0^{\infty} \frac{1}{G_i} \exp\left[\frac{2SG_i}{N_o} \int_0^T m_k(t-\tau_i) \cos(\omega t+\varphi_i)\,dt \right] \exp\left[- \frac{(\log G_i - \mu)^2}{2\sigma^2} \right] dG_i$$

$$= \prod_{i=1}^{n} \frac{K(S,x_k)}{\sigma\sqrt{2\pi}} \int_0^{\infty} \frac{1}{G_i} \exp\left[\left[G_i \int_0^T \frac{2S}{N_o} m_k(t-\tau_i)\cos(\omega t+\varphi_i)\,dt\right] + \left[-\frac{(\log G_i - \mu)^2}{2\sigma^2}\right]\right] dG_i$$

$$= \prod_{i=1}^{n} \frac{K(S,x_k)}{\sigma\sqrt{2\pi}} \int_0^{\infty} \frac{1}{G_i} \exp\left[G_i Z_{ki} + \left[-\frac{(\log G_i - \mu)^2}{2\sigma^2}\right]\right] dG_i$$

...(4.5-20)

where Z_{ki} is given by,

$$Z_{ki} = \frac{2}{N_o} \int_0^T S\ m_k(t-\tau_i)\cos(\omega t+\varphi_i)\,dt$$

The probability Eqn (4.5-20) gives an expression for the a-posteriori probability of receiving symbol S under two channel conditions phase and time delay. From Eqn (4.5-20) it follows that the receiver operates on the received data for each transmission so as to compute the set of a-posteriori probabilities and then decides in favour of that symbol which is most probable a-posteriori. This decision is made independent of previous or succeeding decisions. The scheme shown in Eqn (4.5-20) can be implemented by standard circuitry as shown in Fig. 4.2. From the figure it is clear that the received data is cross-correlated with delayed symbol $m_1(t-\tau_1)$ and with cos $(\omega t+\varphi_1)$. This is passed through an integrater which integrates the correlated output within the limits 0 to T. A multiplier in succession to this multiplies the integrated output with $\frac{2}{N_o}$, product of which is designated as Z_{11}. Z_{11} thus obtained is used to perform a non-linear operation in the next block. For this, Z_{11} is multiplied by G_1 and added with $\frac{(\log G_1 - \mu)^2}{\sigma^2}$. The exponential of this sum is divided by G_1. This quantity $\frac{1}{G_1} \exp\left[Z_{11} G_1 + \left[-\frac{(\log G_1 - \mu)^2}{\sigma^2} \right] \right]$ is integrated within the limit 0 to ∞, which completes the nonlinear operation indicated in the Fig. 4.2. The above process is performed for different values of $k = 1,2,\ldots,M$ and **for a single path.** Similar operation is now repeated for different paths $i = 1,2,\ldots.n$ for each value of $k = 1,2,\ldots.M$. Non-linear operation outputs from each path and for each value of k are multiplied and passed through a circuit which performs the operation of multiplication with $\frac{K(S,x_k)}{\sigma\sqrt{2\pi}}$. The implementation of $K(S,x_k)$ has been discussed earlier in connection with the receiver structure for random phase varying channel. The multiplied output of $\frac{K(S,x_k)}{\sigma\sqrt{2\pi}}$ gives the a-posteriori probabilities $p_k(S/\bar{\varphi},\bar{\tau})$. Finally the maximum of these probabilities gives the desired value.

The receiver structures described above for random phase variations and random gain variations are optimum in the sense that they give the maximum a-posteriori probability. It is evident from Fig. 4.1 and Fig. 4.2 that the hardware implementation of these optimum receiver is physically realizable.

CHAPTER V

CONCLUSION AND SUGGESTIONS FOR FURTHER WORK

5.1 CONCLUSION

The propagation characteristics of atmosphere have been the subject of investigation for several decades at radio frequencies. The advent of laser has triggered the imagination of many workers to think of a very sophisticated system for handling the huge amount of information. This possibility is due to the property of high frequency radiation, a high degree of coherence and monochromaticity of laser radiation. Being a high frequency source of radiation, broad band operations are possible with laser for communication applications. But this hope of laser communication through atmosphere, has been tampered somewhat due to the adverse role played by atmospheric effects. The precipitation and gases present in the atmosphere selectively absorb radiation at certain optical wave lengths hence causing attenuation of signal. Particulate matter and precipitation droplets cause scattering. In addition to these, the major limitation is due to the physical effects-beam displacement, image blurring, random crosssection change, beam spread, frequency and phase fluctuations.

In this thesis a brief description is given of the various atmospheric limitations to laser communication. Laser communication at present is an inter disciplinary activity in which both applied physicist and communication engineers play important roles. Lasers have the inherent advantage of enormous potential bandwidth, high data rates and wide spectral range. This makes the communication possible on earth, in the telephone systems and between computers. Deep space mission depends crucially on its high data returns. To cope with the explosion in communication terminals, many forms of wide band laser transmission systems are being developed to trunk the information across the town and around the world. Laser communication system design is highly dependent on the application. This is specially so, since compromise between component reliability and system design is required for every application.

Laser receiver performance is often limited by background radiation which impairs the laser signal detection by increasing the detector noise level. This is not the only limitation when the transmitted laser signal passes through the turbulent atmosphere. In this case, due to atmospheric inhomogenieties there is a random phase variation and random gain variation also. In this thesis receiver models are proposed for a laser communication system perturbed by random phase varying channel and random gain varying channel.

Until now, every communication satellite has operated on a link from satellite to a ground station. The effort can be made to construct a data relay system which would relay data collected by low flying satellites upto a synchronous satellite hovering over the earth at a 22,000 mile orbit, collect the data from all the smaller satellites and then relay it at high rates either from one sunchronous satellite to another or directly to the ground. For this type of thing laser communication will be most suited.

Anticipated needs for future space communication channels requiring large dynamic range and a high degree of linearity can be met with laser communication system. In addition, eventual shortage of microwave channel for point communication through the atmosphere will require other modes of communication . Laser systems will be ideal to fill the needs.

5.2 SCOPE FOR FURTHER WORK

So far, many valuable studies of laser beam propagation using atmosphere as a useful channel have been undertaken, particularly for ground to ground communication but the quantitative investigation of such a propagation and the available prac tical system is still not very satisfactory [9] [21] [73] [74] [76] [77] [95] [142] [143]. A great deal of effort is still required to have a better understanding of limitations of atmosphere for a laser communication . At present, data on microscale changes of atmosphere refractive index are scarce and their inter-relationship with other atmospheric conditions are not fully analysed. It would be interesting to study the relationship of refractive index variation process to other atmospheric conditions so as to characterize the process fully.

The communication traffic over various distances on overload routes will grow with new services such as videophone and data communication . These new services require a greater signal bandwidth than the telephone links. Moreover a much greater bandwidth on the transmission path is required if digital formats are used. However, digital transmission has significant performance and operational advantages compared with analog transmission.

Because of their very large bandwidths, laser communication systems are capable of meeting the requirements in the future. Optical systems may differ in components, complexity and adaptability in accordance with whether the transmission medium is atmosphere, glass fiber or a beam wave guide. The search for these new transmission media has an important common objective, the reduction of transmission cost per unit of signal band width.

An effort has been made to study the variation of the optical strength of turbulence with heights but it would be worth while to conduct measurements of the variations of the optical strength with height which are useful for remote probing techniques.

The high data rate requirements for space-to-space, space-to-ground, computer-to-computer , as well as requirements for deep space communication, constitute a strong justification for the pursuit of a critical study of optical communication through atmosphere. Many system studies for deep space applications have been performed by many workers in the past, but at the present time, there is no general consensus of opinionon an adequate theoretical solution to the turbulent propagation problem. This may be due to the complex nature of problem and an inadequate coordination between the multidisciplinary activities, such as the technical language barrier existing between laser communication theorist and quantum physicist or between device technologist and the physcist working on the statistical properties of the turbulent atmosphere.

Although some of the atmospheric laser systems have been successfully demonstrated and are currently used as operational systems, it should be mentioned that laser communication systems are still in the so called primitive research and development stage and many technical problems must be explored before the potential advantage of laser systems could be fully and practically utilized.

The effect of various physical parameters such as intensity fluctuations, random beam scanning etc on the signal-to-noise ratio can be studied. The practical significance of this investigation can be emphasized, in a way that both the intensity scintillation and random beam scanning can be correlated with the directly measurable parameters of the atmosphere. The signal intensity at the detector which also appears as a factor in the channel capacity expression can also be correlated to the signal power at transmitter and the quantities like, rain, snow fall and fog condition.

The channel capacity studies including atmospheric effects are yet to be developed in more detail. After finding the posterior probabilities, as has been derived in the previous chapters one can go for the calculation of probability of error and then the reliability considerations for the case when the signal is being perturbed by randomly varying parameters.

APPENDIX I

RELIABILITY CONSIDERATIONS FOR LASER COMMUNICATION

In a laser communication system, the broader objective should be the consideration of optimum performance taking into view the various factors involved such as economy, transmission quality, reliability, flexibility in providing various services, time required for development and proper planning. Also the specifications of various basic requirements must be considered, which are essential for its design and operation to ensure satisfactory performance.

The reliability is discussed taking into account the probability of error bound given by Eqn (3.5-18) derived in Chapter III which is reproduces here as

$$\overline{f(E)} < 2^{-r(I_o - I_r)} \qquad \ldots(3.5\text{-}18)$$

If,

P_s - average transmitted power

N_o - spectral density of additive Gaussian White noise.

The probability of error bound of Eqn (3.5-18) can be written as

$$\overline{f(E)} < 2^{RT} e^{-TP_s/2N_o} \qquad \ldots(A.I\text{-}1)$$

where,

R - information rate in bits/sec.

Eqn (A.I-1) can be put in a more suitable form as

$$\overline{f(E)} < 2^{-T(C_\infty - R)} \qquad \ldots(A.I\text{-}2)$$

where

$$C_{\infty} = \frac{P_s}{N_o} \log_2 e$$

If the information rate is measured in nats per interval, the bound can be expressed as

$$f(E) < A \exp\left[-T\, C_{\infty}\, E(R)\right] \qquad \ldots(A.I-3)$$

where A is a constant and E(R) is termed as the reliability function of the system. In the laser communication system, the transmitted power is given as

$$P_s = \frac{1}{2\pi}\, p\, h\, \omega \qquad \ldots(A.I-4)$$

and

$$N_o = \frac{1}{2\pi}\, \bar{n}\, h\, \omega \qquad \ldots(A.I-5)$$

where,

$\bar{n}$ - average noise photo-electron

p - n_r / T

n_r - average signal photo electron.

h - Plank's constant

With the help of Eqns(A.I-4) and (A.I-5) channel capacity can be given as

$$C = p \log\left(\frac{1+\bar{n}}{\bar{n}}\right) \qquad \ldots(A.I-6)$$

when $\bar{n}$ is large

$$C = \frac{p}{\bar{n}} = C_{\infty} \qquad \ldots(A.I-7)$$

It has been found that for the rate R in the range R = C the reliability function can be given as [84] :

$$E(R) = \frac{p}{e}\left[\frac{1+2\bar{n}RC - [(1 + 4\bar{n}\ (1+\bar{n})\ R/C\ )]^{1/2}}{\bar{n} - \bar{n}\ [1+4\bar{n}(1+\bar{n})\ R/C]} - \frac{R}{2C}\ \frac{[1+ 4\bar{n}\ (1+\bar{n})\ R/C\ ]^{1/2}}{(1+\bar{n})^2\ \ R/C}\right] \quad \text{...(A.I-8)}$$

The reliability equation shows that reliability depends on number of parameters such as average number of signal photons, average number of noise photons, information rate and channel capacity. It is difficult to judge the exact variation of the reliability with these equations by the above complicated equation. The variation has been shown graphically by calculating E(R) with various numerical values of the parameter. The results have been found on the IBM 1620 computer. E(R) is positive for all values of R less than C when $\bar{n}$ is non zero. Its behaviour for several different values of $\bar{n}$ is shown in Fig. A.1. Fig.A.2 shows the values of channel capacity per unit average signal photons as a function of $\bar{n}$. The exponent factor CE(R) is plotted as a function of R for $p/\bar{n} = 1$ and $n_r = 5 \times 10^3$ and $n_r = 25 \times 10^5$. It is shown in Fig. A.3 and Fig. A.4 . The variation of reliability with noise photon for different values of n_r is shown in Fig. A.5. The optimum performance of the system is independent of time at which the observation is made.

APPENDIX II

```
C   C  N MALAVIYA ECE  UOR
   99  READ 100,L,N
  100  FORMAT(212)
  101  FORMAT(E16.8)
  102  AL=L
       AL1=1/(AL*AL)
       AL2=(AL-1.)*(AL-1.)
       DO 500I=1,N
       SUM=0
       DO400J=1,L
       U=K
       AN=I
       ASU=ABSF(S-U)1.25
       P=(ASU*ASU*AN)/AL2
       AP=EXPF(P)
       PUNCH 102,AP,U,S
  400  SUM=SUM+AP
       A10=-1.4427*LOGF(SUM*AL1)
       PUNCH 101,A10
  500  CONTINUE
       GO TO 99
       END
```

Computed values of information rate (I_o) for different values of signal-to-noise ratio (b_ℓ^2 / V)

0.28659480	0.15375380 E+01
0.88618972	0.18713444 E+01
0.96646790	0.19668404 E+01
0.99031587	0.19916653 E+01
0.99972217	0.19979228 E+01
0.99920651	0.19994872 E+01
0.99977551	0.19998775 E+01
0.99993868	0.19999740 E+01
0.99998528	0.19999991 E+01
0.99999870	0.20000051 E+01
0.10000025 E+01	0.20000051 E+01
0.10000036 E+01	0.20000067 E+01
0.10000040 E+01	0.20000072 E+01

0.28153372E+01	0.39895948E+01
0.29847298E+01	0.39999743E+01
0.29988123E+01	0.40000135E+01
0.29999164E+01	0.40000135E+01
0.30000027E+01	0.40000135E+01
0.30000093E+01	0.40000135E+01
0.30000098E+01	0.40000135E+01
0.30000098E+01	
0.30000098E+01	
0.30000098E+01	0.50000115E+01
0.30000098E+01	0.50000173E+01
0.30000098E+01	0.50000173E+01
0.30000098E+01	0.50000173E+01

R E F E R E N C E S

1. Aein, J.M., "Effect of Co-channel interference on CPSK Carriers", IEEE Trans. Comm.Vol. COM-21,July 1973 pp 783-790.

2. Alcaraz, E.C. " The beam Wander Phenomenon in the turbulent near-earth atmosphere" Proc. of the Technical programme, Electro optical design conference, USA,18-20 May, 1971.

3. Anderson, L.K. and McMurty, B.J., "High speed photo detectors" Proc. IEEE, Vol. 54, Oct. 1966, pp.1335-1349.

4. Armstrong, J.A. and Smith A.W., "Intensity fluctuations in Lasers" Progress in Optics, E.Wolf Ed. (John Wiley and Sons,) Vol.6, p.213.

5. Arrigucci, A, " Criterion for the choice of exposure time in atmospheric turbulence investigation with an optical wave" Applied Optics, Vol. 12, Jan ,1973, pp.136-138.

6. Arthur, E. and Dyme H," On the Optimum detection of digital signals in the presence of White Gaussian Noise-A geometric Interpretation and a study of three basic data transmission systems" IRE Trans. Comm. System Vol.CS-10 Dec. 1962 pp 336-372.

7. Bar-David, I.," Communication under Poisson Regime" IEEE Trans. Inf. Theory, Vol. IT-15, Jan. 1969, pp.31-37

8. Baghdady, E.J., "Lectures on Communication System Theory" Mc Graw Hill Book Co. N.Y., 1961.

9. Borner, M. and Rosenberg, D.,"Laser Communication Technology in Germany" IEEE Trans. Comm. Vol. COM-22, Sept. 1974,pp.1305-1310.

10. Benddetoo, S., " Combined effect of Intersymbol inter-channel and cochannel interference in M-ary CPSK ".IEEE Trans. Comm. Vol. COM-21, Sept. 1973, pp.997-1008.

11. Bello, P.A. and Boarthmann, "Effect of multipath on ranging error for an airplane-satellite link". IEEE Trans. Comm. Vol. COM-21, May 1973,pp.564-576.

12. Bello,P.A., "The influence of fading spectrum on Binary error probabilities of incoherent and differentially coherent matched filter receiver". IRE Trans. Comm. System. Vol. CS-10, June 1962 pp.160-168.

13. Bello, P.A., " Binary error probability over selective fading channel containing specular components" IEEE Trans. Comm. Tech. Vol.COM Tech-14,Aug. 1966,pp.400-416.

14. Bello, P.A. and Nelin, B.D., "The effect of frequency selective fading on the binary error probabilities of incoherent and differentially coherent matched filter" IEEE Trans. Comm.System Vol.CS-11, June 1963,pp.170-186.

15. Bershad, N.J., "Optimum binary FSK for Transmitted reference systems over Rayleigh fading channel" IEEE Trans. Comm. Tech. Vol. COM Tech-14, Dec. 1966, pp.784-790.

16. Brookner, E.,"Atmosphere propagation and communication channel model for laser wave length" IEEE Trans.Comm. Vol.COM-18, Aug.1970,pp.396-416.

17. Brookner, E., " Multipath dispersion for atmosphere laser channel" Proc. IEEE Vol. 58, Oct. 1970 p.1767.

18. Brookner, E., "Limit imposed by atmosphere dispersion on the minimum laser pulse width that can be transmitted" Proc. IEEE, Vol. 57, June 1969, pp. 1234-1235.

19. Brookner, E., " Effect of ionosphere on radar waveform" J. Franklin Institute Vol.280, July 1965, pp.1-22.

20. Brookner, E., et al "Deep space optical communication" IEEE Spectrum Vol.4, Jan. 1967, pp.75-82.

21. Bucher, E.A., "Experiments on light pulse communication and Propagation through atmospheric clouds," Applied Optics, Oct. 1973, pp 2401

22. Bussgang, J.J. and Middleton, M., "Optimum sequential detection of signals in noise" IEEE Trans. Inf.Theory Vol. IT-1, Dec. 1955, pp. 5-18.

23. Bussgang J.J. and Leiter, M., " Error rate approximation for differentially PSK," IEEE Trans. Comm. System, Vol. CS-2, March 1964, pp.18-27.

24. Cahn, C.R., " Performance of digital phase modulation Communication System" IRE Trans. Comm.System, Vol.CS-7, May 1959, pp.3-6.

25. Capon, J., " High resolution frequency wave number spectrum analysis", Proc.IEEE Vol.57, Aug.1969, pp.1408-1418.

26. Campbell, L.L., "Error rates in pulse position coding" IRE Trans. Inf. Theory, Vol.IT-3, March 1957, pp.18-24.

27. Chiba, T., "Beam spread of laser light propagation through atmosphere" Electronics and Comm. in Japan Nov. 1971, pp.90-91.

28. Chu, T.S., " On the wavelength dependence of the spectrum of laser beam traversing the atmosphere" App. Optics Vol. 6, Jan.1967, pp.163-164.

29. Chu, T.S. and Hogg, D.C. "Effect of precipitation on propagation at 0.63 μ, 3.5 μ and 10.6 μ " Bell System Tech.Journal,Vol.47, May 1968, pp.723-759.

30. Clifford, S.F., " Temporal frequency spectra for a spherical wave propagating through atmosphere turbulence" J.Opt. Soc. Am. Vol.61, Oct. 1971, pp.1285-1292,

31. Curran and Ross , " Optimum detection thresholds in optical communication"Proc.IEEE, Vol.53,Nov.1965, pp. 1770- 1771.

32. Cole, D.J., " Radio frequency modulation and demodulation of lasers for communication" J. Inst. Engrs. , Australia, 1972 pp.9-15.

33. Cooper, B. "Optical Communication in earth's atmosphere" IEEE Spectrum, Vol.3, July 1966, pp.83-92.

34. Davis, R.C.,"The detectability of random Signal in the presence of noise" IRE Trans. Inf. Theory, Vol.IT-3, Jan. 1956, pp.52-62.

35. Davis, J.I., " Consideration of atmospheric turbulence in laser system design" App.Optics,Vol.5, Jan.1966, pp.139-149.

36. Diament, P. and Teich, M.C., "Photo electron counting Distribution for irradiance modulated radiation" J.Opt. Soc. Am.Vol.60, 1970 p682.

37. Diament, P. and Teich, M.C., "Photodetection of low level radiation through the turbulent atmosphere" J. Opt. Soc. Am.Vol.60,1970, p1489.

38. Diament, P., and Teich, M.C., "Optical detection of laser or scattered radiation transmitted through the turbulent atmosphere" App.Optics, Vol.10,July 1971, pp.1664-1667.

39. Dewolf, D.A.,"Saturation of Irradiance flucuation due to turbulent atmosphere, J.Opt. Soc.Am.,Vol.58, 1968,pp.461-466.

40. Dewolf, D.A., " Are strong fluctuations lognormal or Rayleigh distributed", J.Opt. Soc.Am.Vol.59,1969,pp.1455-1460.

41. Delange, O., "Optical Heterodyne detection"IEEE Spectrum Vol.5, Oct.1968, pp.77-85.

42. Denton and Kinsel,"Terminals for high speed optical PCM" Proc. IEEE, Vol.56, 1968, pp.110-154.

43. Dunphy, J.R. and Kerr, J.R., "Scintillation measurement for large integrated path turbulence".J.Opt.Soc. Am.August 1973, p 981.

44. Episto, R., et al,"Advantage of amplitude and phase adaptivity in the detection of signal subject to slow Rayleigh fading", IEEE Trans.Inf. Theory, Vol.IT-13,Oct.1965, pp.473-481.

45. Episto, R.,"Error Probabilities for Nagakami Channels",IEEE Trans. Inf. Theory Vol.IT-13,Jan. 1967, pp.145-148.

46. Freed, C. and Haus H.A., "Photo electron statistics produced by laser operating below and above the threshold of oscillation", IEEE J. Quantum Electronics, Vol.QE-2, Aug. 1966, pp.190-195.

47. Fillmore, G.L. and Lachs, G., " Information rates for photo count detection system", IEEE Trans. Inf. Theory, Vol. IT-15, 1969, pp.465-468.

48. Fried, D.L. and Cloud, J.N., " Propagation of Infinite plane wave in a randomly inhomogeneous medium", J.Opt. Soc. Am.Vol.56, Dec.1966, pp.1667-1676.

49. Fried, D.L., et al, "Measurement of laser beam scintillation in the atmosphere", J.Opt.Soc.Am.Vol.57,June 1967, pp.787-797.

50. Fried, D.L., and Schmetzer, R.A., " The effect of atmospheric scintillation on an optical data channel- laser radar and binary communication". App. Optics, Vol.6, Oct., 1967, pp.1729-1739.

51. Fried, D.L., "Optical heterodyna detection of an atmospherically distorted signal wave front", Proc. IEEE, Vol.55, Jan. 1967, pp.55-57.

52. Fried, D.L.,"Remote Probing of optical strength of atmospheric turbulence and wind velocity", Proc. IEEE Vol.57, April 1969, pp.415-421.

53. Fried,D.L., " Atmospheric modulation noise in an optical heterodyne receiver", IEEE J. Quantum Electronics Vol.QE-3 June 1967, pp.213-221.

54. Fried, D.L., and Seidmen, J.B.,"Laser beam scintillation in atmosphere",J.Opt.Soc.Am.Vol.57,Feb.1967,pp.181-185.

55. Fried, D.L., " Scintillation of a ground to space laser illuminator", J.Opt.Soc.Am. Vol.57, 1967,pp.980-983.

56. Gaarder, N.T., " The design of point detector arrays". IEEE Trans. Inf. Theory., Vol. IT-13, Jan.1967,pp.42-50.

57. Gallager, R.E., " Information Theory and Reliable Communication", John Wiley andSons, Inc., N.Y. 1968.

58. Gagliardi, R.M., "Synchronization using pulse edge tracking in optical pulse position modulated Communication system" IEEE Trans. Comm.Vol.COM-22,Oct.1974,pp.1693-1702.

59. Geusic, J.E., et al, " Coherent optical sources for Communication".Proc.IEEE, Vol.54, Oct. 1966, pp.1419-1439.

60. Goodwin, F.E., " A 3.39 μ infrared optical heterodyne communication system",IEEE J.Quantum Electronics, Vol.QE-3, Nov. 1967, pp.524-531.

61. Gordan J.P.,"Quantum effects in Communication System", Proc. IRE Vol.50, Sept. 1962.

62. Gordan, J.P.,"Information Capacity of a Communication channel in presence of Quantum effects",Advances in Quantum Electronics, Ed.Singer,Columbia University Press,1961.

63. Goldstein, E.,et al, "Heterodyne measurement of light propagation through turbulent atmosphere" Proc. IEEE,Vol.53, 1965, pp.1172-1180.

64. Harger, R.O.,"Maximum likelihood estimation of focus of Gaussian signal" IEEE Trans. Inf. Theory Vol.IT-13, 1967 pp. 318-319.

65. Helstrom, C.W., "Statistical Theory of signal detection" Pergamon Press, 1960.

66. Hecht, M. and Schwartz, M., " M-ary sequential detection for AM signal in one or two dimensions," IEEE Trans. Comm. Vol. COM-16, Oct.1968, pp.669-675.

67. Hernandez, E.N., "Field test of a two laser optical distance measuring instrument correcting for the atmospheric index of refraction". J. Geophysical Research Vol.77, 10 Dec. 1972, pp.6994-6998.

68. Hingorand, G.D., " A transmitted reference system for communication in random or unknown channel" IEEE Trans. Comm. Vol.COM Tech-13, Sept.1965, pp.293-301.

69. Hingorand, G.D., "Error rates for a class of binary receivers", IEEE Trans. Comm. Tech.,Vol.CO M Tech.-15,April1967, pp.209-215.

70. Hiedbreder, G.R., and Mitchell, R.L., " Detection probabilities for lognormally distributed signal" IEEE Trans. Aerospace and Electronic Systems, Vol. AES-3, 1967,pp.5-13.

71. Hodara, H.,"Laser wave propagation through the atmosphere", Proc. IEEE, Vol.54, March 1966, pp.368-375.

72. Hodara, H., "Effect of Turbulent Atmosphere on the phase and frequency of optical waves ", Proc. IEEE Vol. 56, Dec. 1968, pp.2130-2136.

73. Hoverston, E.V. and Harger, R.O., "Direct detection optical Communication receiver" IEEE Trans. Comm.Tech. Vol.COM Tech -22, Jan. 1974, pp.17-28.

74. Hoverston, E.V., "The atmosphere as an optical communication channel" IEEE Int. Convention Record, Vol.15,1967, pp.137-147.

75. Hufnagel, R.N. and Stanley, N.R., "Modulation Transfer Function associated with image transmission through turbulent media", J.Opt. Soc. Am., Vol.54, Jan.1964, pp.52-61.

76. Hoverston, E.V., et al.,"Communication theory for turbulent atmosphere". Proc. IEEE Vol. 58, Oct.1970, pp.1626-1651.

77, Herrman, G.F., "Optimum versus suboptimum detection under Poisson Regime - Application to optical communication us-using Biphase and quadriphase modulated subcarriers."IEEE Trans. Comm.Tech.Vol. COM.Tech-21, 1973, pp. 800-809.

78. Jacob, I.M.,"The asymptotic behaviour of incoherent M-ary communication system", Proc. IEEE, Vol.51, Jan.1963, pp.251-252.

79. Jacob, I.M., " Probability of error bound for binary transmission on the slowly fading Rician channel" IEEE Trans. Inf. Theory, Vol.IT-12, Oct. 1966, pp.431-441.

80. Jodion, R. and Mandel, L., "Information rates in an optical communication channel", J.Opt. Soc.Am. Vol.61, 1971,p.191.

81. Kodata, T.T., "Optimum reception of Binary Sure and Gaussian signal", Bell, Syst.Tech.J. Oct.1965,pp.1621-1658.

82. Kadota, T.T., "Optimum reception of M-ary Gaussian Signal in Gaussian Noise" Bell Syst. Tech. J.Nov.1965, pp.2187-2197.

83. Kadota, T.T., "Optimum reception of binary Gaussian Signal", Bell.Syst. Tech.J. Nov.1964, pp.2767-2811.

84. Kamal, A.K. et al, "Reliability of a laser communication system" Microelectronics and Reliability, Vol.13,1974, pp.91-95.

85. Kamal, A.K., and Malviya, N., "Remote Probing of atmospheric turbulence",J.Inst.Engg.Vol.53,May,1973,pp.173-176.

86. Karp, S. et al, " Communication theory for free-space optical channel".Proc.IEEE Vol.58,Oct.1970,pp.1611-1626.

87. Karp, S. and Gagliardi, R.M., "M-ary Poisson detection and optical communication". IEEE Trans. on Comm.Tech.Vol.COM Tech.-17 April 1969. pp.208-216.

88. Karp, S. and Clark ,"Photon counting- A problem in classical Noise Theory". IEEE Trans. Inf. Theory Vol.IT-16 Nov. 1970, pp.672-680.

89. Kennedy, R.S., and Karp, S., "Optical communication" Proc. Workshop on Optical Communication, MIT,-NASA,1968.

90. Kennedy, R.S., " Signal Design for Dispersive channels" IEEE Spectrum, March, 1964, pp.231-237.

91. Kennedy, R.S.and Hoverston, E.V., " On atmosphere as an optical communication channel" IEEE Trans. Inf. Theory Vol. IT-14, Sept. 1968, pp. 716-725.

92. Kennedy, R.S., " Fading dispersive channel" John Wiley and Sons Inc. 1969.

93. Kerr, J.P., "Experimental effects of finite transmitter apertures on scintillation," J. Opt. Soc.Am.Vol.63, Jan. 1973, pp.1-8.

94. Kerr J.P.,"Transmitter size and focus effects on scintillation", J.Opt. Soc. Am, May 1972 p.682.

95. Kerr, J.P.,et al, " Atmospheric optical communication system" Proc. IEEE Vol.58, Oct.1970, pp.1691-1710.

96. Kleen, R.H., and Ochs, G.R., " Measurement of the wavelength dependence of scintillation in strong turbulence"J.Opt. Soc. Am., Vol. 60, Dec, 1970, pp. 1695-1697.

97. Koubanitsas, T.S. "Performance of multiphase CPSK system with Intersymbol interference", IEEE Trans. Comm. Vol. COM-22, Oct. 1974, pp.1722-1726.

98. Lachs G. " Theoretical aspects of mixtures of Thermal and coherent radiation", Phy. Rev., 1965, B-1012-B-1016.

99. Lachs, G. and Jankowich, E., "Some results on error rates for a laser binary communication system" Proc. IEEE, Vol.56, 1968, p.744.

100. Lasher, G.J., " The channel capacity problem of information theory" Advances in Quantum Electronics, Ed. Singer Columbia University Press, 1966.

101. Lawrence R.S. and Strohbehn, J.W., " A Survey of clear air propagation effect relevent to optical communication" Proc. IEEE Vol. 58, Oct. 1970, pp.1523-1545.

102. Lawrence, R.S., " Experimental Results in Optical waves", ESSA, Electromagnetic wave propagation report 1968.

103. Lawrence, R.S., et al, "Measurementof atmospheric turbulence relevant to optical propagation," J. Opt.Soc. Am. Vol. 60, June 1970, pp. 826-830.

104. Lucovsky, R.F. and Yura, H.T., " Wave structure function and mutual coherence function of an optical wave in turbulent atmosphere" J.Opt. Soc. Am. Vol.61, April 1971, p. 482.

105. Mandel, L., " Fluctuation of photon beam and their correlation" Proc. Phys-Soc. Vol.74, 1959, p.253.

106. Mandel, L. "Coherence properties of optical fields" Rev. Mod. Physics, Vol. 37, April, 1965, p.231.

107. Maiman, T.H., " Stimulated optical radiation in ruby", Nature Vol. 187, Aug. 1960, pp. 493-494.

108. Masen, P., " Digital Transmission performance on fading dispersive channels " IEEE Trans. Comm. Vol. COM-21, Jan. 1973, pp.33-39.

109. Mason, J.B. et al " Laser beam behaviour on a long high path". App. Optics Vol.12, Sept. 1973, pp.187-190.

110. McIntyre, C.M. et al, "Optical components and technology in laser space communication system", Proc. IEEE Vol. 58, Oct. 1970, pp.1491-1504.

111. Melechoir, H. et al, " Photodetection for Optical Communication" Proc. IEEE, Vol.58,Oct.1970,pp.1466-1487.

112. Miller, S.E., and Tillostan, L.C.,"Optical transmission Research "Proc. IEEE, Vol.54, Oct. 1966, pp.1300-1311.

113. Montgomery, G.P., "Message error in diversity Frequency shift reception" Proc.IRE,July 1954,pp.1184-1187.

114. Middleton, D., " Statistics Communication Theory" McGraw Hill Book Co., 1960

115. Middleton, D., " An optimum multiple alternative detection of signal in noise"IRE Trans. Inf.Theory, Vol.IT-1,Sept. 1955, pp 1-9.

116. Montgomery, G.P., " A comparison of amplitude and angle modulation for narrow band communication of binary coded message in fluctuation noise" Proc. IRE, Vol.42, Feb.1954, pp.447-454.

117. Nishikawa, S., " Sequential M-ary PAM System", IEEE Trans.Comm.Vol.COM-21 Jan. 1973, pp.22-32.

118. Nuttal, A., " Error probability for equi-correlated M-ary signals under phase coherent and phase incoherent reception, " IRE Trans. Inf.Theory Vol. IT-8, July 1962, pp. 305-314.

119. Ochs, G.R. et al, " Laser beam scintillation over horizontal path from 5.5 to 140 km." J. Opt. Soc.Am. Vol. 59, 1969, pp.231-234.

120. Ochs, G.R. and Lawrence, R.S., " Measurement of Laser beam spread and curvature over near horizontal atmospheric path" ESSA Tech. Report, 1969.

121. Ochs, G.R. and Lawrence R.S., " Saturation of laser beam scintillation under conditions of strong atmospheric turbulence", J. Opt.Soc. Am. Vol.59, Feb. 1960, pp.226-227.

122. Oliver B.M., " Thermal and Quantum noise," Proc. IEEE Vol. 53, May 1965, pp.436-454.

123. Picibono, B., " Optimum filtering and multichannel receiver", IEEE Trans. Information Theory, Vol.IT-12, April 1966, pp.256-260.

124. Price, R. and Green, R.F., " Communication Technique for multipath channels". Proc. IRE, Vol.46, March 1958, pp. 555-570.

125. Price, R.," Error probability for adaptive multichannel reception of binary signals" IEEE Trans. Inf.Theory Vol. IT-8, Sept. 1962, pp.305-316.

126. Price R. "Optimum detection of stochastic signal in noise with application to scatter multipath communication" IRE Trans. on Inf. Theory Vol. IT-2, 1956, pp.125-155.

127. Price, R., "Optimum detection of random signal in noise with application to scatter multipath communication" IEEE Trans. on Inf. Theory, Vol.IT-2, Dec. 1956, pp.125-135.

128. Prabhu, V.K., " Error probability performance of M-ary CPSK with intersymbol interference" IEEE Trans. Comm. Vol.COM-21, Feb 1973 , pp.97-109.

129. Prabhu, V.K., "Inter Symbol interference performance of systems with correlated digital signal" IEEE Trans. Vol. COM-21, October 1973, pp 1147-1152.

130. Proakis, J.G., "On the probability of error for multichannel reception of binary signal", IEEE Trans. Inf. Theory, Vol. IT-13, April, 1967, pp.346-348.

131. Pratt, W.K., " Laser Communication System, "John Wiley Inc., 1969.

132. Pratt, W.K., " Binary Optical Polarization System" IEEE Trans. Comm. System Vol.CS-14, Oct. 1966.

133. Pratt, W.K. and Stoker, S., " Optimization of Optical Communication system" Proc. IEEE Vol.58, Oct.1970, pp.1737-1741.

134. Pulleyblack, R.W.,"A comparison of receivers designed on the basis of minimum mean square error and probability of error for channel with inter symbol interference and noise" IEEE Trans. Comm. Vol. COM-21, Dec.1973, pp. 1434-1438.

135. Reifann, B., Shermann, R, " An optimum demodulator for Poisson Processes: Photon source detector" Proc. IEEE Vol.51, Oct. 1963 pp.1316-1320.

136. Riesz,H., " High speed semiconductor photodiodes",Rev. Sci.Inst. Vol. 33, Sept. 1962, pp.994-998.

137. Rieger, S.H., " Error probabilities of binary data transmission system in the presence of random noise" IRE Convention Record, Pt.8, 1953, pp.72-79.

138. Rosenbaum, A.S., " PSK error performance with Gaussian noise and interference", Bell Syst. Tech. J. Vol.47, Feb. 1968, pp.413-442.

139. Ross, M., " Laser receivers" John Wiley and Sons, 1966.

140. Ross, M.,"Laser Applications" Academic Press, 1971.

141. Saucer, M.I. and Yavatis, A.D., " Saturation Calculations for light propagation in turbulent atmosphere." J.Opt. Soc. Am., Aug. 1972, p.966

142. Saito, S., "Optical Communication in Japan" IEEE Trans. Comm. Vol. COM-22, Aug.1972,pp.725-730.

143. Saleh, A.A.M., " An investigation of laser wave depolarization due to atmospheric transmission",IEEE J. Quantum Electronics, Vol. QE-3, Nov.1967,pp.540-543.

144. Shenker, H.,"Propagation of focussed laser beam". Proc. of Technical Program, Electrical Optical System Design Conference, May 18-20, 1971.

145. Seigman, A.E., " Antenna properties of optical heterodyne Receivers" Proc. IEEE Vol. 54, Oct. 1966, pp.1350-1356.

146. Schweppe, F., " Sensor array data processing for multiple signal sources"IEEE Trans.Inf.Theory.Vol.IT-14,1968, pp.294-305.

147. Schwartz M., Bennett R.B. and Stein S., " Communication System and Techniques" McGraw Hill Book Company, 1966.

148. Solimeno, S. et al, "Optical Communication in Turbulent atmosphere, J. Opt. Soc. Am.Vol.60, Sept.1970, pp.1245-1251.

149. Stiffler, J.J., " Theory of Synchronous Communication" Prentice Hall, Inc., 1971.

150. Stein and Jone, "Principles of Communication Engineering" John Wiley Inc.,

151. Strohbehn, J.W. and Clifford S.F., " Polarization and angle of arrival fluctuations for a plane wave propagated through a turbulent medium" IEEE Trans. Antenna and Propagation, Vol.AP-15, May 1967,pp.416-421.

152. Strohbehn, J.W., " Simplified equation for amplitude scintillation in turbulent atmospheres" J.Opt.Soc. Am. Sept. 1972,pp.1061.

153. Strohbehn, J.W., " Line of sight propagation for turbulent atmosphere". Proc. IEEE Vol.56,Aug.1968,pp.1301-1318.

154. Stern, T.E., "Some quantum effects in Information channel" IRE Trans. on Inf. Theory Vol.IT- 6,Sept. 1960.

155. Subramanian, M., " Atmospheric limitations for laser communication" EASCON Record, 1968.

156. Sun, C. and Walsh, T.E., " A Solid state microwave biased photo conductive detector for 10.6 μ " IEEE J. Quantum Electronics Vol.QE-5,June 1969, pp.320-321.

157. Susman, J.M.,"A matched filter communication System for multipath channel". IRE Trans. Inf. Theory June 1960, pp. 367-373.

158. Tatarski, V.I.,"Wave propagation in a random medium" Dover Publications. 1969.

159. Torrieri, D.J., " Irradiance fluctuation in Optical Transmission through the atmosphere". J.Opt. Soc.Am. Jan. 1972, p.105.

160. Turin, G.L.,"Error probability for binary symmetric ideal reception through non-selective fading and noise". Proc. IRE, Sept. 1958, pp.1603-1619.

161. Tyez, M. et al, " Optical communication system performance with tracing error induced signal fading" IEEE Trans. Comm.Vol.COM-21,Sept.1973,pp.1069-1072.

162. Ulrich,P.B., " Propagation characteristics of collimated pulsed laser beam through an absorbing atmosphere". J.Opt. Soc.Am.Vol.63,Jan.1973, pp.8-12.

163. Ueno, Y. and Nagura, R., " An optical communication system using envelop detection". IEEE Trans. Comm. Vol.COM-20, Aug.1972, pp.813-819.

164. Vantrees, H.L., " Detection, estimation and modulation Theory" Wiley Inc., 1969.

165. Viterbi, A.J., " Optimum detection and signal selection for partially coherent binary communication". IEEE Trans. Inf. Theory. Vol. IT-11, April 1965, pp.239-247.

166. Viterbi, A.J., " Principles of Coherent Communication" McGraw Hill, Book Co., 1966.

167. Waggoner, A.P. et al , " Measurement of aerosol total scatter-backscatter ratio". App. Optics, Vol. 11, Oct. 1972, pp. 2886-2889.

168. Warner, J. "Photomultiplier detection of 10.6 μ radiation using optical upconversion in proustite" Appl. Physc. Letters Vol.12 Feb. 1967, pp.222-224.

169. Woodward, B.M., "Probability and random variables with application to Radar " Pergamon Press, 1953.

170. Wozencraft, and Jacobs, "Principles of Communication Engineering", John Wiley Inc., 1967.

171. Yura, H.T., "Optical propagation through turbulent medium" J. Opt. Soc. Am. Vol. 59, Jan.1969 pp.111-112.

172. Yura, H.T., " A physical model for strong optical amplitude fluctuations in a turbulent media," J.Opt. Soc. Am., Vol. 64, Jan. 1974.

173. Ziv, J. "Probability of decoding error for random phase and Rayleigh fading channel". IEEE Trans. Inf. Theory Vol. IT-11, Jan. 1965, pp.53-61.

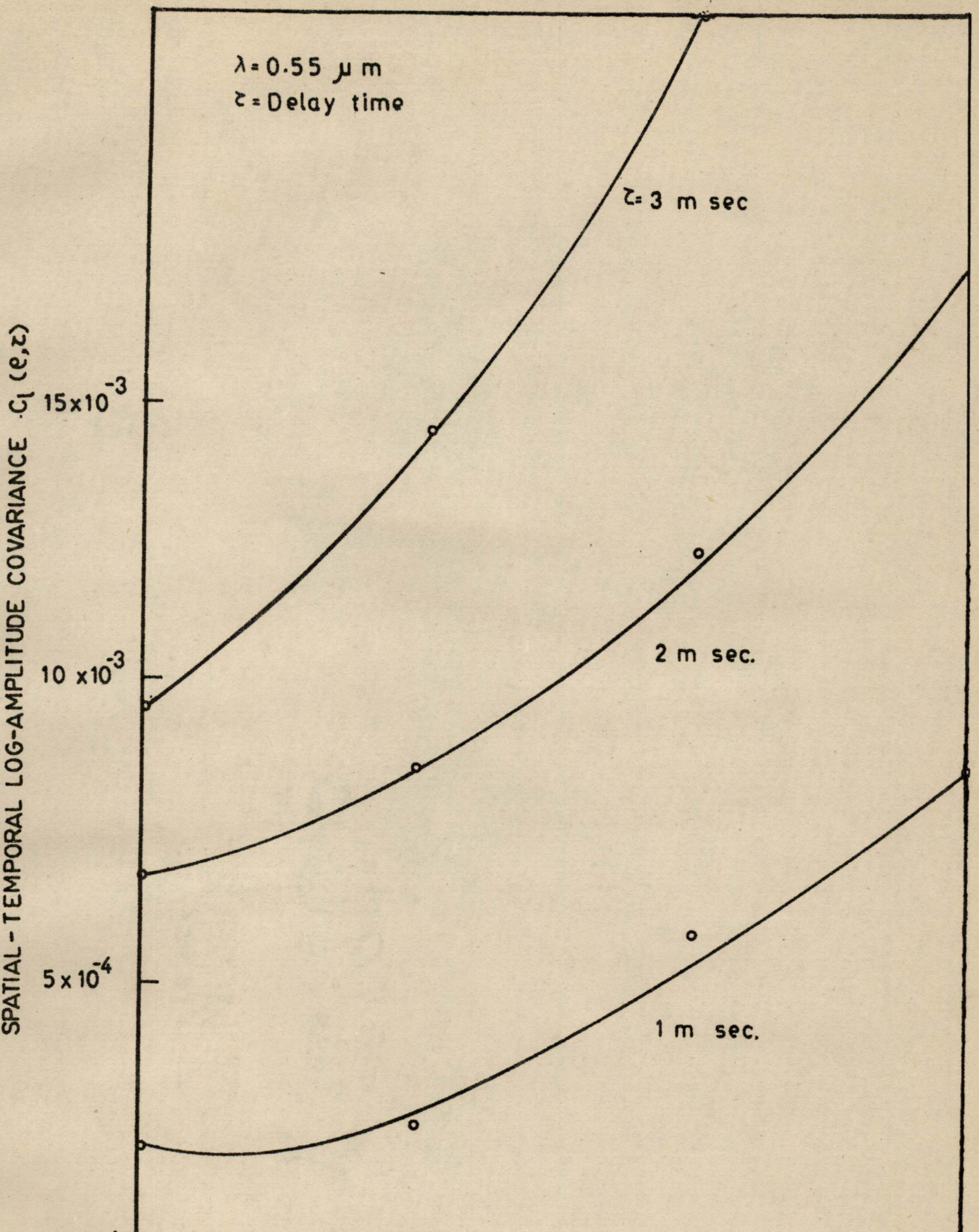

FIG.2.1 - VARIATION OF SPATIAL-TEMPORAL Log-AMPLITUDE COVARIANCE C_l WITH COLLECTING APERTURE DISTANCE (e)

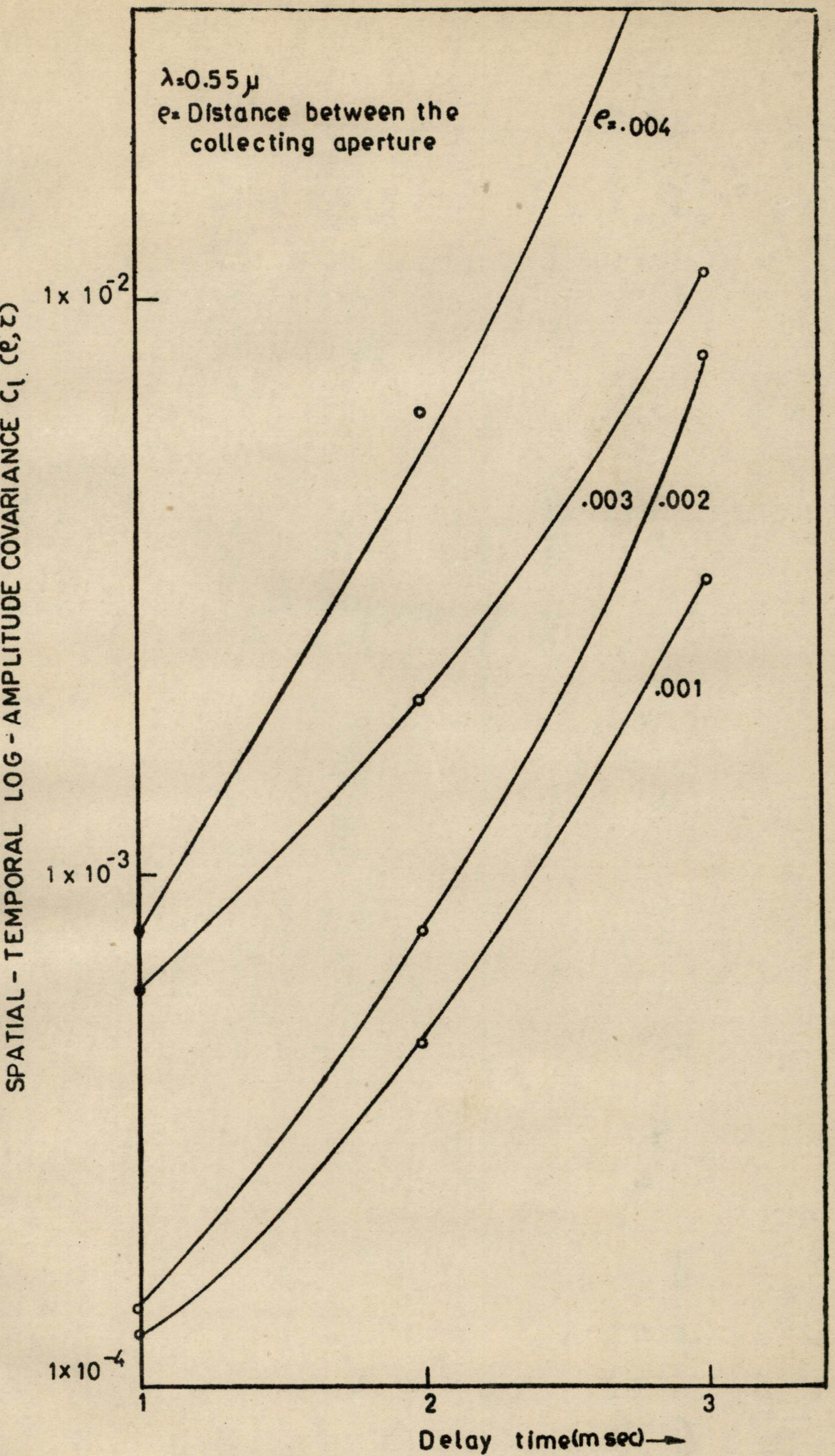

FIG. 2-2 - VARIATION OF SPATIAL - TEMPORAL LOG - AMPLITUDE COVARIANCE $C_l(\rho,\tau)$ WITH DELAY TIME

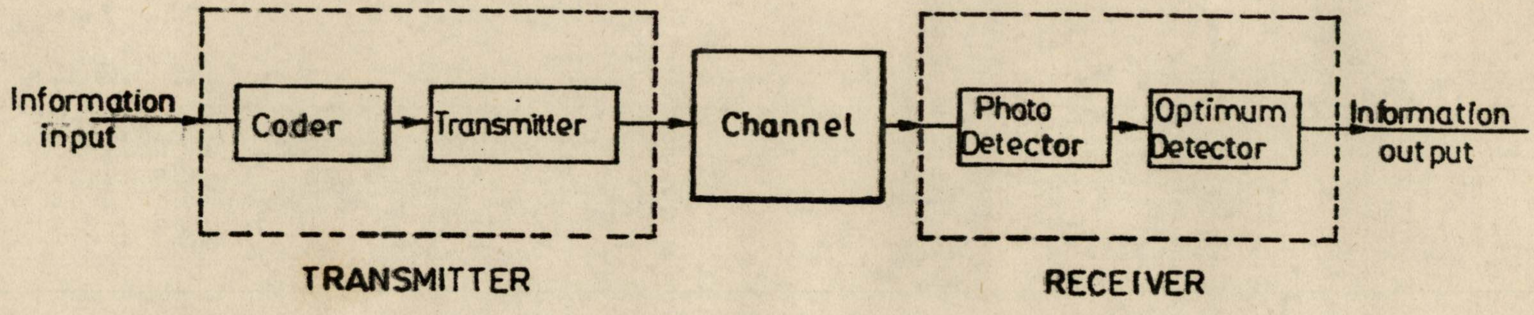

FIG.3.1-BLOCK DIAGRAM OF LASER COMMUNICATION SYSTEM

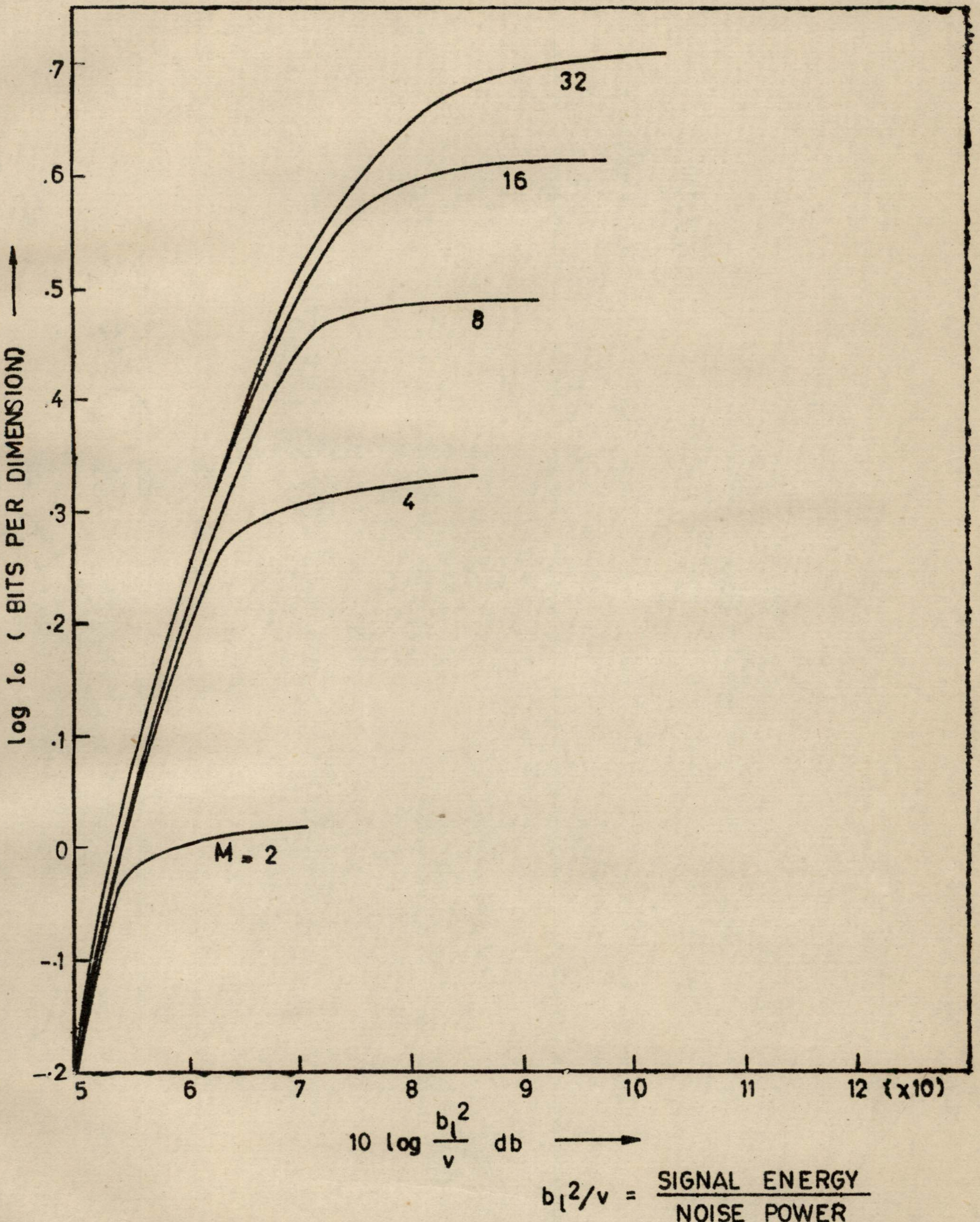

FIG.3·2- RELATION BETWEEN INFORMATION RATE (log Io) AND THE RATIO OF SIGNAL ENERGY TO NOISE POWER (b_l^2/v)

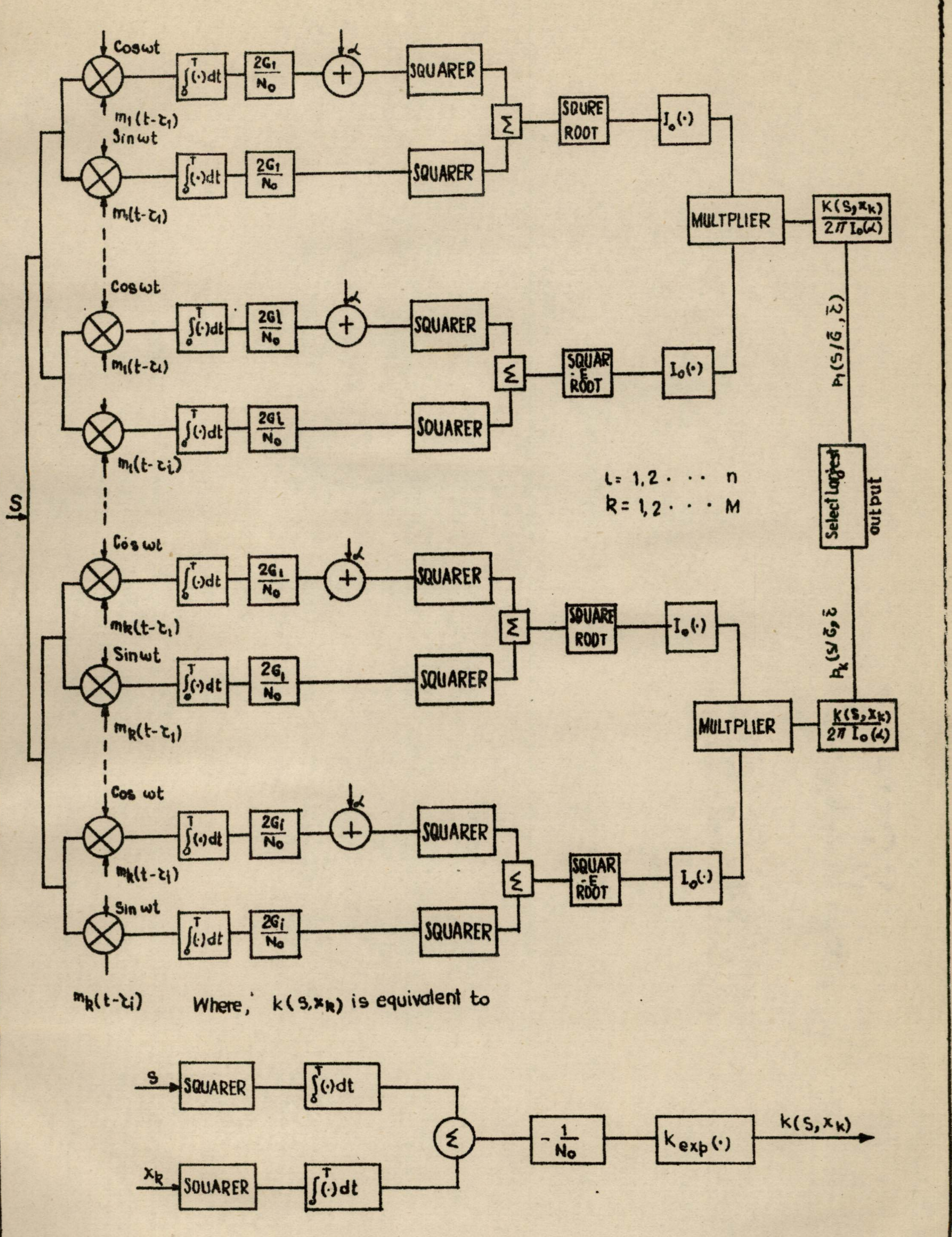

FIG. 4.1 Receiver Model For Random Phase Varying Channel

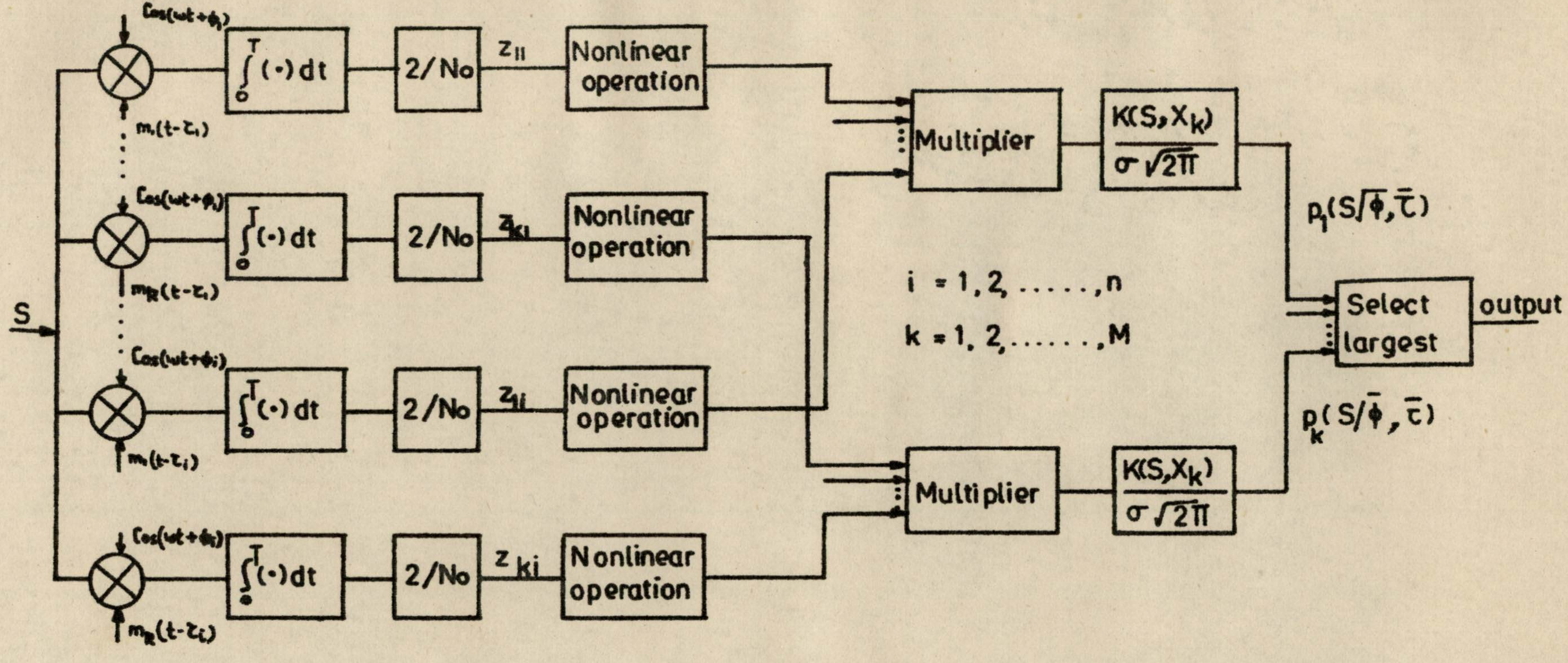

FIG.4.2-RECEIVER MODEL FOR RANDOM GAIN VARYING CHANNEL. THE NONLINEAR OPERATION IS $\int_0^\infty \frac{1}{G_i} \exp\left[G_i Z_i + \left\{ \frac{(\log G_i - \mu)^2}{2\sigma^2} \right\} \right] d\,G_i$

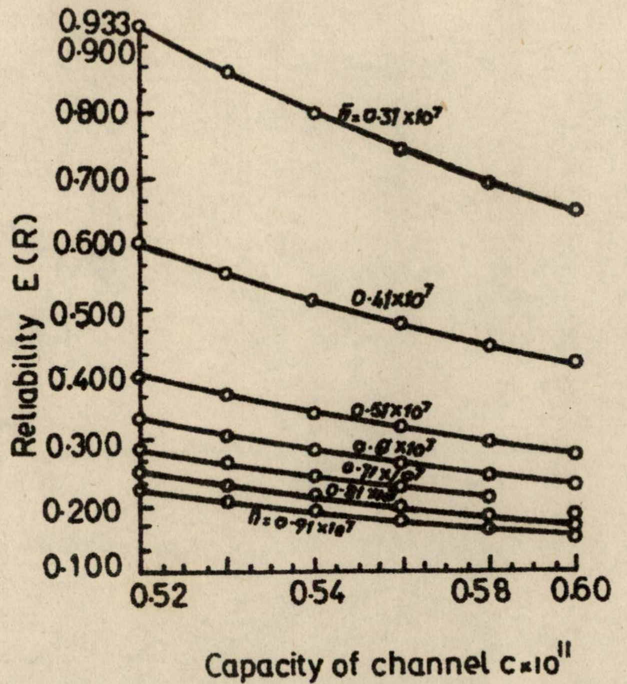

FIG.A.1-VARIATION OF RELIABILITY WITH INFORMATION RATE CAPACITY

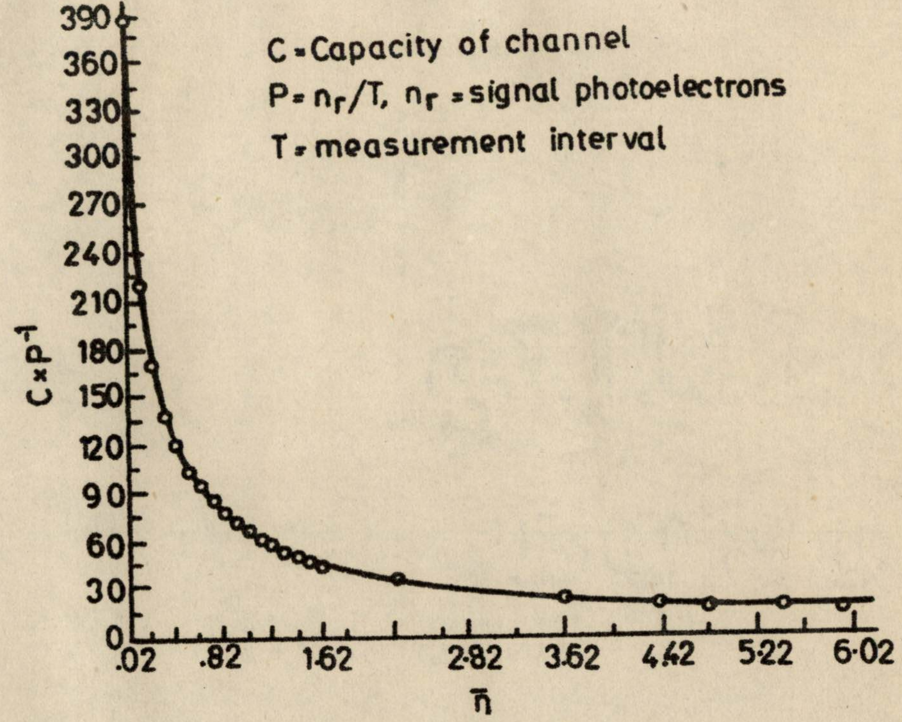

FIG.A.2-VARIATION OF $C \times P^{-1}$ WITH NOISE PHOTON

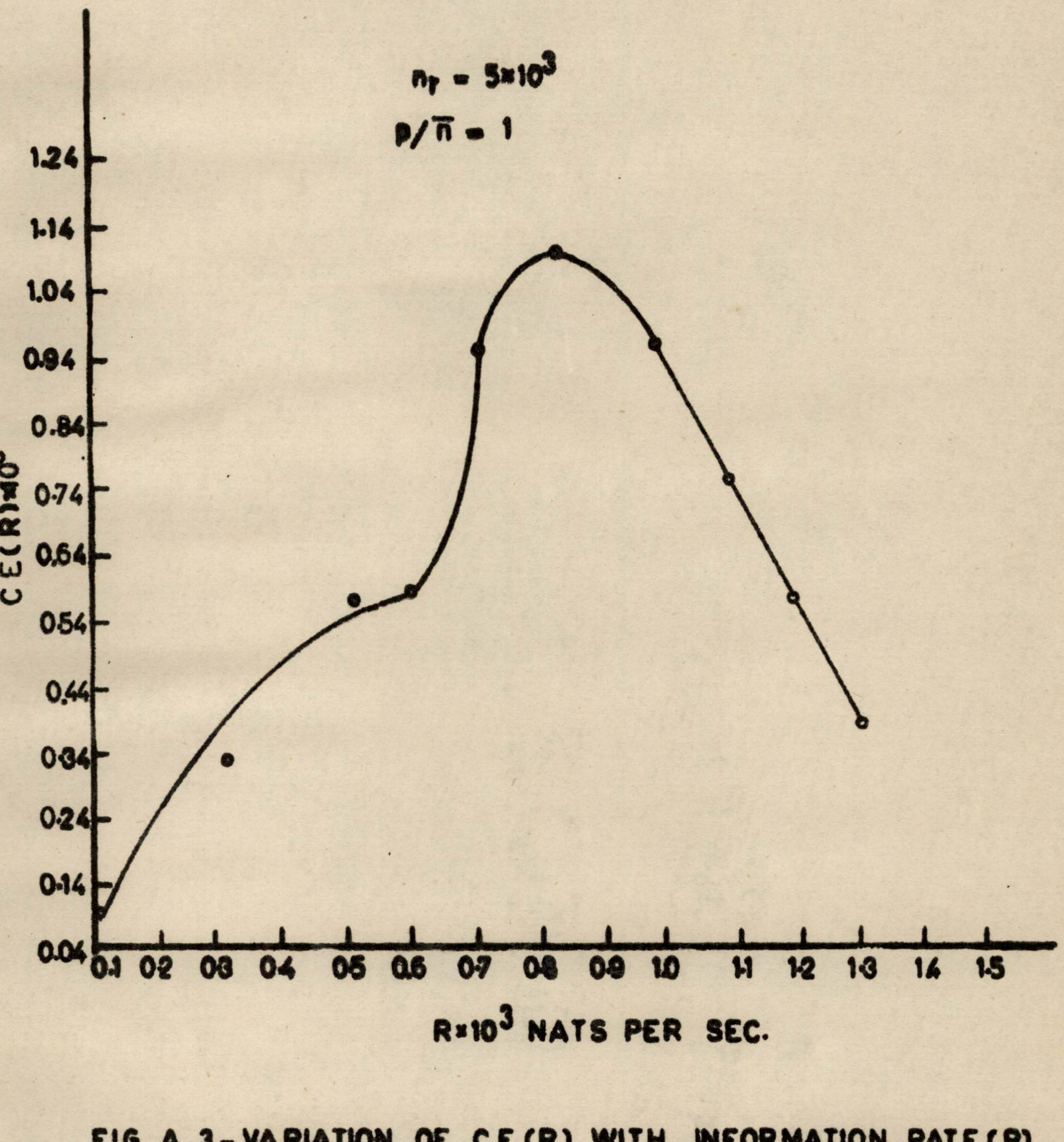

FIG. A.3 - VARIATION OF CE(R) WITH INFORMATION RATE (R)

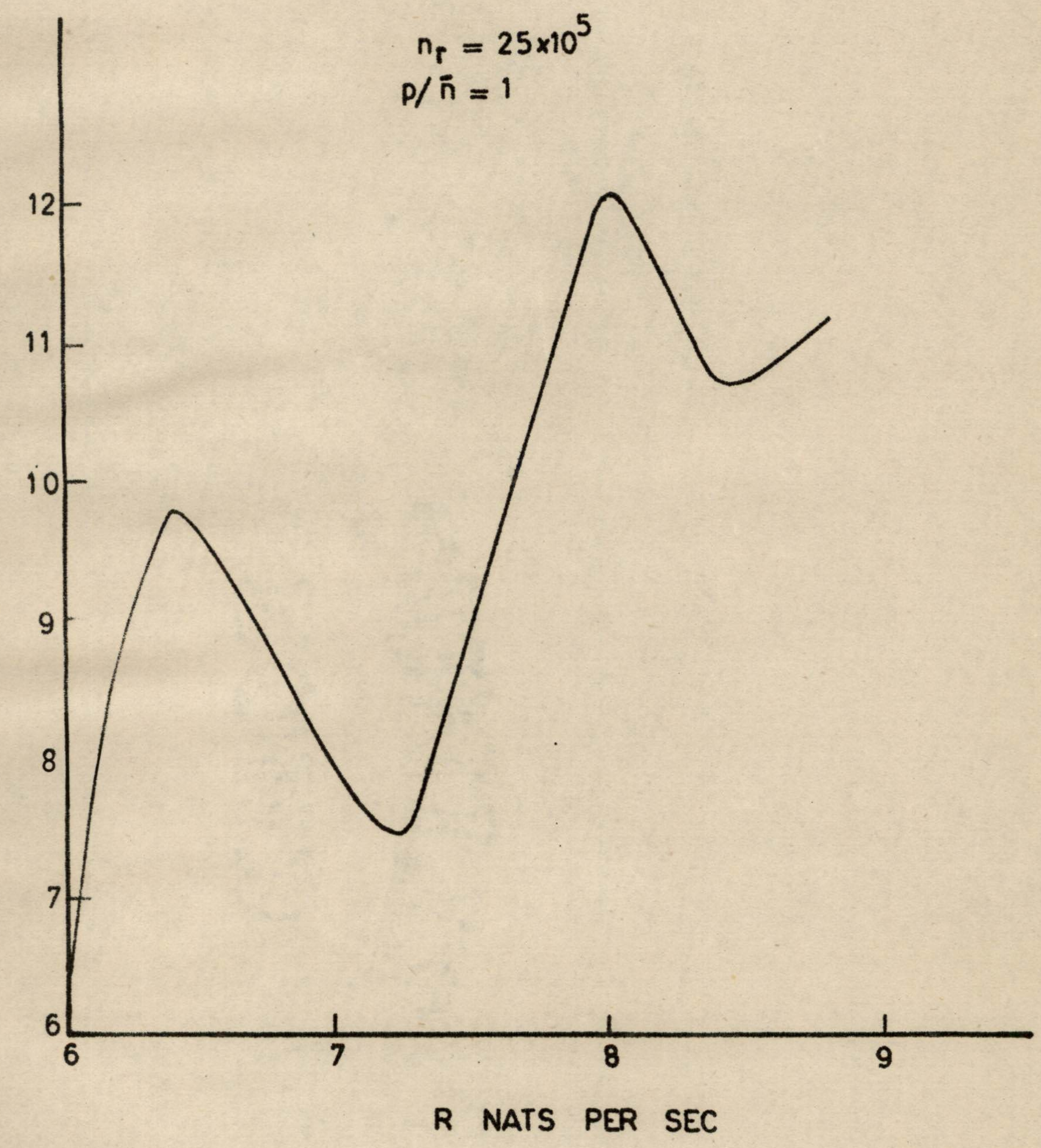

FIG.A.4-VARIATION OF CE (R) WITH INFORMATION RATE (R)

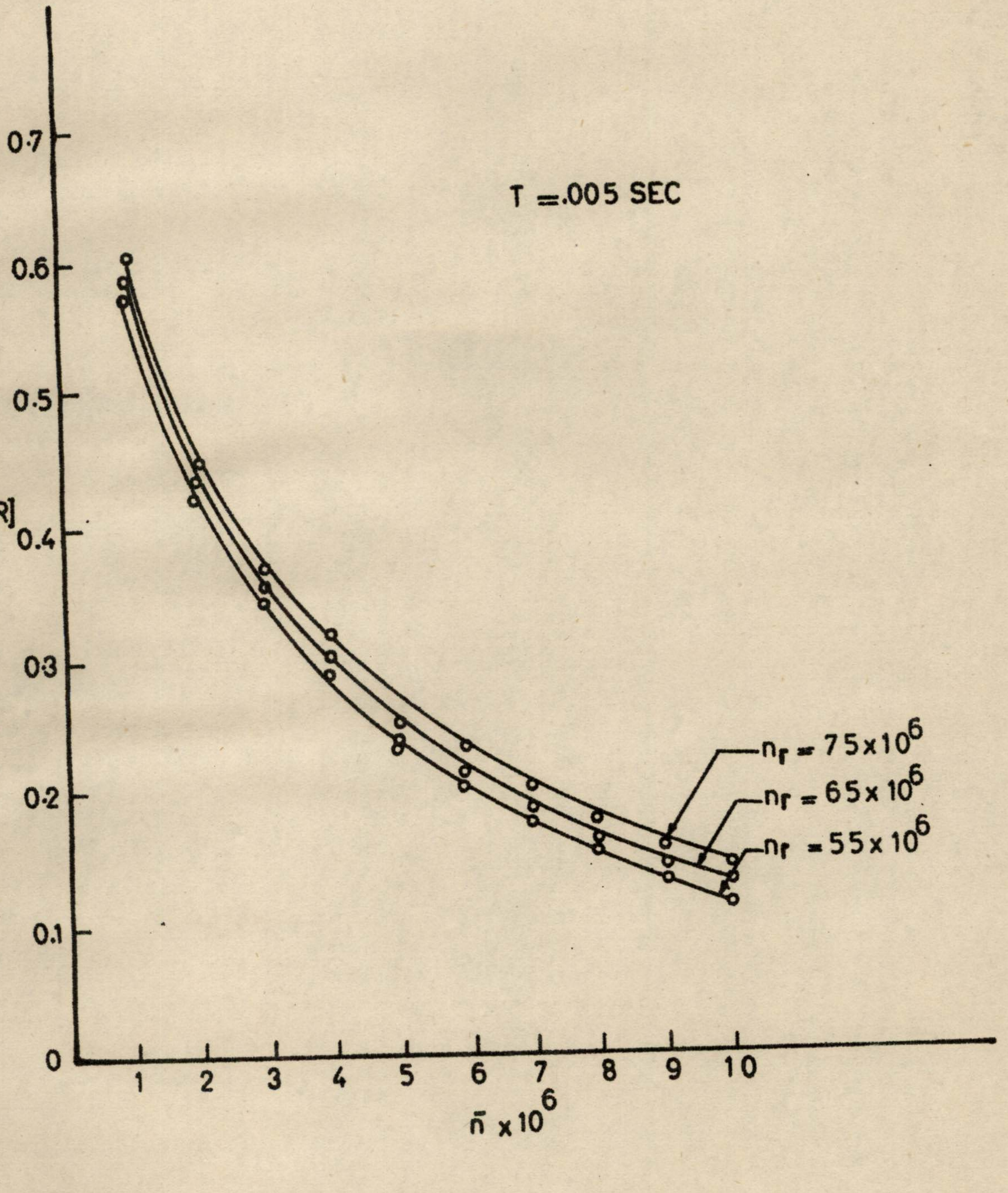

FIG. A.5. VARIATION OF RELIABILITY WITH NOISE PHOTONS

LIST OF PAPERS OF NILAMBER MALAVIYA

1. "Remote detection of Claear Atmosphere by Laser Radar" Proceedings Seminar on Radar and Microwave Communication Ed. A.K. Kamal, Sept. 1971 pp.214-219.

2. "Theory of Optimum M-ary laser detection" Electronics Letters, U.K., 14, 8, p.347, 13th July, 1972.

3. "Remote probing of atmospheric turbulence" J.Inst. of Engineers, May 1973, Vol. 53, pp.173-175.

4. "Remote probing of atmospheric turbulence" presented at the Annual meeting of the Institution of Engineers, India January, 1973.

5. "Laser signal detection" Proc. Symp. "Quantum and Opto-Electronics." Department of Atomic Energy, Govt. of India, February , 1974.

6. "Reliability of a laser communication system" Micro-Electronics and Reliability, U.K., Vol.13, pp.91-95, 1974

7. "A Theory of photon count detection" International J. of Electronics, U.K. (Accepted for Publication)

8. " Laser detection by random phase varying channel" Presented at 1974 IEEE International Symposium on Information Theory, NotreDame, U.S.A., Oct. 27-31, 1974.

9. "Error probability bound for M-ary laser detection" Proceedings of International Symposium on Digital Communication, Allahabad, India, Nov. 15-17, 1974 (To be published).

10. "Detection of laser signal perturbed by log-normal varying channel" presented at IEEE (India Section) Annual Convention, Banglore, Feb. 5 - 8, 1975.

11. "Laser signal detection perturbed by randomly varying channel" Proceedings of Eighteenth Annual Convention of Institution of Electronics and Telecommunication Engineers, India, March 8-10, 1975 (To be published).