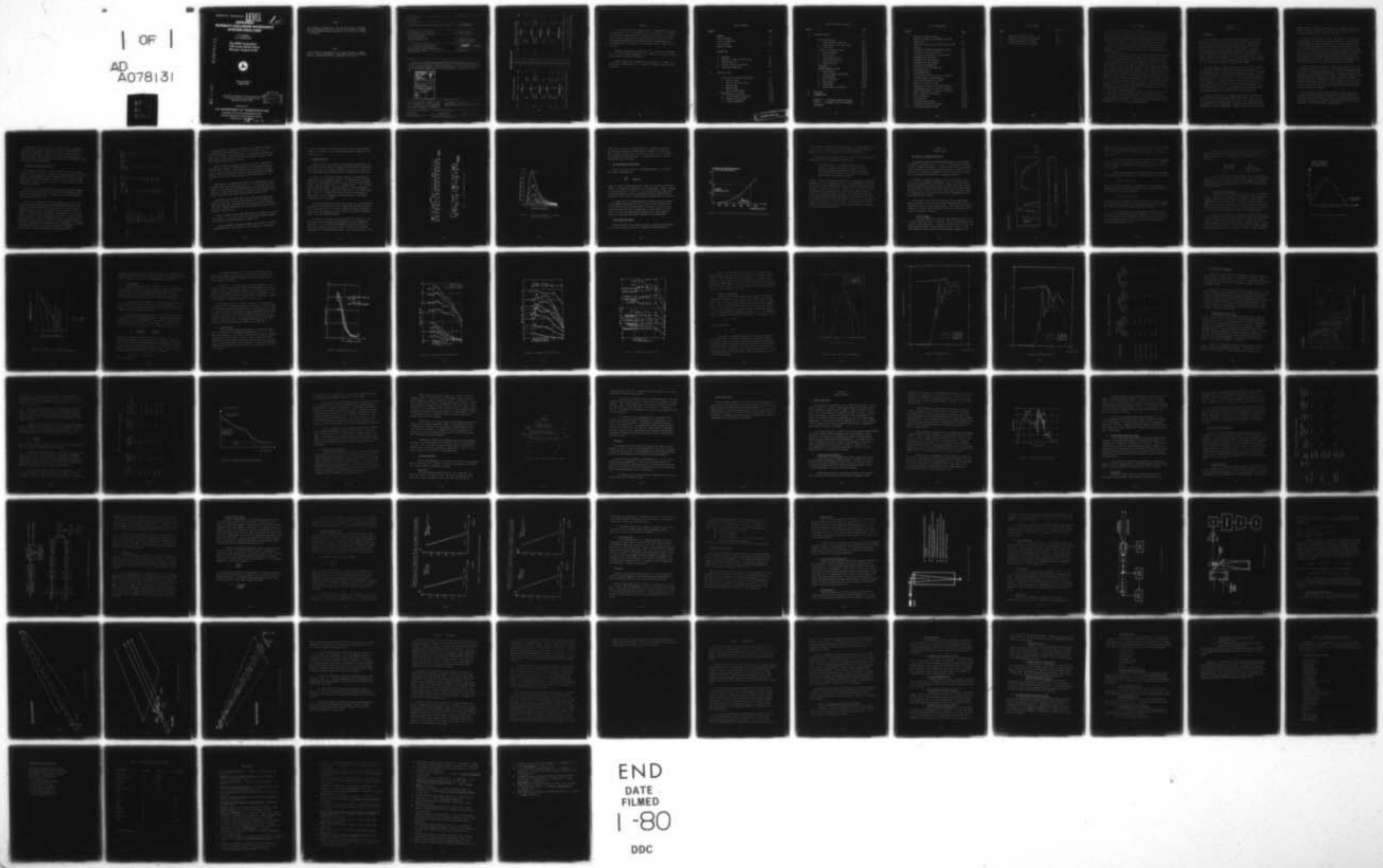
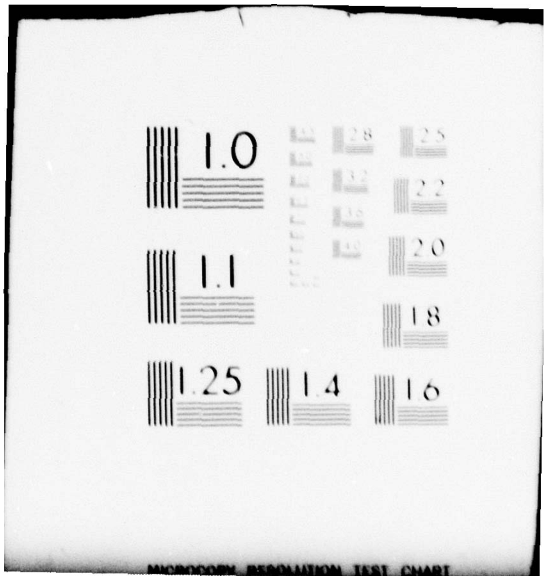
AD-A078 131 BDM CORP MCLEAN VA F/G 1/5
INFRARED RUNWAY COLLISION AVOIDANCE SYSTEM ANALYSIS.(U)
APR 79 P E POWELL , G H GREENLEAF DOT-FA78WA-4196
UNCLASSIFIED BDM/W-79-099-TR FAA-RD-79-32 NL

1 OF 1
AD
A078131



END
DATE
FILMED
1-80
DDC



MICROCOPY RESOLUTION TEST CHART

REPORT NO.: FAA-RD-79-32

12

INFRARED RUNWAY COLLISION AVOIDANCE SYSTEM ANALYSIS

P. E. POWELL
G. H. GREENLEAF

The BDM Corporation
7915 Jones Branch Drive
McLean, Virginia 22102

FINAL REPORT
APRIL 1979

Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161.

Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
Systems Research & Development Service
Washington, D.C. 20590

Technical Report Documentation Page

1. Report No. (19) (18) FAA-RD-79-32	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle (6) Infrared Runway Collision Avoidance System Analysis.		5. Report Date (11) Apr~~il~~ 1979 6. Performing Organization Code
7. Author(s) (10) P. E. Powell, G. H. Greenleaf		8. Performing Organization Report No. (14) BDM/W-79-099-TR
9. Performing Organization Name and Address The BDM Corporation 7915 Jones Branch Drive McLean, Virginia 22102		10. Work Unit No. (TRAIS) 11. Contract or Grant No. (15) DOT-FA-78WA-4196
12. Sponsoring Agency Name and Address U. S. Department of Transportation Federal Aviation Administration Systems Research and Development Service Washington, DC 20590		13. Type of Report and Period Covered (9) Final Report Sept~~ember 1~~978-March 1979 14. Sponsoring Agency Code FAA/ARD-250
15. Supplementary Notes (12) 86		

16. Abstract

Analysis of aircraft and ground mounted infrared devices for runway collision avoidance in low visibility conditions; Evaluation of IR signatures of commercial aircraft, strobes and beacons, and ground vehicles; Study of IR atmospheric transmission and laser propagation in fog and haze; Design of a two-color IR system for jet engine detection; and Application of laser technology to obstacle detection in fog.

Accession For
NTIS GRA&I ☒
DDC TAB ☐
Unannounced ☐
Justification______
By______
Distribution/
Availability Codes

Dist.	Avail and/or special
A	

17. Key Words	18. Distribution Statement
Collision Avoidance, Infrared, Electro-Optics, Runway, Fog, Takeoff, Airport Fog, Two-Color IR, Laser Propagation, CO_2 Lasers, Atmospheric Transmission	This document is available to the U. S. public through the National Technical Information Service, Springfield, VA 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
UNCLASSIFIED	UNCLASSIFIED	86	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized ✓ 391 962

- A -

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

LENGTH

Symbol	When You Know	Multiply by	To Find	Symbol
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km

AREA

Symbol	When You Know	Multiply by	To Find	Symbol
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha

MASS (weight)

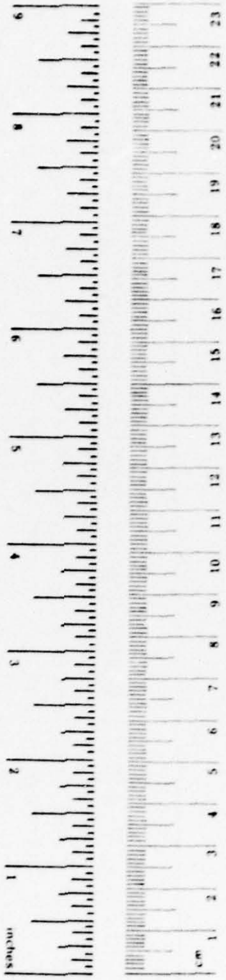
Symbol	When You Know	Multiply by	To Find	Symbol
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t

VOLUME

Symbol	When You Know	Multiply by	To Find	Symbol
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3

TEMPERATURE (exact)

Symbol	When You Know	Multiply by	To Find	Symbol
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



Approximate Conversions from Metric Measures

LENGTH

Symbol	When You Know	Multiply by	To Find	Symbol
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi

AREA

Symbol	When You Know	Multiply by	To Find	Symbol
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	

MASS (weight)

Symbol	When You Know	Multiply by	To Find	Symbol
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	

VOLUME

Symbol	When You Know	Multiply by	To Find	Symbol
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3

TEMPERATURE (exact)

Symbol	When You Know	Multiply by	To Find	Symbol
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

---

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

FOREWORD

This report describes and assesses concepts for developing an automated infrared runway collision avoidance device for ground and aircraft mounted applications. Systems evaluated include a passive two-color IR jet engine detector and an infrared laser runway scanning system. This effort was sponsored by the Federal Aviation Administration, System Research and Development Service, Washington, D.C. 20590 under contract number DOT-FA-78-WA-4196.

Important information was provided by R. W. Fenn and R. A. McClatchey (U.S. Air Force Geophysics Laboratory) and J. Mudar and R. Maxwell (Environmental Research Institute of Michigan).

Valuable suggestions and comments were provided by K. M. Haught (U.S. Naval Research Laboratory) and W. F. Herget (Environmental Sciences Research Laboratory).

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF ILLUSTRATIONS

LIST OF TABLES

EXECUTIVE SUMMARY

This report addresses the applicability and effectiveness of active and passive infrared devices for use in runway collision avoidance systems during low visibility airport operations. Emphasis is placed on systems available to the pilot which provide a positive indication of vehicles or aircraft on the runway prior to takeoff or immediately prior to landing.

The initial technical analysis focuses on the optical attenuation caused by conditions of fog and haze as a function of detector system wavelength. Atmospheric windows are identified and suitable detector wavelengths designated.

The technical analysis of Chapter III points out two feasible approaches to the use of infrared techniques in runway collision avoidance systems.

The recommended approach involves the use of a runway-mounted active CO_2 laser system which will provide an unambiguous indication of aircraft on the runway. The CO_2 laser application has several desirable characteristics which include required range of detection, fog penetration, and excellent reliability under all weather conditions. Such a system would not only enhance safe ground operations, but would serve as a significant means of expanding airport capacity as aircraft traffic densities increase. The hardware cost of a one runway system produced in volume is estimated at $20,000.

The alternative approach involves the use of a runway-mounted two-color passive IR system for jet engine heat detection. The two-color system is feasible but falls short of providing satisfactory detection range in fog without excessive hardware deployment.

These two systems are compared in Chapter IV and specific conclusions are drawn regarding the advantages of the IR laser blanking technique.

The analysis is concluded in Chapter V with a discussion of the recommended approach to development of a system specification which would include experimental tests and design of a prototype system.

CHAPTER I

INTRODUCTION

1. BACKGROUND

The rapid growth in recent years of both commercial carrier aviation and especially general aviation has resulted in increasing ground congestion and takeoff queueing at many metropolitan airports. System loading, delay, and resultant backup become most acute in low level visibility conditions such as rain, fog, and snow. The difficulty of maintaining reliable ground control for safe takeoff clearance is illustrated only too well by the March 1977 Tenerife collision at Los Rodeos Airport in the Canary Islands in which two Boeing 747's collided under 900 foot visibility and 583 lives were lost. Several dangerously near misses in the continental U.S. serve as further reminders of a growing safety problem.

This study addresses the feasibility of utilizing infrared (IR) detection techniques to enhance runway collision avoidance by providing the earliest possible alarm in the event of a runway takeoff hazard. Preliminary calculations indicated that IR techniques could provide adequate weather penetration and the additional benefits of high reliability and proven technology at low cost. Of primary interest is infrared detection of jet aircraft, propeller aircraft, ground vehicles, anticollision beacons, and strobes which might be found in a low visibility runway environment. The study considers both aircraft mounted systems which offer mobility and runway mounted systems which offer economy and increased sensitivity.

In particular, two-color IR techniques are evaluated with emphasis on false alarm rejection and reliable target identification. Many airports have expressways and waterways nearby, and under certain conditions automotive exhausts or ship smokestacks may have sufficient thermal signatures to deceive an unsophisticated sensor. However, experience with the Defense

Advanced Research Projects Agency (DARPA) Hostile Weapons Location System (HOWLS) and other two-color IR programs has shown a dramatic reduction in false alarm rate compared to one-color approaches.

The basic concept of two-color IR is that the ratio of two distinct IR signal bands is a function of the target temperature. Prior knowledge of target temperature range (plus other factors such as atmospheric transmission) permits the determination of acceptance criteria for the color ratio. Any target generating a ratio outside this range would be rejected as invalid. In this way a two-color system can be designed to discriminate against targets several degrees above ambient background (such as motor vehicles) and seek out targets hundreds of degrees above background (such as jet engines) or vice versa. In any case, an accurate knowledge of the target infrared signature is necessary for reliable system design.

Analysis of the passive two-color concept and atmospheric transmission characteristics leadsto the concept of an IR blanking technique which uses a CO_2 laser for enhanced weather penetration. The basic principle of this technique involves propagating a collimated CO_2 laser beam (or beams) through fog down the length of a runway to a reciever. Any object breaking or blanking the beam would be considered a runway hazard. The discussions and analysis in this report indicate it is highly probable that such a system can be successfully utilized to provide reliable runway hazard detection during low visibility conditions.

Topics considered in this study include aircraft and motor vehicle infrared signatures, atmospheric transmission and fog/haze attenuation characteristics, infrared detection systems, and infrared state-of-the-art technology. Optimum system parameters are described for the two feasible approaches to infrared detection of runway obstacles.

The remainder of this chapter will provide background information on fog and haze, infrared detection, two-color target identification, and system range requirements. The body of the report is dedicated to a discussion of the scientific basis for infrared transmission through fog, a technical analysis of the two-color and laser blanking techniques, followed by conclusions and recommendations.

2. ATMOSPHERIC STATES OF FOG AND HAZE

The atmospheric aerosol is a complex mixture of dust, volcanic ash, biological matter (e.g., pollen), industrial pollutants, combustion particles, smog, etc. These components serve as condensation nuclei for water vapor and can produce conditions commonly referred to as fog and haze. Haze may extend to an altitude of several miles whereas a typical fog bank is only a few hundred feet thick.

The practical distinction between fog and haze is the greatly reduced visiblility imposed by the former. Physical transitions between haze and fog do not occur abruptly, but are a continous process with intermediate states often referred to as mist.

Table 1.1 is a representation of the International Visibility Code in terms of conventional nomenclature and shows corresponding values of the exponential attenuation coefficient for visible light (with path loss represented by exp $(-\beta R)$, R in kilometers and β a function of visibility level). Of interest here are conditions of "moderate fog" to "light haze." In terms of minimum visibilities permitted for takeoff the relevant Runway Visual Range (RVR) values are 700 feet (213 meters) for an appropriately configured runway and 1200 feet (366 meters) without appropriate equipment. This study is concerned with atmospheric states corresponding to exponential attenuation coefficients of up to 20 per kilometer (87 dB/km) for visible light. More severe conditions are not considered here.

TABLE 1.1. INTERNATIONAL VISIBILITY CODE

CODE NO.	DESCRIPTION	DAYLIGHT VISUAL RANGE (METERS)		EXPONENTIAL ATTENUATION COEFFICIENT (KM^{-1}), β [†]	
		FROM	TO	FROM	TO
0	DENSE FOG		< 50		> 86.00
1	THICK FOG	50	200	86.00	21.00
2	MODERATE FOG	200	500	21.00	8.50
3	LIGHT FOG	500	1000	8.50	4.30
4	THIN FOG	1000	2000	4.30	2.10
5	HAZE	2000	4000	2.10	1.10
6	LIGHT HAZE	4000	10000	1.10	0.43
7	CLEAR	10000	20000	0.43	0.21
8	VERY CLEAR	20000	50000	0.21	0.07
9	EXCEPTIONALLY CLEAR	> 50000		< 0.07	

[†] ATTENUATION REPRESENTED HERE AS $T(R) = \exp(-\beta R)$

There are several classes of fog and each is the result of a particular environmental condition causing a transition from haze to fog as a result of an increase in relative humidity. For purposes of discussion fog types may be classed as one of the following: advection, radiation, advection-radiation, evaporation, and frontal.

Advection refers to horizontal motion of an air mass. Advection fog forms when moist, warm air traverses water or land of a lower temperature. This fog type is typical of the Grand Banks, one of the world's foggiest regions, where air originating in the Gulf Stream blows across the Labrador Currents. Similar fog is usually found on the Pacific coastline of the U.S.

Radiation fog is caused by surface heat loss at night through a clear atmosphere which cools the overlying moist air. This fog type occurs frequently in inland areas and is intensified by cold air drainage from sloping terrain. Advection-radiation fog is the result of two processes and is common in the Great Lakes region and the Atlantic coastal plains.

Evaporation fog occurs when vapor from a water surface meets colder quiet air, resulting in a shallow layer of dense fog. This condition is often found over lakes and streams and during autumn mornings following a cold night. However, evaporation fog is also produced when warm rain falls through a layer of cold air.

Frontal fog results from a warm front moving into a region with a cold surface layer. It is similar to warm rain fog since the required temperature inversion is usually provided by a weather front.

From the standpoint of detection, whether using visible or infrared techniques, the most critical aspect of a fog situation is the particle size distribution which can vary quite rapidly as the relative humidity changes. This aspect of fog is evaluated from several viewpoints in the present analysis.

3. INFRARED DETECTION

The basic thrust of this study is to evaluate the possibility of infrared detection of hazards on a runway during low visibility operations. A hot object such as a jet engine produces a significant IR signature and to this end the radiative characteristics of targets must be understood.

Figure 1.1 illustrates the relative location of the wavelengths of interest in the electromagnetic spectrum. All bodies above zero degrees absolute emit electromagnetic radiation with a distribution determined by Planck's Law and the emissivity, ϵ, of the body surface. If $\epsilon=1$ then the body is a perfect emitter. A perfect emitter is a perfect absorber as well, and for this reason a body with an emissivity of 1 is termed a blackbody. Figure 1.2 illustrates the Planckian spectral distribution for blackbodies at several temperatures which are typical of the exhaust characteristics of jet engines.

Although blackbodies are an ideal case, the emissivity of most objects (especially hot cavities such as jet tailpipes) does not radically depart from 1 and values of 0.8 - 0.9 are not uncommon for metallic surfaces so that the ideal blackbody curves shown in Figure 1.2 are fairly representative of real world thermal behavior.

The practical difficulty in predicting target IR signatures is one of obtaining precise knowledge of target geometry and surface temperature distribution. This is an empirical problem and requires hard data. In practice, such data is usually as difficult to obtain as are complete measurements of infrared emittance spectra. The primary difficulty in the

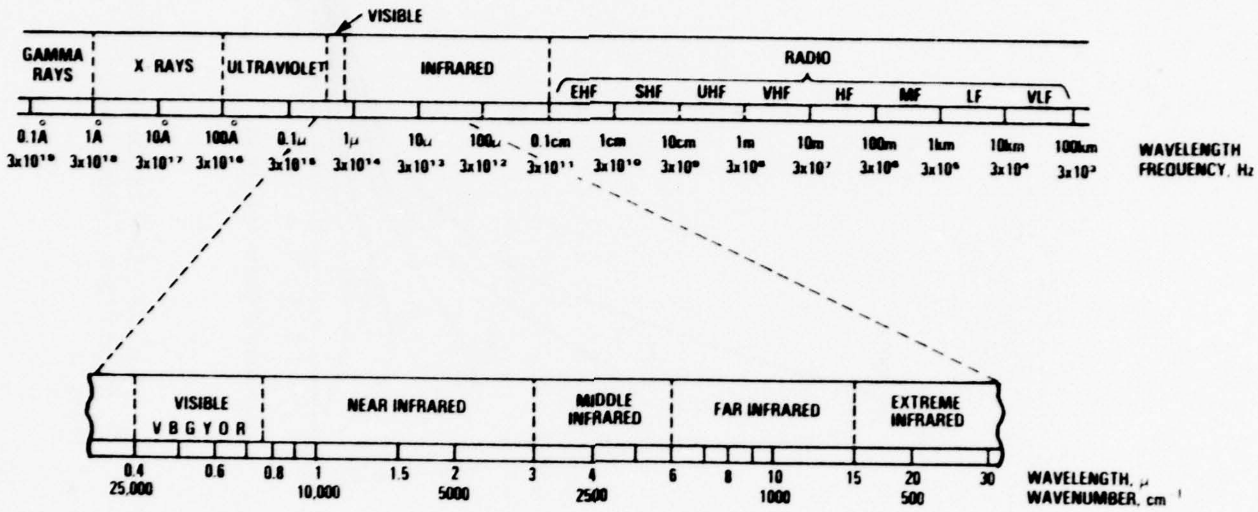


Figure 1.1. The Electromagnetic Spectrum

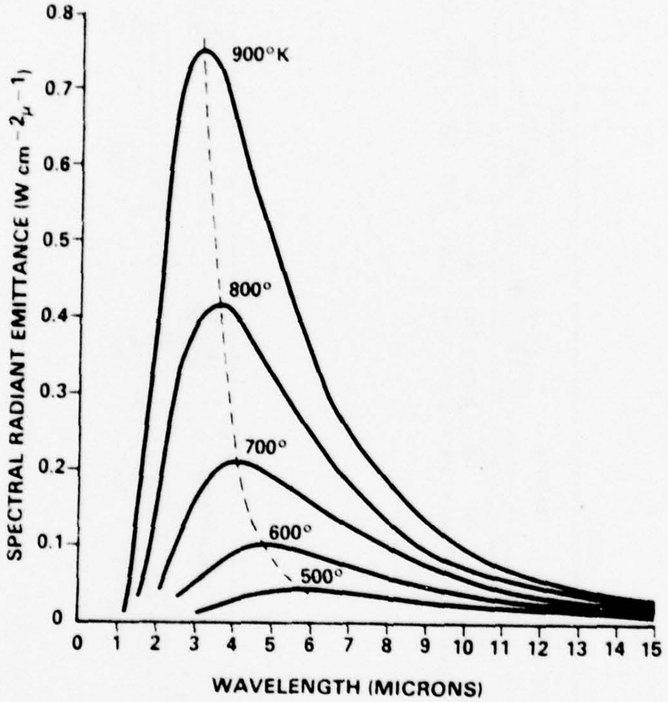


Figure 1.2. Spectral Emittance of a Blackbody at Various Temperatures

latter case is that most infrared signatures of interest are classified, as is much of the technical literature on this subject. In some cases, data on specific target thermal characteristics does not exist and theory and extrapolation must be employed. Fortunately the levels of accuracy required are easily attainable.

4. TWO-COLOR TARGET IDENTIFICATION

Planck's radiation law which is reflected by Figure 1.2 is given by the relation (See Appendix B)

$$W = \frac{2\pi hc^2}{\lambda^5} \cdot \frac{1}{e^{hc/\lambda KT}-1}$$

Where W is spectral radiant emittance or power per unit area per unit wavelength, T is the absolute temperature, λ is the wavelength. Planck's constant is h and the velocity of light is c. This relation basically states that the radiant power at a specific wavelength emitted by an object per unit surface is a function only of the wavelength and temperature of the surface.

For reasons that will become apparent the two-color system discussed in the present study operates in the 3-5 and 8-12 micron infrared bands. The ratio of the total 3-5 micron signal to the total 8-12 micron signal is the two-color ratio for the target, and it is the value of this ratio which is utilized for target identification and false alarm rejection. Figure 1.3 illustrates the principle applied to jet engine targets.

5. SYSTEM RANGE REQUIREMENT

Perhaps the most critical aspect involved in assessing the feasibility of a collision avoidance system is its detection range performance. A

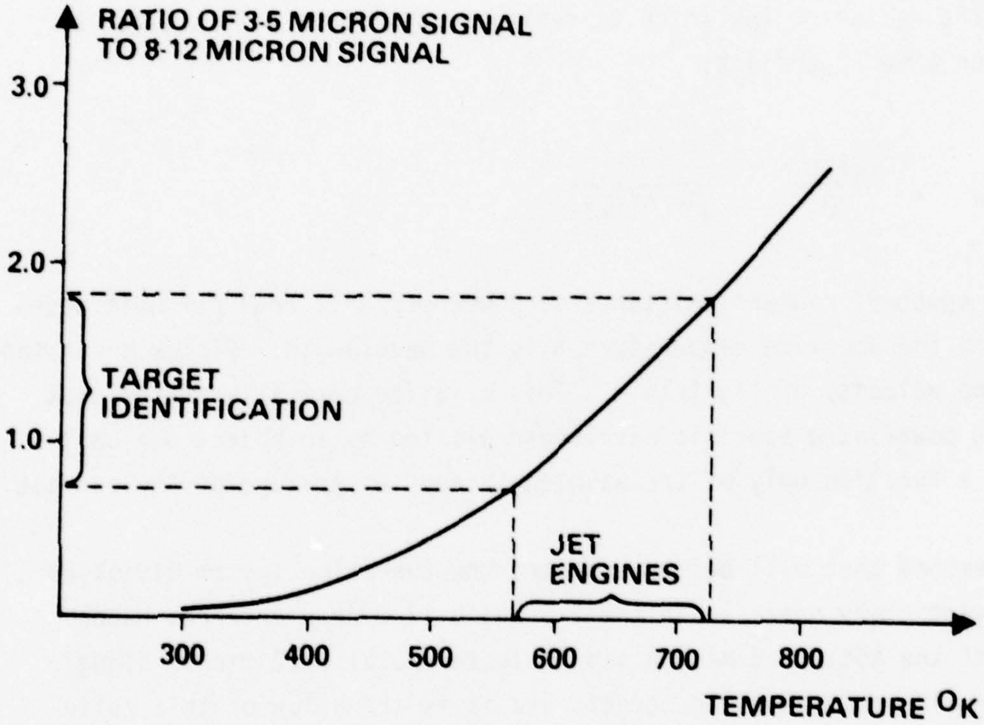


Figure 1.3. Two-Color Target Identification and False Alarm Rejection

pilot preparing for takeoff must receive warning of a runway obstacle at a distance sufficient to permit effective avoidance maneuvers, by either bringing the aircraft to a complete stop or changing direction.

Of interest here is the definition of V_1, the critical engine failure speed, more specifically defined as (Reference 40):

> "The speed at which, if an engine failure occurs, the distance to continue the takeoff to a height of 35 feet will not exceed the usable takeoff distance, or the distance to bring the airplane to a full stop will not exceed the accelerate-stop distance available."

Clearly V_1 and the corresponding distance R_1 are runway, weather and aircraft dependent. The pilot should be notified of any obstacle before he attains V_1, so that a minimum hazard detection range requirement would be the stop distance for a given aircraft at V_1. However, since low visibility may be accompanied by wet runway conditions, and a hazardous obstacle may be moving, it is deemed advisable to require a hazard detection range equal to the entire acceleration and stop distance for the worst case aircraft. This has been determined to be 11,000 feet for the Boeing 707 freighter,which exceeds the runway length of most airports. The nominal length of major runways, 10,000 feet, will therefore be utilized to assess the feasibility of IR runway collision avoidance.

CHAPTER II
SCIENTIFIC BASIS

1. LOW VISIBILITY INFRARED TRANSMISSION

The greatest constraint on infrared system design is that imposed by atmospheric attenuation of the IR signal. Transmission of infrared is, in general, wavelength dependent. The major physical effects are absorption and scattering resulting from aerosol and molecular content in the optical path. Knowledge of atmospheric optics is critical for judicious choice of wavelength and estimation of operating conditions.

An aerosol is a gaseous suspension of small particles and is the normal condition throughout the atmosphere. Haze is a specific state of the aerosol whereby the scattering effect is greater than that attributable to gaseous molecular scattering but less than that of water droplet scattering in fog. Volcanic ash, cosmic dust, foliage particles, combustion products, bits of sea salt and various other components make up the particulate structure of haze.

Certain types of particles such as dust grains are nonhygroscopic, whereas components such as sea salt are highly hygroscopic and serve as condensation nuclei for water droplet growth. Thus a typical haze particle might be a dry solid, a solid coated with water, or a water droplet with a hygroscopic substance in solution.

a. Physical Theory

Molecular absorption is the most common attenuation effect, and is present even under clear air conditions. The principle absorbers in the infrared are H_2O, CO_2, and O_3. In addition to these, CH_4, CO, and N_2O have strong absorption bands in certain spectral regions. Figure 2.1 shows typical absorption regions and notes the major gases responsible (see

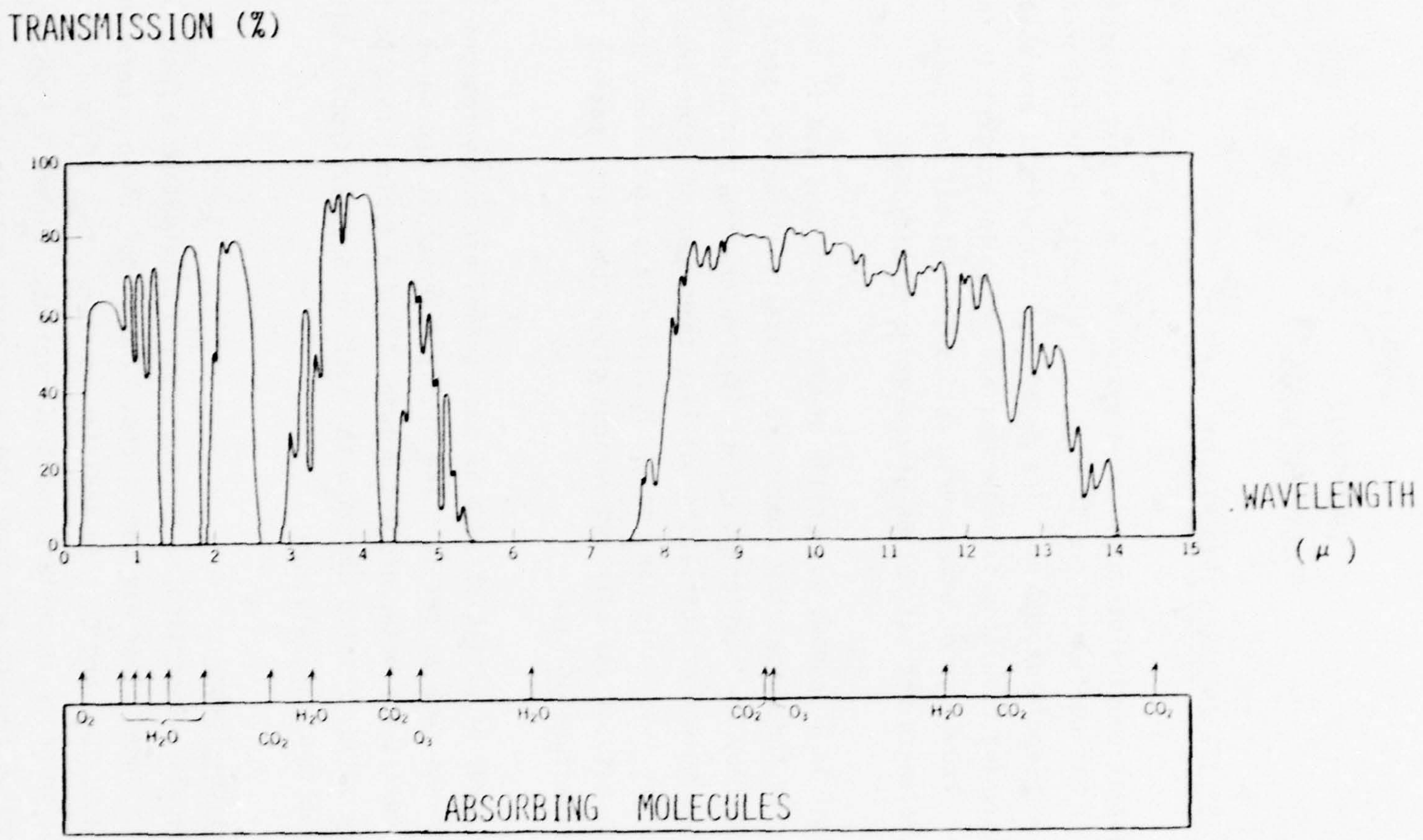


Figure 2.1 Atmospheric Windows and Absorbing Molecules

Appendix B). The regions of high transmission are referred to as atmospheric windows and represent potential operating wavelengths for IR systems. Of particular interest are the 3-5 and 8-12 micron intervals considered in the present study.

Within a given window the IR signal will be further attenuated by molecular scattering (Rayleigh) and aerosol scattering (Mie). Of these, aerosol scattering is potentially the most severe effect under low visibility conditions.

Atmospheric attentuation of an infrared signal is conventionally represented by a path loss function or transmission coefficient in the form

$$T_\lambda (R) = \exp(-\beta_\lambda R)$$

where R is optical path length in kilometers and β_λ is the wavelength dependent exponential extinction coefficient (per kilometer) which in turn is a function of its various components:

$$\beta_\lambda = \alpha_M + \alpha_A + \sigma_M + \sigma_A$$

Absorption has been denoted by "α" and scattering by "σ" so that α_M and α_A are, respectively, molecular and aerosol absorption coefficients, whereas σ_M and σ_A are molecular and aerosol scattering coefficents.

For a given optical path length, absorption will show little variation with changing weather and the atmospheric "windows" may be taken as a nominal baseline loss contribution (see Figure 2.1). At the same time, the molecular scattering loss due to σ_M is usually negligible for wavelengths beyond about 1 micron.

Hence, for a specific optical path, the total exponential extinction coefficient may be considered to be the sum of a constant and a weather-dependent term (for wavelengths in the intermediate and far infrared regions):

$$\beta_\lambda = \underbrace{\alpha_M + \alpha_A + \sigma_M}_{\text{Near constant term}} + \underbrace{\sigma_A}_{\text{Weather dependent aerosol scattering}}$$

Aerosol scattering is thus the dominant effect in fog/haze conditions, whereas the other effects show relatively little change as weather becomes more severe. The physical theory of electromagnetic scattering by spherical particles was described by G. Mie in 1908 and has since been verified extensively.

b. Particle Size Distribution

The particle size distribution for a fog or haze is an important physical factor from the standpoint of electro-optical signal penetration. A general observation is that transmission tends to decrease at those wavelengths which are near the peak of the particle size distribution. Figure 2.2 illustrates a representation of particle size data in histogram form. Such a fog would exhibit minimum signal transmission in the region of 2.3 microns, with transmission increasing for longer wavelengths.

For hazes, which generally correspond to visibilities not less than 1 kilometer, the particle size distribution commonly will peak between 0.1 and 1.0 microns. With fogs (visibility $<$ 1 kilometer) the particle size distribution may peak somewhere between 1.0 and 10 microns. Of course these are approximate values, and a real world aerosol is usually dynamic with a shifting particle size distribution. Figure 2.3 shows a theoretical

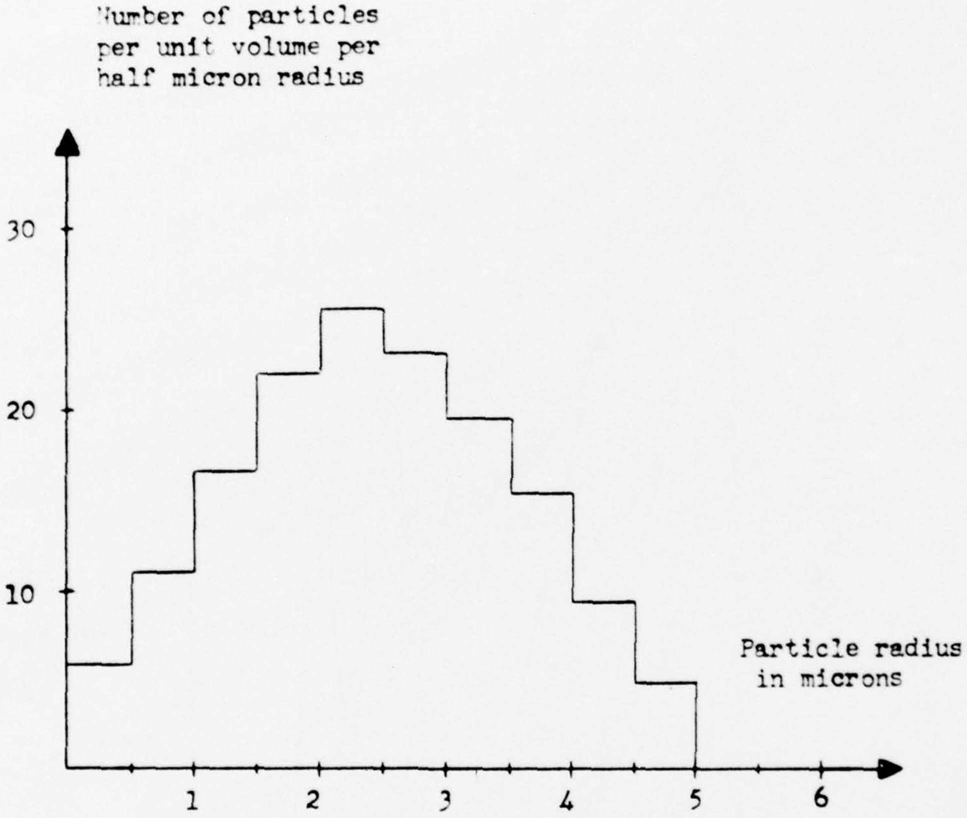
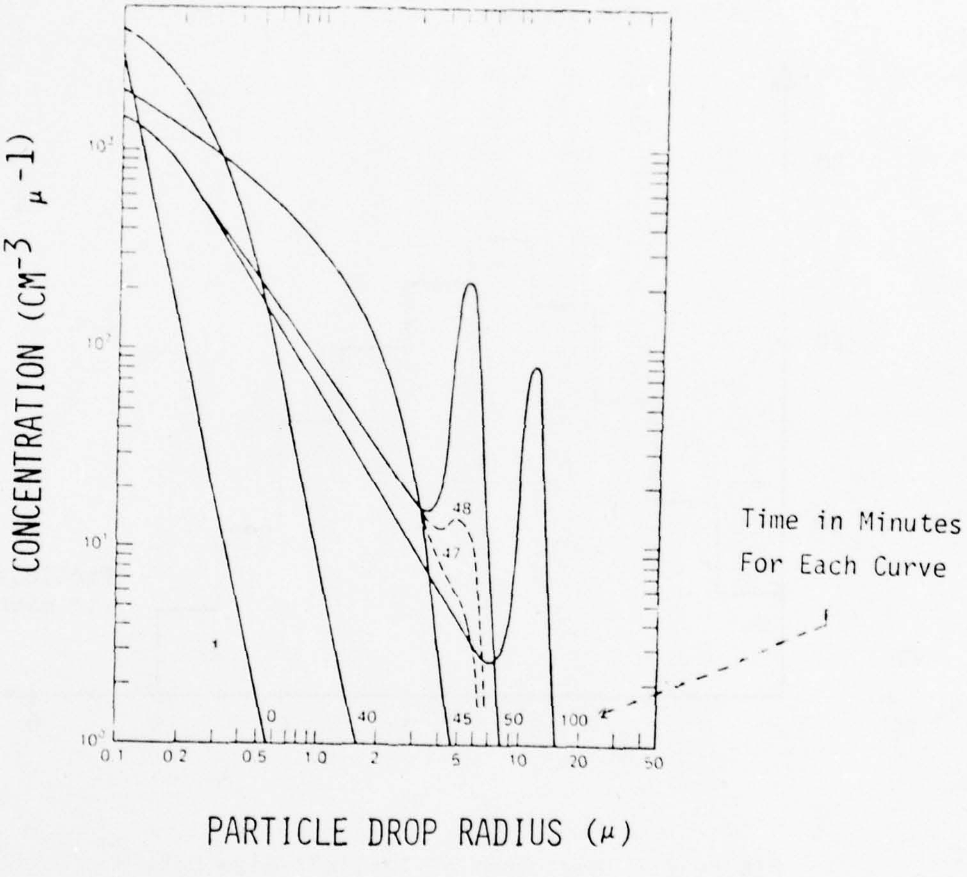


Figure 2.2 Histogram of Particle Size Data



Time in Minutes
For Each Curve

Figure 2.3 Evolution of Fog Droplet Size Distribution fog evolution over a period of 100 minutes (reference 10). The transition from the single mode (0, 40, and 45 minutes) curves to the bimodal distributions (after 47 minutes in this case) is typical behavior for many fogs.

c. Measured Data

Numerous examples of empirical data as it relates to IR transmission through fog were examined and evaluated. It was found there is no unique one-to-one functional relationship between an observed value of visibility (RVR) and infrared transmission characteristics. Values of visible propagation data do not imply exact values for IR propagation.

From a deterministic standpoint, in principle a detailed particle size distribution completely defines IR scattering characteristics. In practice such data is usually not available or is of limited accuracy due to particle size measurement difficulties.

The key to judicious estimation of IR transmission for specific visibilities lies in the relationship between "visibility" and the scattering coefficient for visible wavelengths. From Figure 1.1, visible wavelengths roughly cover the 0.4 to 0.7 micron range. The visible light midrange (0.55 micron) scattering coefficient is related to visibility by

$$\beta_{Vis} = \frac{-\ln (0.02)}{\text{Visibility}} = \frac{3.91}{\text{Visibility}}$$

The 0.02 in the numerator represents the visual contrast criteria (2% International Standard) for assigning a value of visibility. Criteria for RVR not conforming to this standard must be scaled accordingly. The units of β_{Vis} are the inverse of those of visibility. For example, 1 kilometer visibility implies a visible scattering coefficient of 3.91 per kilometer and the visible extinction function for such a fog would be:

$$\tau_{0.55} (R) = \exp (-3.91 R)$$

with R in kilometers.

The approach taken here is to select data on fogs which have values of β_{Vis} roughly in the regions corresponding to RVR values of interest and with this data base to determine reasonable ranges of β_{IR} (λ) to be expected in most cases.

Figures 2.4 - 2.7 contain sample data from reference 15. This particular study included over 600 transmission measurements taken over a 3-year span and is a recognized data source. The attenuation here is represented in the photometric units of "optical density" corresponding to a base 10 path loss function $10^{-D\ R}$. Optical density as used here is related to the exponential attenuation coefficient by $D = \beta/2.3$.

Extinction by a rural haze is shown in Figure 2.4. The marked drop in extinction with increasing wavelength is quite typical of haze. Figure 2.5 illustrates attenuation characteristics of highly selective fogs, that is, those which favor IR transmission at long wavelengths (note the dramatic drop in extinction coefficient as wavelength approaches ten microns). Attenuation characteristics of evolving and stable fogs are shown respectively in Figures 2.6 and 2.7. The tendency toward improved IR transmission with increasing wavelength is again seen in both cases.

d. AFGL Fog Model

The most widely known accepted model for low resolution atmospheric transmission is the LOWTRAN code developed at the U.S. Air Force Geophysical Laboratory. This highly refined analytical model has undergone considerable evolution since its origin in 1972, and the current model (version 3B) may be considered accurate for weather conditions corresponding to visibilities greater than 2 kilometers. For more severe conditions LOWTRAN 3B predictions diverge from observed values and yield overly optimistic results.

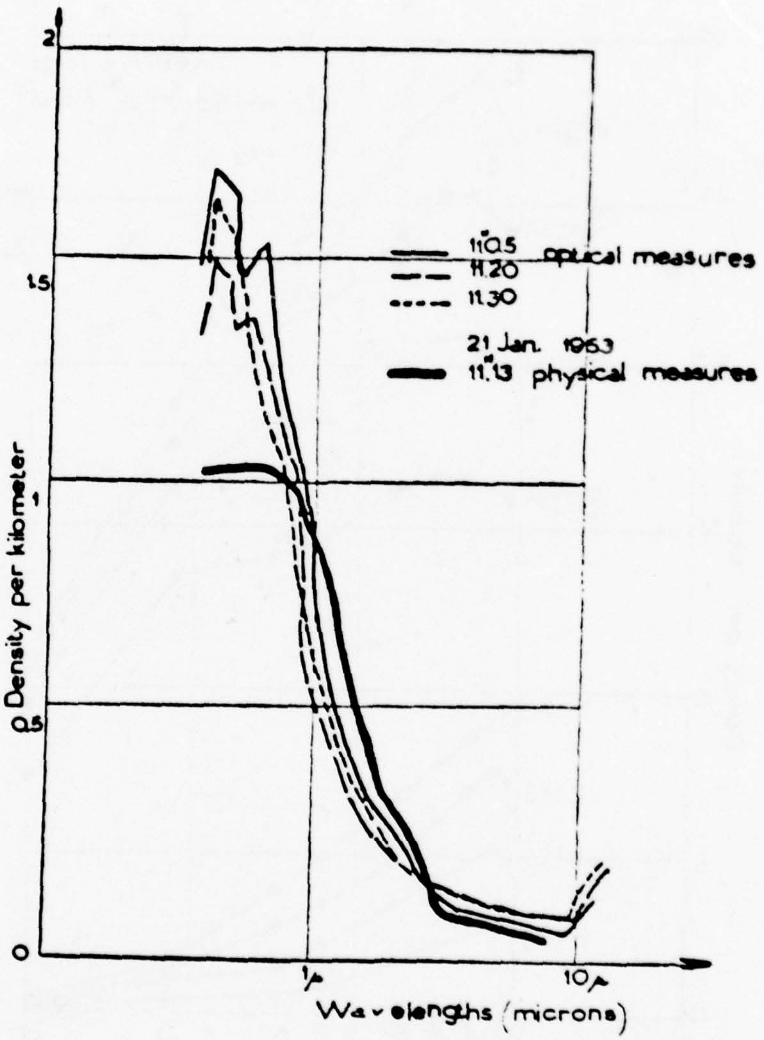


Figure 2.4 Attenuation By Rural Haze

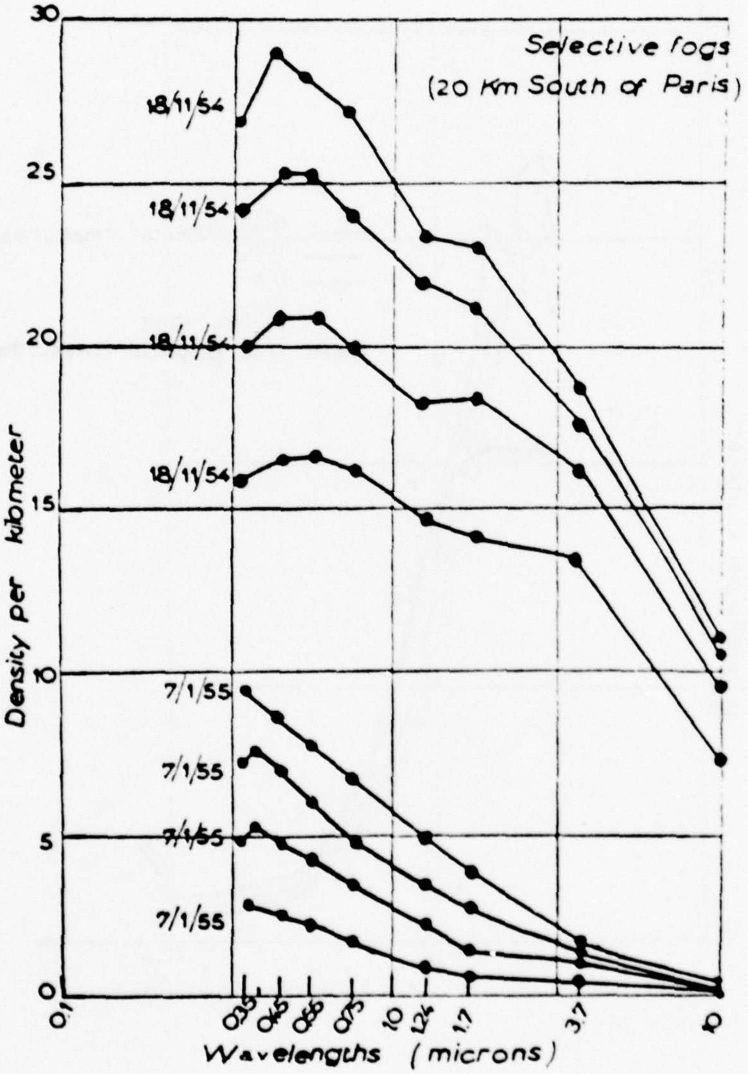


Figure 2.5 Attenuation By Selective Fogs

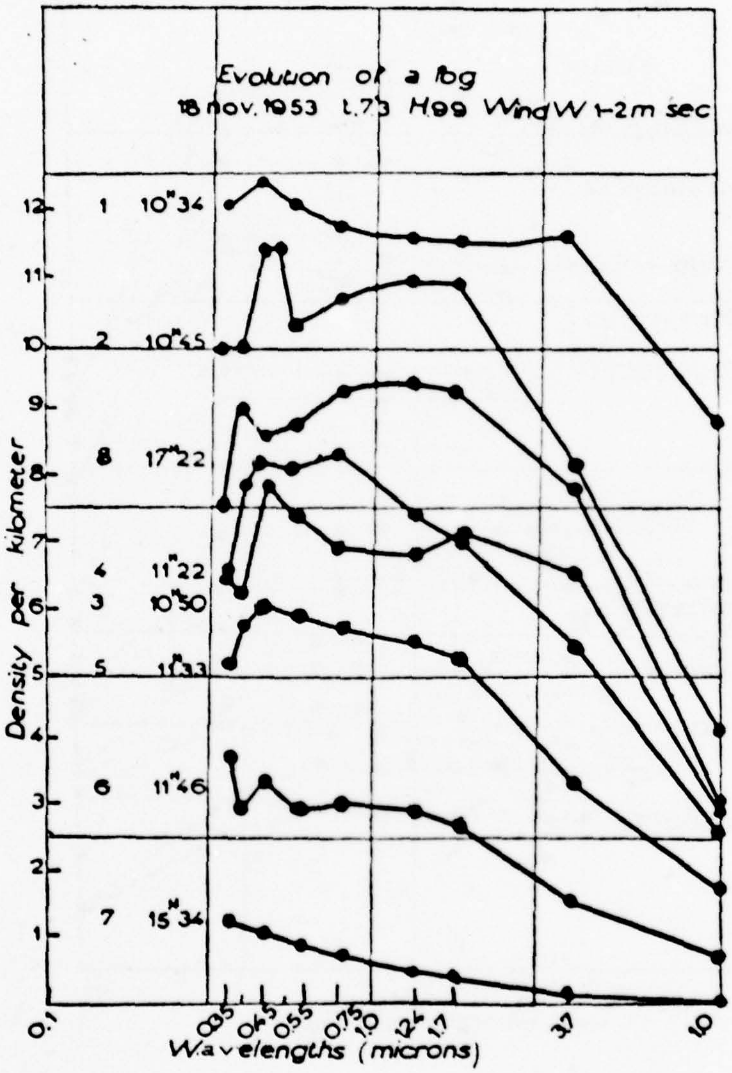


Figure 2.6 Attenuation By Evolving Fog

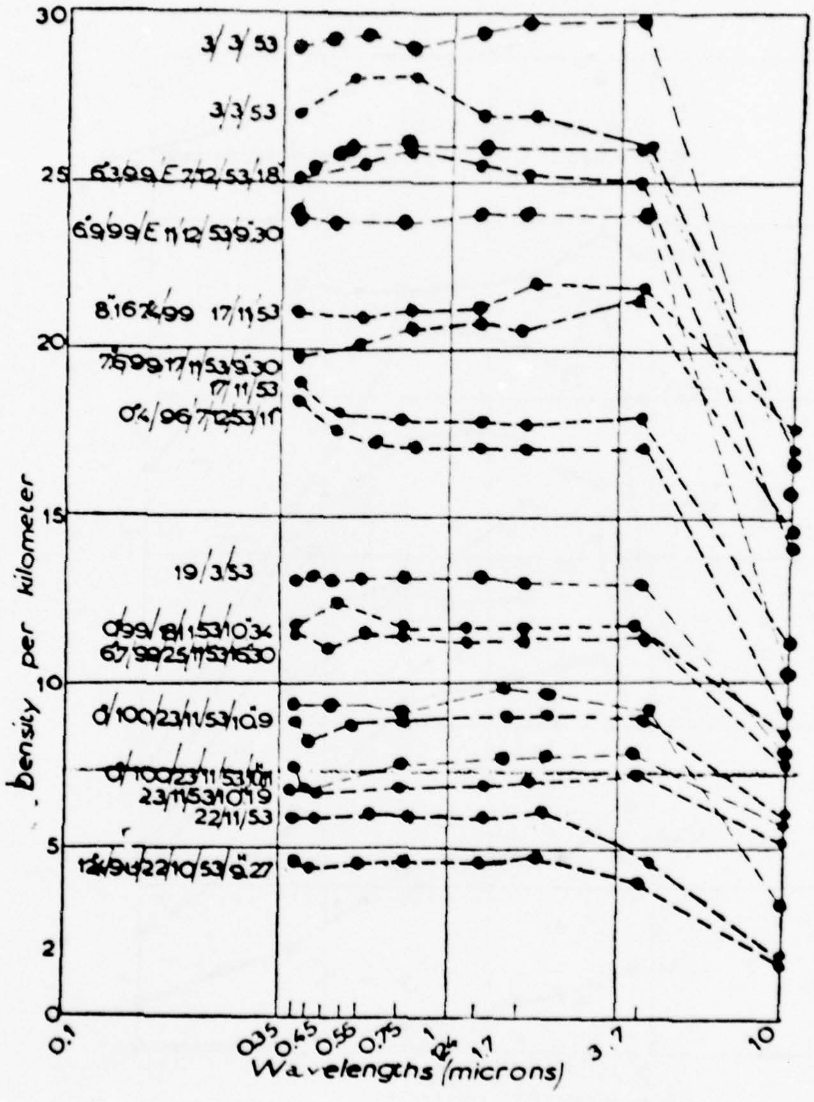


Figure 2.7 Attenuation By Stable Fogs

AFGL has recently developed a specialized fog model for low resolution IR propagation under very low visibility conditions and these results have been included in the present analysis. In Figure 2.8 are shown the various aerosol particle size distributions which were input to the models. Number density, or particles per unit radius, is plotted versus particle radius. Figures 2.9 and 2.10 illustrate the corresponding predictions for IR transmission in these fogs.

e. Nominal Fog/Haze Model

Integration of available measured data, computer code results, and engineering analysis has culminated in the formulation of a nominal model for low visibility infrared transmission in the 3-5 and 8-12 micron bands. Table 2.1 illustrates IR attenuation characteristics of fog/haze conditions for visibilities from 700 feet (0.21 km) RVR to 5000 feet (1.53 km) RVR. Total extinction is expressed in terms of both optical density D (km^{-1}) and the exponential attenuation constant (km^{-1}). The transmission factor T at range R in kilometers is then given by the photometric form

$$T(R) = 10^{-D\,R}$$

or the exponential form

$$T(R) = e^{-\beta R}$$

The trend of improved transmission with increasing wavelength indicated by Table 2.1 should be interpreted as a statistical tendency. As visibility levels drop, aerosol scattering increasingly dominates the attenuation process and infrared transmission becomes critically sensitive to the particle size distribution, which can vary quite rapidly along a given optical path. As a result of this effect the prediction of IR transmission based upon visible transmission (visibility) becomes more difficult as visibility decreases.

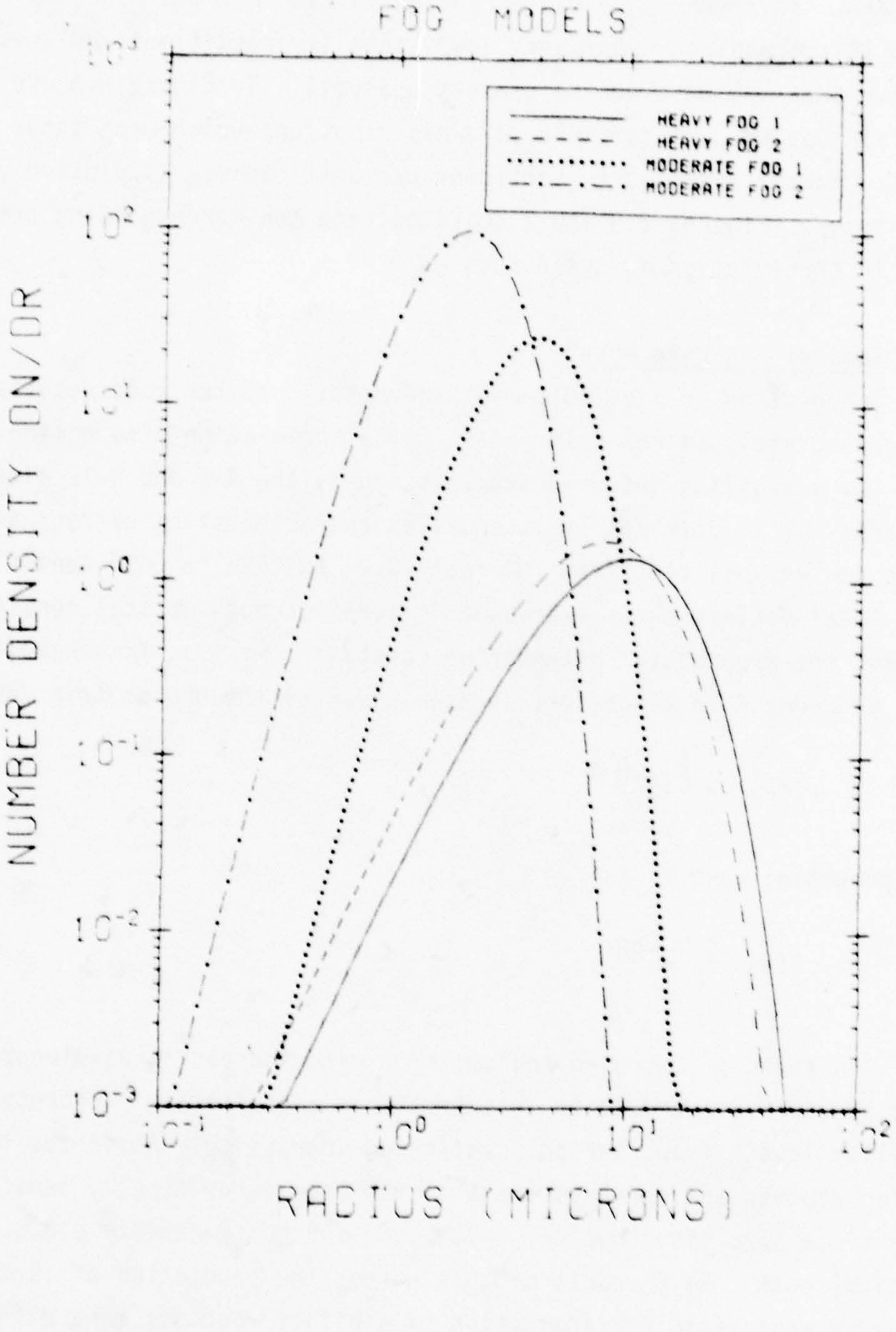


Figure 2.8 AFGL Particle Size Distributions

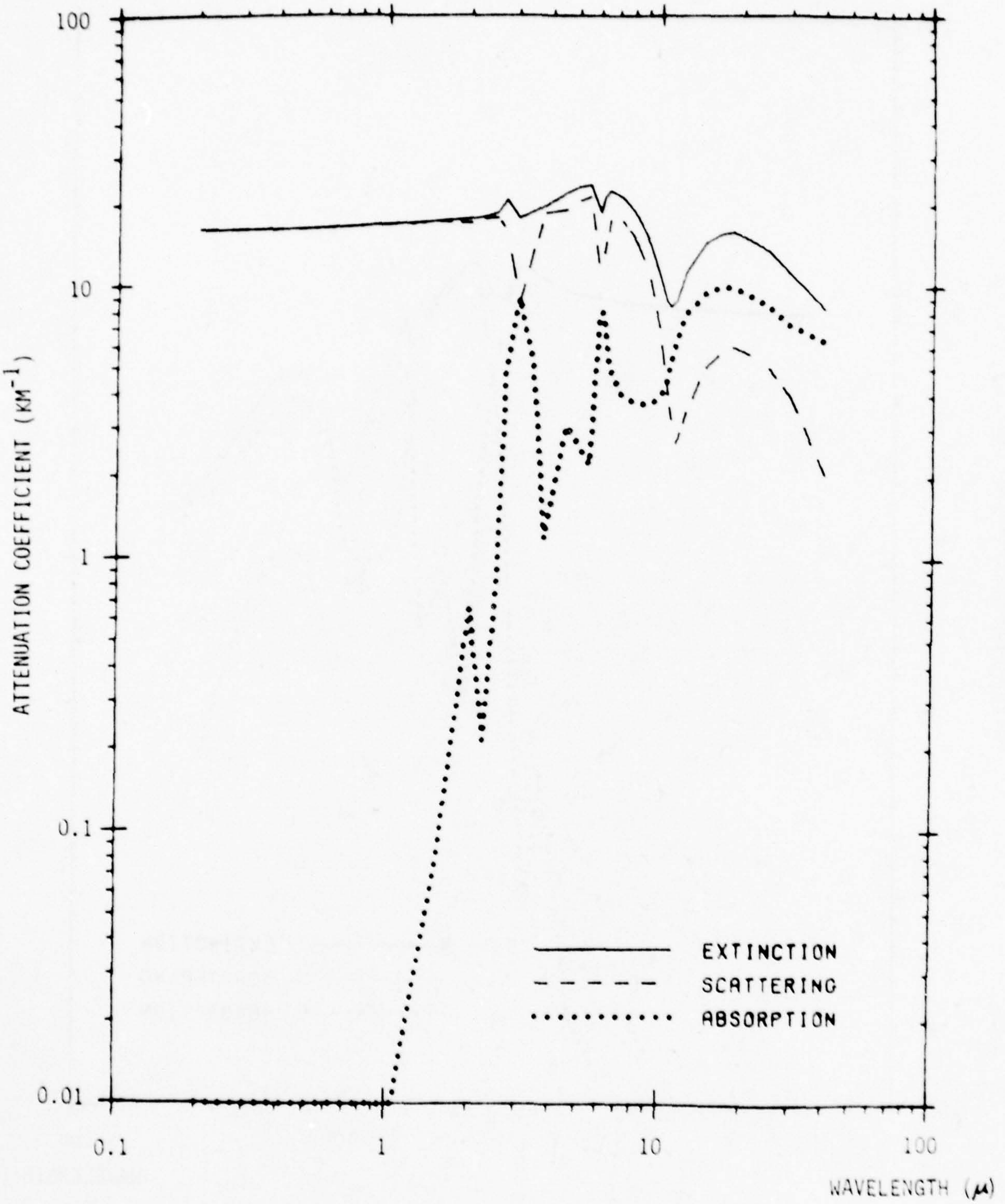


Figure 2.9 AFGL Moderate Fog 1

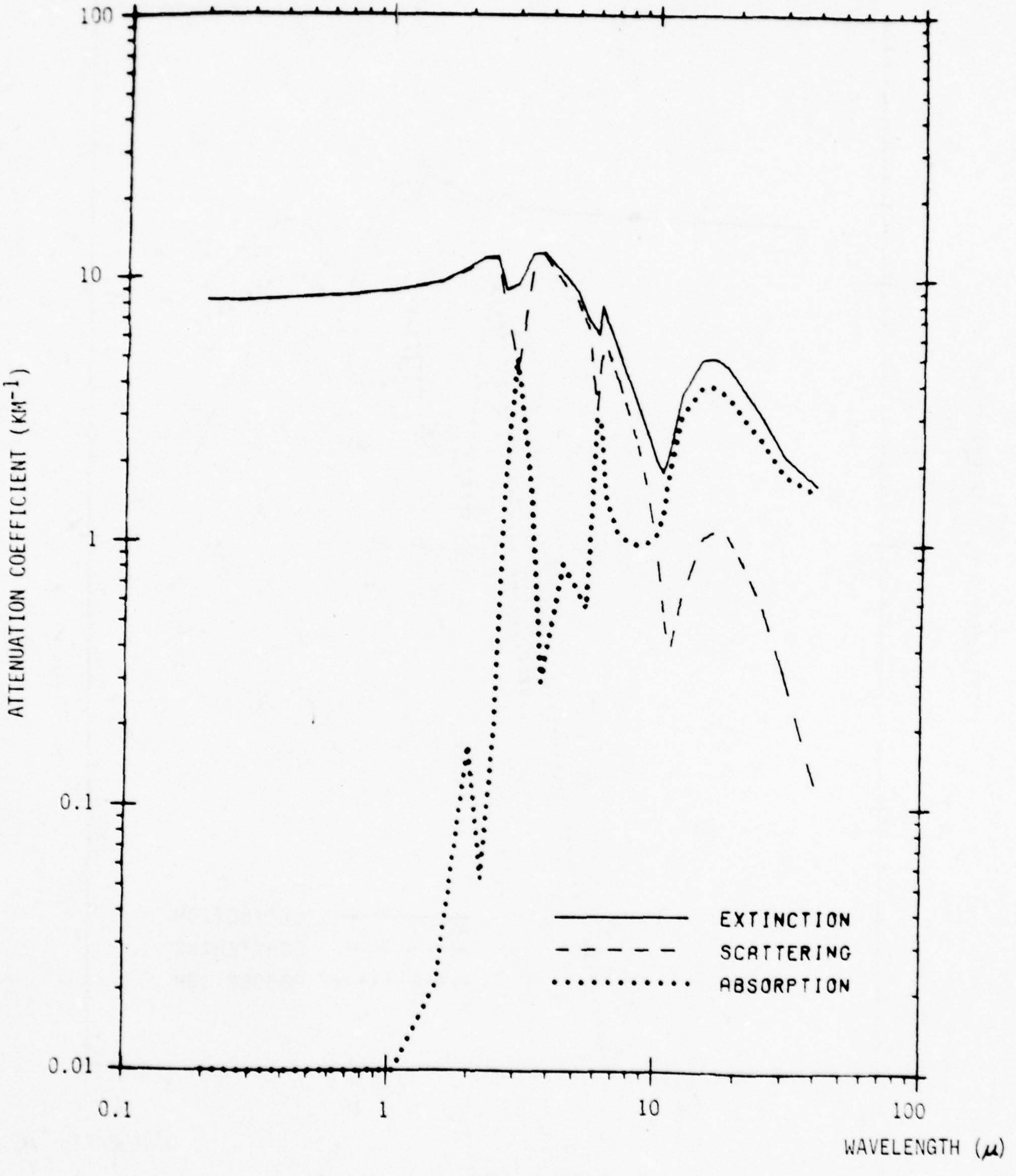


Figure 2.10 AFGL Moderate Fog 2

TABLE 2.1 NOMINAL LOW VISIBILITY IR ATTENUATION

VISIBILITY (RVR)	VISIBLE LIGHT 0.4-0.7 MICRON		3-5 MICRON IR		8-12 MICRON IR	
	OPTICAL DENSITY D (Km^{-1})	EXTINCTION COEFFICIENT β (Km^{-1})	OPTICAL DENSITY D (Km^{-1})	EXTINCTION COEFFICIENT β (Km^{-1})	OPTICAL DENSITY D (Km^{-1})	EXTINCTION COEFFICIENT β (Km^{-1})
700 ft = 0.21 Km	8.12	18.67	6.5	15	5.0	11.5
1200 ft = 0.37 Km	4.60	10.59	3.5	8	2.8	6.4
2000 ft = 0.61 Km	2.80	6.43	2.0	4.6	1.6	3.7
3000 ft = 0.91 Km	1.85	4.26	0.5	1.15	0.3	0.7
5000 ft = 1.52 Km	1.18	2.57	0.3	0.7	0.1	0.23

2. ELECTRO-OPTICAL TECHNOLOGY

Feasibility analysis for an infrared runway collision avoidance system has included an extensive survey of the available technology in order to assess the current capabilities of IR systems. The impact of new technology on system performance has been estimated based on present research and development efforts.

The basis of infrared system design includes numerous scientific areas. Thermal radiation physics and atmospheric optics must be taken into account in order to choose system operating wavelengths compatible with target emission characteristics and the available transmission windows and scattering effects. Solid state physics and cryogenic technology interface to minimize IR detector noise by means of low temperature operation. Signal processing theory and microelectronics must be utilized to extract maximum information from the available signal.

a. Infrared Detector Sensitivity

The performance of an infrared system depends upon a number of factors among which the most critical is the intrinsic sensitivity of the detector element or array. Detector sensitivity is usually represented by the figure of merit known as detectivity or D* ("D-star"). In general D* depends on the temperature of the detector and the wavelength of the incoming radiation. Cooling requirements are minimal in the near IR regions and tend to become more necessary as longer wavelength IR regions are utilized. Lower temperatures are required to obtain sufficient sensitivities (D*) for the longer wavelengths. The most sensitive IR detectors operate with D* values in excess of 10^{10} cm-Hz$^{1/2}$W^{-1}.

Figure 2.11 provides an overview of detector types and detectivity ranges in the near and intermediate IR regions. The values of D* are generally peaked (by design) in the wavelength region allowing maximum

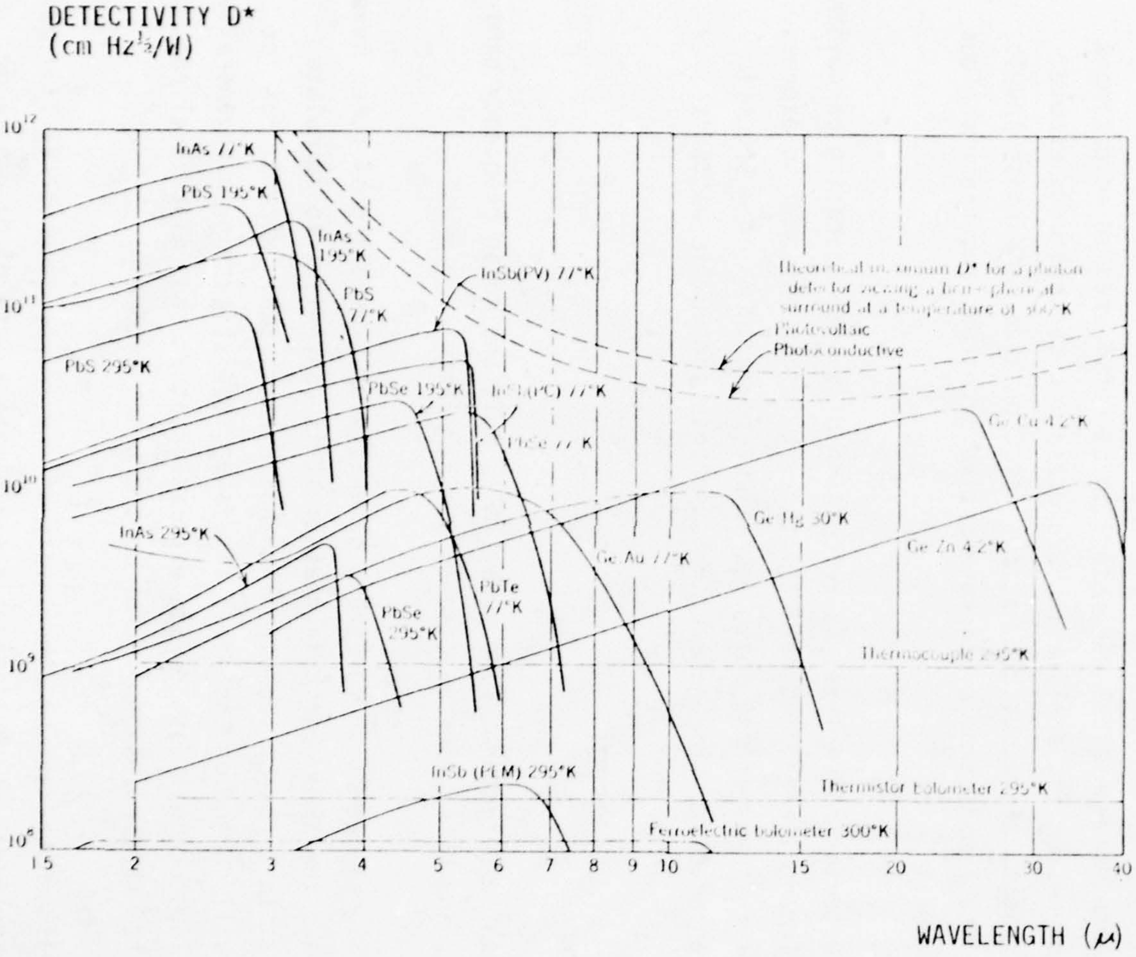


Figure 2.11 Characteristic Sensitivities of IR Detectors

sensitivity for a given material, but bi-metallic tellurides such as Mercury-Cadmium-Telluride (HgCdTe) and Lead-Tin-Telluride (PbSnTe) can be tuned to either narrow or broadband applications by varying their ratio of metallic components.

Among the physical parameters to be considered in selecting a detector for a specific application are operating temperature, usable wavelength range, time constant, active detector area, and noise level. Table 2.2 is a compilation of representative detectors and their various figures of merit.

Detector noise level is a function of system operating bandwidth, detector elemental area, and detectivity. It is conventional to express noise level in terms of the noise equivalent power (NEP) at a specific detector temperature. The general relationship for NEP in watts is

$$\mathrm{NEP} = \frac{\sqrt{A_d \quad B}}{D^*}$$

where A_d is the detector active area (cm^2), B is the noise frequency bandwidth (Hz), and D* is the detectivity ($\mathrm{cm\text{-}Hz}^{1/2}/\mathrm{watt}$).

Signal detection threshold generally will be a signal power level several times the NEP. For this reason, it is convenient to formulate signal level in terms of the signal-to-noise ratio SNR. Minimum SNR for detection will depend on the level of system sophistication, but generally the total input signal must be at least as great as the noise level and SNR detection thresholds of five or more are not uncommon.

Since the maximum sensitivity of any infrared sensor is limited by its noise level, all system designs ultimately attempt to reduce or eliminate noise sources. Shown in Figure 2.12 are the relative magnitudes

TABLE 2.2 FIGURES OF MERIT FOR IR DETECTORS

DETECTOR TYPE	WAVELENGTH RANGE (μ)	OPERATING TEMPERATURE	TIME CONSTANT (μ-sec)	DETECTIVITY D^* AT PEAK (cm-Hz$^{\frac{1}{2}}$ W $^{-1}$)
Si	0.4-1.1	300^0 K	10^{-3}	3×10^{12} (0.9μ)
PbS	1-2.5	300^0 K	250	1×10^{11} (2.4μ)
PbSe	2-5	300^0 K	1.5	2.5×10^9 (3.8μ)
InSb	1-5.5	77^0 K	1	1×10^{11} (5μ)
HgCdTe	5-14	77^0 K	0.5	3×10^{10} (11.5μ)
PbSnTe	6-11.5	77^0 K	0.5	2×10^{10} (10.5μ)

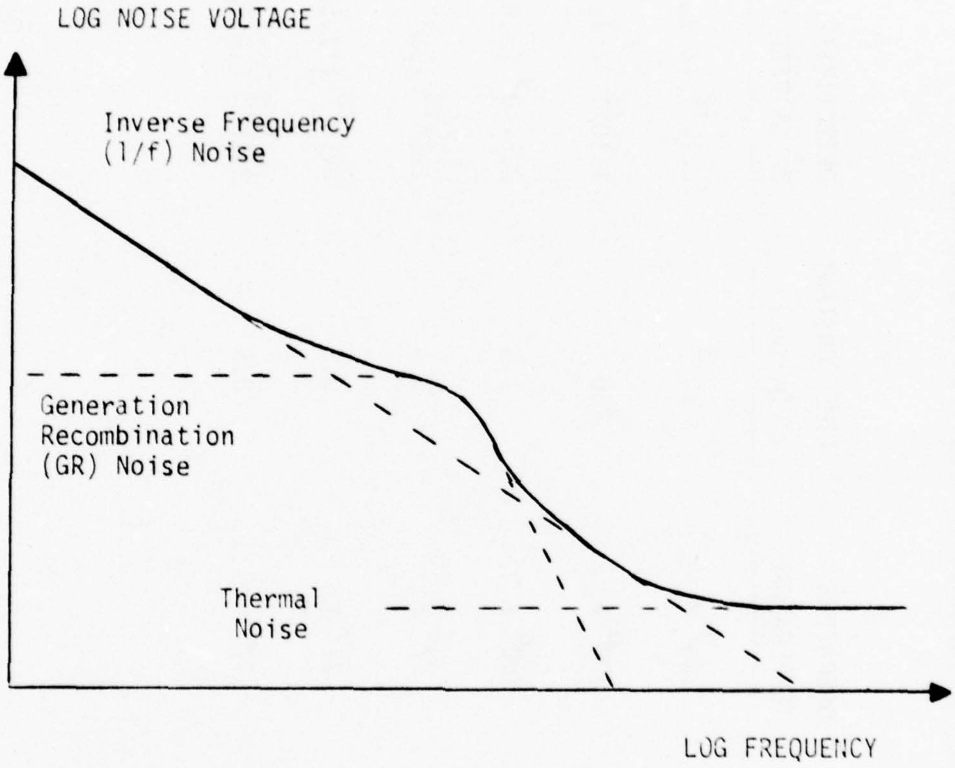


Figure 2.12 Dominant Detector Noise Components

of three major types of system noise as a function of operating frequency. The advantage of high-frequency operation is clearly shown.

At a sufficiently low temperature the noise components of Figure 2.12 are reduced to a level below the quantum noise contributed by the random arrival of photons at the detector. This desirable system mode is referred to as background limited operation and is a necessary condition if maximum detector sensitivity is to be achieved. Most infrared systems capable of detecting very weak signals (less than 10^{-12} watts/cm^2) must achieve background limited operation. For IR systems operating in low visibility environments the background noise contribution may be quite high as a result of scintillation effects due to strong aerosol scattering.

From the standpoint of signal integration the detector response time is especially important in weak signal applications. Since the system signal-to-noise ratio is proportional to the square root of the number of integrations, an IR system may achieve high performance levels when the ratio of system decision time to detector time constant is large. Typical high performance detectors have response times on the order of a microsecond.

b. Detector Cooling Systems

Approaches to low temperature cooling applicable to IR technology include open and closed cycle solid, liquid, and gas systems, and solid state thermoelectric refrigerators. From a design standpoint the critical factors are operation temperature, hold time (dewars) or mean time before failure (MTBF), heat load capacity, power consumption, and such physical considerations as weight and dimensions. In certain applications, the operation time/complexity tradeoff will be determined not only by detector cooling requirements, but also by whether or not the system is of an expendable nature (for example, an IR-tracking missile).

Dewars generally utilize a cryogenic gas, liquid, or solid as a temporary coolant. Hold times will vary from several hours to several days for open cycle systems. Closed cycle systems usually employ a compressor to repressurize gas leaving a cryostat and improve hold times. Candidate materials for cryogenic cooling include CO_2 "dry ice" (219^oK), liquid nitrogen (77^oK), liquid helium (4^oK), and their various intermediate states. Refrigeration techniques usually employed are the Joule-Thompson, Stirling, and Vuilleumier cycles. At present, closed cycle He gas systems are capable of 1000 hour MTBF operation.

Thermoelectric (TE) systems offer simplified operation and do not require exotic cryogenic substances. These p-n junction devices operate on combinations of several solid state effects including Seebeck, Peltier, Joule, Fourier, and Thomson. At present TE coolers do not provide the refrigerative capacity of other approaches, but for simplified IR systems their convenience is a major advantage.

Thermoelectric capacity and temperature levels can be improved by cascading. A simple one-stage unit will achieve -20^oC and a two-stage unit will yield -30^oC. Four and six stage units are currently available with temperatures of 193 and 170 degrees Kelvin respectively. Figure 2.13 illustrates the basic TE principle for a three-stage system.

c. IR System Components

Each of the subsystems of an infrared device involves a considerable degree of sophistication. The basic IR system can be broken down into sensor unit, signal processor, and control and display.

Sensor Unit

The sensor package includes the optics, the IR detectors, and coolers as required. The optics include the scanning lenses and mirrors used to focus the instantaneous field of view (IFOV) and the scanning

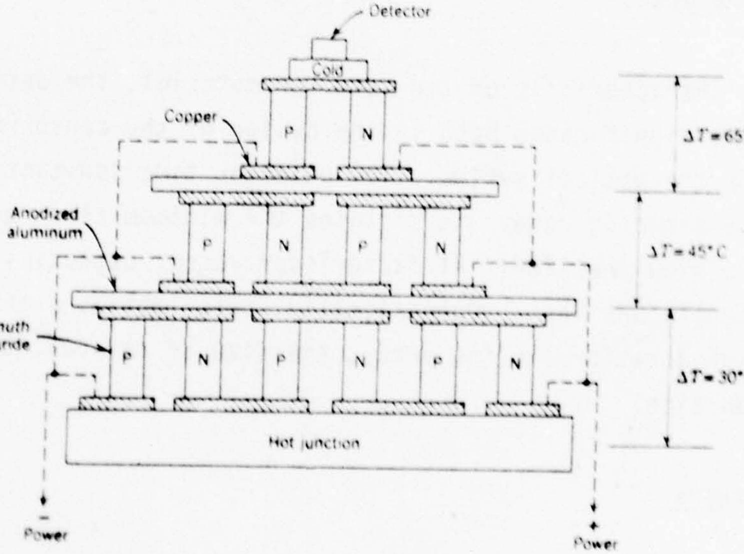


Figure 2.13 Three Stage Thermoelectric Cooler

mechanism to search the FOV. To achieve significant range in fog, an optical aperture of 4-6 inches is anticipated.

High sensitivity detectors such as cooled Mercury-Cadmium-Telluride (HgCdTe), Indium Antimonide (InSb), or Lead-Tin-Telluride (PbSnTe) are widely employed. Small arrays (under twenty) offer improved performance with only a slight increase in cost compared to a single detector. Each detector usually is on the order of a few square mils in size and can operate reliably for about one year.

A characteristic of the detector material, the detector time constant, has significance both in the design of the sensor and in the operation of the optical system. The detector time constant imposes a limit to the scanning rate: it dictates the minimum time required by the detectors to view the IFOV. At faster scan rates, detectivity decreases and weak signals are lost. Operationally, this implies a tradeoff among the number of detectors in the array, the size of the FOV, the resolution, and the scan time.

Processors

The processor functions include receiving low-level signals from the detectors, amplifying them, limiting the bandwidth, extracting information, and applying decision rules for target detection and false target rejection. Outputs from the processor drive the control and display components.

Processing functions commonly are performed by a mix of focal plane processing and microprocessors. Current state-of-the-art offers many attractive alternatives. Charge-couple devices (CCD) and charge-injection devices (CID) that will allow initial processing to be done at the detector array are being developed by several manufacturers.

Microprocessors are widely employed to execute the target discrimination logic and to control the system.

Control and Display

The third system component is the control and display package, which can be a part of the same physical unit as the sensor or, depending on the application, can be remoted from other system components. For an aircraft mounted runway collision avoidance system the control may be automated and the display might consist of a simple alarm buzzer and warning light in the cockpit. A runway mounted system would be accessed by the controller and elaborate CRT displays might be desirable.

CHAPTER III
TECHNICAL ANALYSIS

1. INFRARED SIGNATURES

For the purpose of evaluating passive IR detection techniques, infrared thermal signatures of potential runway takeoff obstacles have been examined from a theoretical viewpoint and in a number of cases have been verified empirically using data sources available in the public literature. Specific signals evaluated are those from jet engines of three representative aircraft, light propeller aircraft, ground vehicles, and anticollision strobes and beacons. In the case of aircraft and ground vehicles, critical considerations are aspect angle, time since ignition (warm-up time), and operating power level (idle versus cruise power).

In all cases the approach has been to utilize measured data when available and in other cases to rely on professional opinion of technical experts. Theoretical calculations for jet engines are blackbody thermal estimates based upon known exhaust nozzle tailpipe dimensions. Cell temperatures of specific engines at idle will vary, but for the purposes of this study an exhaust gas temperature (EGT) of $758^{o}K$ is taken as a nominal case. At this temperature 32.3% of the total radiant power is in the 3-5 micron region and 14.9% is in the 8-12 micron region.

a. Strobe and Beacon Detection

Conventional aircraft mounted anticollision strobes are typified by a xenon short-arc gaseous discharge principle. Characteristic spectra of these devices exhibit emission in the infrared and ultraviolet as well as the visible regions and their radiative properties have been utilized in various approaches to air-to-air collision avoidance.

Nominal power levels of anticollision strobes are 10-30 joules/flash in the visible region with UV and IR output at comparable levels.

Flash duration is typically 2 milliseconds with FAA regulations specifying repetition rate between 40 and 100 flashes/min for a single strobe. Not more than 180 flashes/min are permitted as the net signal from a complete aircraft system. Industry standards generally conform to 50, 90, and 160 flash/min rates.

Certain airborne IR systems have employed a time or spatially variable strobe rate to signify directional or altitudinal information. One system tested on a DC-10 utilized double flash forward strobes (150 millisecond separation) to signal approach and single flash rear strobes to denote departure. Other approaches provide for an altitude dependent flash rate to be acquired by an airborne IR strobe seeker and interpreted automatically by rate-calibrated electronics thereby serving a pilot as a proximity warning system.

Weather penetration characteristics of strobe infrared wavelengths are almost identical to the propagation of visible wavelengths (0.4 to 0.7 microns). Figure 3.1 shows a typical output spectrum of a xenon arc lamp in the range from 0.2 microns (UV) to 1.4 microns (near IR). Strongest emission is noted to be in the 0.8 - 0.9 micron region with a continuum spectrum below 0.4 microns. Infrared emission begins to fall at wavelengths longer than a few microns and most strobe sensors utilize an uncooled silicon detector ($D^* \sim 10^{12}$) to lock on to the 0.9 micron spectral lines.

Although xenon arc strobes have a quartz window which transmits well out to 7.0 microns, the two-color system under consideration (3-5 and 8-12 microns) would register an extremely weak signal. While the modulated flash provides some gain in signal-to-noise ratio, the strobe emission is at least two orders of magnitude below a level deemed adequate for threshold IR detection at significant ranges in fog.

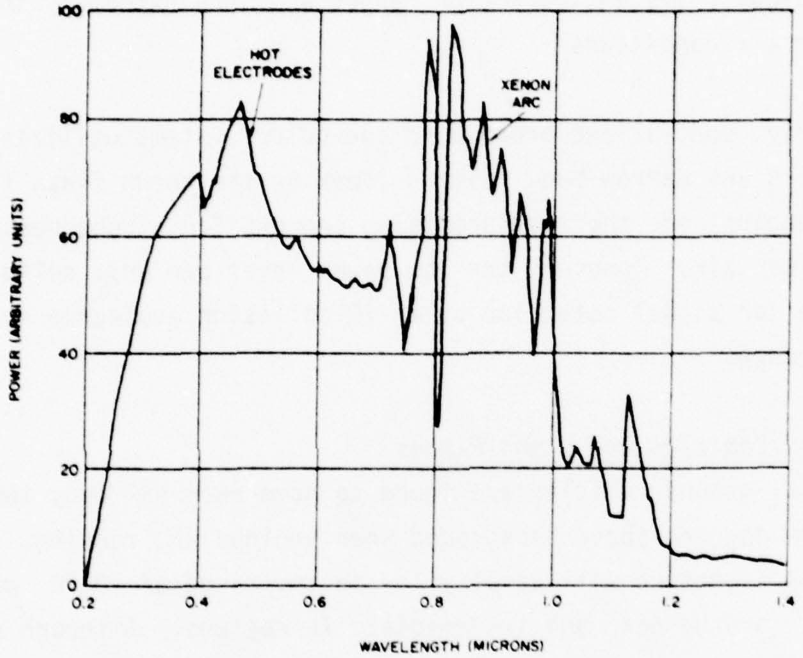


Figure 3.1 Spectrum of Xenon Arc Strobe

Infrared emissions of rotating beacons are even more difficult to detect. Such beacons usually consist of a tungsten lamp (at a nominal $2800^{o}K$) with a low emissivity of 0.23 in the region from 2 to 3 microns. Long wavelength IR does not escape the window since borosilicate glass does not transmit appreciably beyond about 4 microns. For the case of a 3-5 and 8-12 micron two-color system, detection ranges would be extremely short except in clear air conditions.

Clearly, specialized broad band one-color systems utilizing silicon detectors and narrow band filters (seeking the known flash frequencies and wavelengths) are the most promising sensors for strobe/beacon detection in clear air. However, the low power level per unit solid angle is not adequate for signal detection by an IR collision avoidance system in fog at runway ranges.

b. Ground Vehicles and Light Planes

Typical ground vehicles are found to have external body temperatures only a few degrees above background when engines are running. The corresponding IR signature will usually lie in the range of 10-30 watts per steradian total for the near and intermediate IR regions. Although such signatures are easily detected under clear weather conditions, analysis has shown that these thermal emission levels do not provide sufficient signal penetration in fog to be useful from the standpoint of passive IR detection at runway ranges.

Light planes with reciprocating engines have IR signatures comparable to those of ground vehicles. The minimum exposure of hot parts and small cross sectional areas limit thermal output to very low levels.

c. Jet Aircraft

Commercial aircraft chosen for a sampling of jet engine IR signatures include the Gates Learjet, Boeing 707 and MacDonald Douglas

DC-10. The analysis is based upon engine exhaust nozzle areas obtained from manufacturers, a nominal exhaust gas temperature of 758°K, and blackbody radiation characteristics of a typical engine cavity with thermal emissivity of 0.9. Results of the calculation for tailpipe radiant power levels are shown in Table 3.1 along with relevant data on specific engines.

It has been found that engine thermal emissions from the side and frontal aspects are insignificant compared to the rear (tailpipe) view. Typical rear aspect infrared emissions are hundreds of watts per steradian whereas plume emission at idle is usually on the order of one twenty-fifth as much. Radiance of hot parts for engines at idle (or not warmed up) has been determined to be negligible from the standpoint of IR detection in fog.

2. TWO-COLOR JET ENGINE DETECTOR

Analysis of the infrared signatures of potential takeoff hazards indicates that a two-color IR system could be utilized for runway collision avoidance if jet engines at rear aspect are the primary targets and if the problem of limited system range in fog can be circumvented by using several detectors mounted on the runway (at least four detectors to cover both runway directions for RVR down to 1200 feet). These limitations are quite stringent (front and side aspects are more likely in a collision), but in certain cases the system could be of value. At present, the concept of a mobile aircraft mounted sensor does not seem feasible in view of the limited range a single sensor can achieve in fog (~ 3000 feet for 700 feet RVR).

a. System Components

Figure 3.2 illustrates the basic elements of a two-color IR jet engine detector operating in the 3-5 and 8-12 spectral bands. The incoming radiation would be collected by a four to six inch aperture (lens or mirror) and undergo focal plane processing by a scanning element or simple chopping

TABLE 3.1 JET AIRCRAFT NOZZLE IR SIGNATURES

AIRCRAFT	NUMBER OF ENGINES	ENGINE MODEL	NOZZLE AREA (cm^2)	RADIANT INTENSITY PER ENGINE (W/sr)	TOTAL INTENSITY (W/sr)	3-5 MICRON SIGNATURE (W/sr)	8-12 MICRON SIGNATURE (W/sr)
GATES LEARJET	2	GARRETT NO. 731 TURBOFAN	656	353.5	707	228	105
BOEING 707	4	PRATT & WHITNEY JT3D-3 TURBOFAN	3502	1878.0	7512	2426	1119
MACDONALD DOUGLAS DC-10	3	GENERAL ELECTRIC CF6-50 TURBOFAN	7707	4133.0	12399	4005	1847

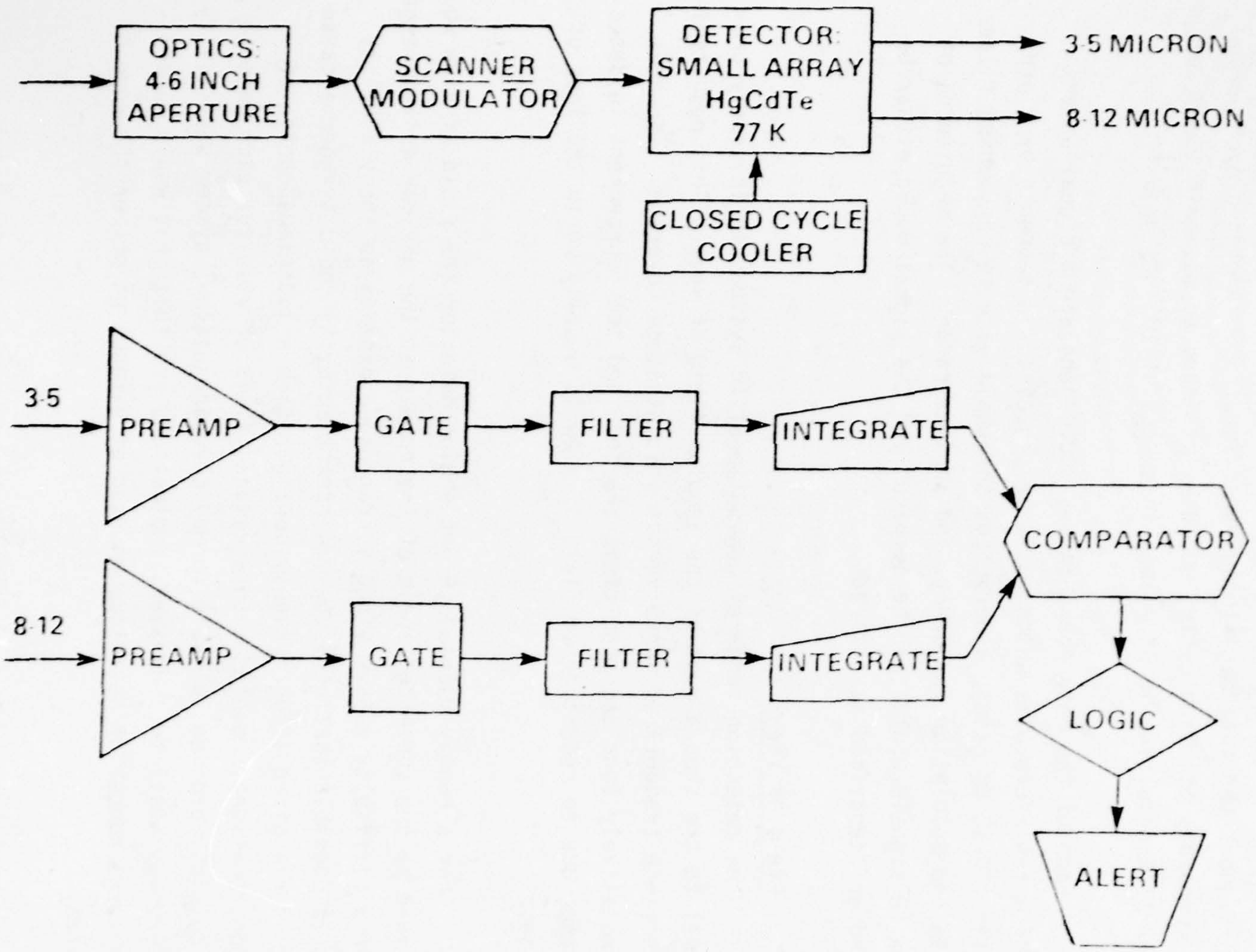


Figure 3.2 Components of Two-Color Jet Engine Detector

modulator. The detector array would consist of a small set of spectrally filtered detectors for each IR band (not more than nine). Each of the signal channels could utilize HgCdTe detectors since this material performs well throughout the intermediate infrared spectrum. A closed-cycle cryocooler (probably Stirling cycle) would be utilized to maintain the detector array at 77^0K resulting in D* values in excess of 10^{10} cm $Hz^{\frac{1}{2}}W^{-1}$.

Each of the detector channels would generate a signal on the order of a few microvolts which would be processed in sequence by a preamplifier (20-50 dB gain), a detection threshold gate, a narrowband filter tuned to the modulation frequency, and an integrator. The magnitudes of the two IR signals would then be compared and the signal would either be rejected or identified as a target.

b. Field of View

The detection range of conventional IR systems is inversely proportional to the square root of the angular field of view. This results in a performance tradeoff of range versus instantaneous coverage. In cases where relatively long decision times are involved the improvement in detection range due to reduction of field of view is usually worth the loss of coverage.

For a runway mounted IR jet engine detector the field of view would be defined by the subtended angle of the runway at the maximum system range. However a difficulty arises since system range depends on the visibility and it is possible that off-runway aircraft activity could trigger a false alarm. For a given airport runway configuration a judicious choice of detector locations, coupled with a reduced field of view for each detector, could possibly provide suitable runway coverage without system sensitivity to off-runway activity. However, indications are that this would necessitate a large number of detectors mounted at various points on the edge of the runway.

c. Signal-To-Noise Ratios

Detector system noise limits the detection of weak IR signals from targets that are small, cool, or distant. Distance has several effects: IR radiation becomes increasingly spatially dispersed, scattered and attenuated by the atmosphere. Additionally, at increased ranges, the image of a target fills a decreased fraction of the detector area. Beyond some range, these effects reduce the power received from the target to the level of the random photon noise received by the detector and result in non-detection of the target. Larger optical apertures can be used to compensate for the effects of range by intercepting and focusing more of the irradiance and allowing larger signal-to-noise ratios.

In determining target detectability, signal-to-noise ratios are derived as follows. The received detector signal(s) is calculated as a function of target IR signature (J_t), the optical aperture "area" (A_o), the range (R) to the target, the range dependent atmospheric transmission coefficient (T) and the internal optical transmittance (T_o). The resulting expression for the signal strength (S), is

$$S = \frac{J_t A_o T T_o}{R^2}$$

The noise equivalent power (NEP) of the detector is related to the normalized spectral detectivity (D*), the detector area (A_d), and the noise frequency bandwidth (B). An estimate of the signal-to-noise ratio is made by taking the ratio of the signal strength to the NEP.

$$SNR = \frac{J_t A_o T T_o D^*}{R^2 \sqrt{A_d B}}$$

Signal-to-noise ratios for an optical diameter of 15 centimeters (6 inches) with $T_o = 0.75$ are shown in Figures 3.3 and 3.4 for a Boeing 707 target in 700 and 1200 feet visibilities. In the present analysis system range may be considered the point at which the SNR reaches a value of one.

d. Signal-To-Clutter Ratios

While many runway hazards, such as large jet aircraft, have exposed hot parts greatly above ambient, others, such as ground vehicles, differ only slightly. The signal-to-clutter ratio measures the potential detectability of a target. The actual detection probability depends on how cleverly the signal-to-clutter ratio is exploited both by the system hardware and by the processing algorithms used. For example, a system whose optics fill only a small fraction of a detector with the target image would not receive the full benefit of the signal-to-clutter ratio.

The signal-to-clutter ratio is given by:

$$\frac{S}{C} = \frac{W_T - \overline{W}_B}{\Delta W_B}$$

where W_T is the radiant emittance of the target, and $\overline{W}_B$ and ΔW_B are the mean and variance of the background's radiant emittance due to local temperature differences. This ratio estimates how well the target IR signature stands out from the distribution of background signals. For relatively uniform backgrounds, targets with small temperature differences can be detected. Against more "cluttered" backgrounds, i.e., those with much less uniform temperatures, targets will have to be hotter to be detectable.

Backgrounds can be multimodal in their temperature distributions due to terrain differences or to shadow effects. The background variations referred to are within each of these terrain regions, and are measured from

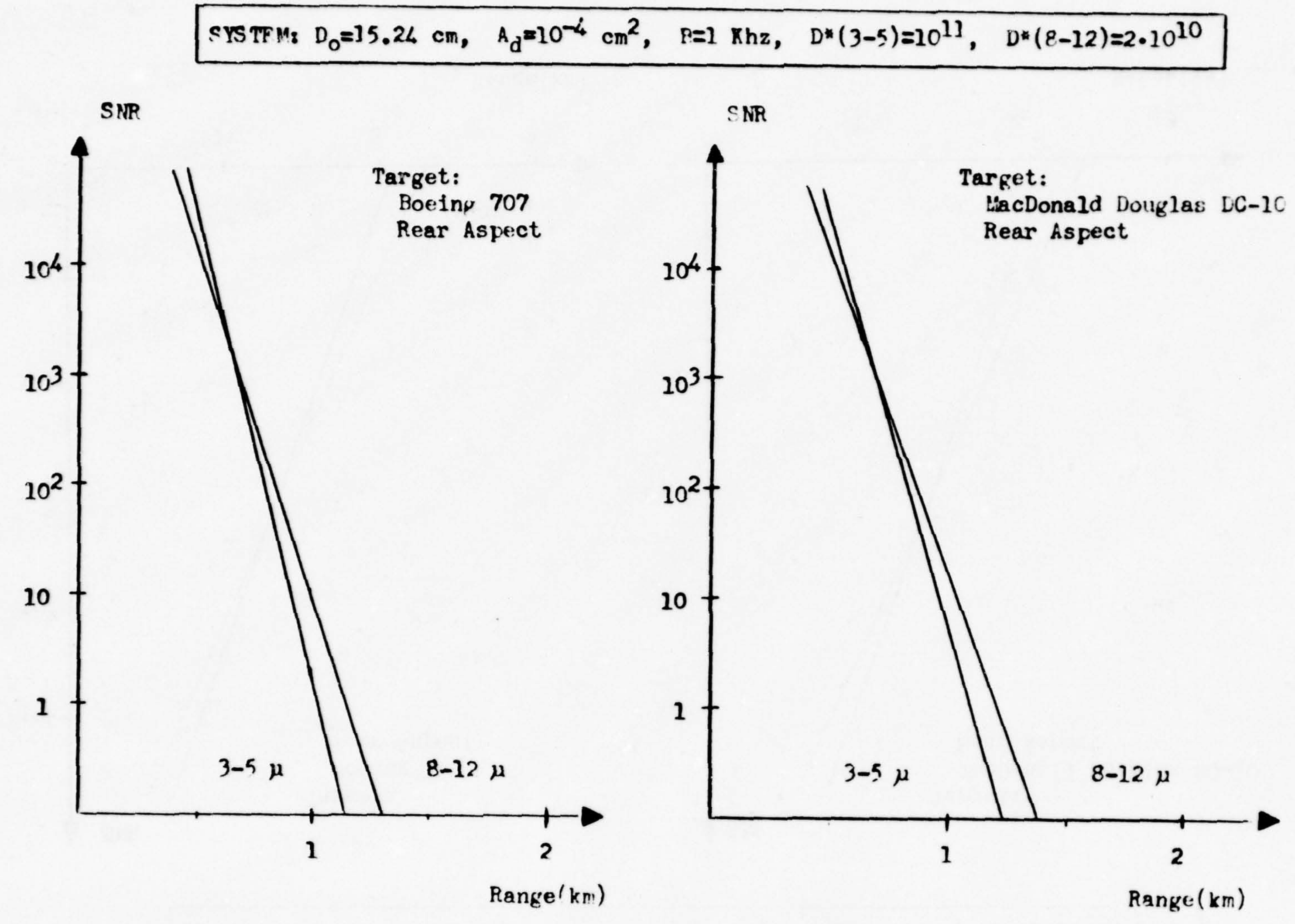


Figure 3.3 Signal-to-Noise Ratio in 700 Foot Visibility

SYSTEM: $D_o=15.24$ cm, $A_d=10^{-4}$ cm^2, B=1 Khz, $D^*(3-5)=10^{11}$, $D^*(8-12)=2.10^{10}$

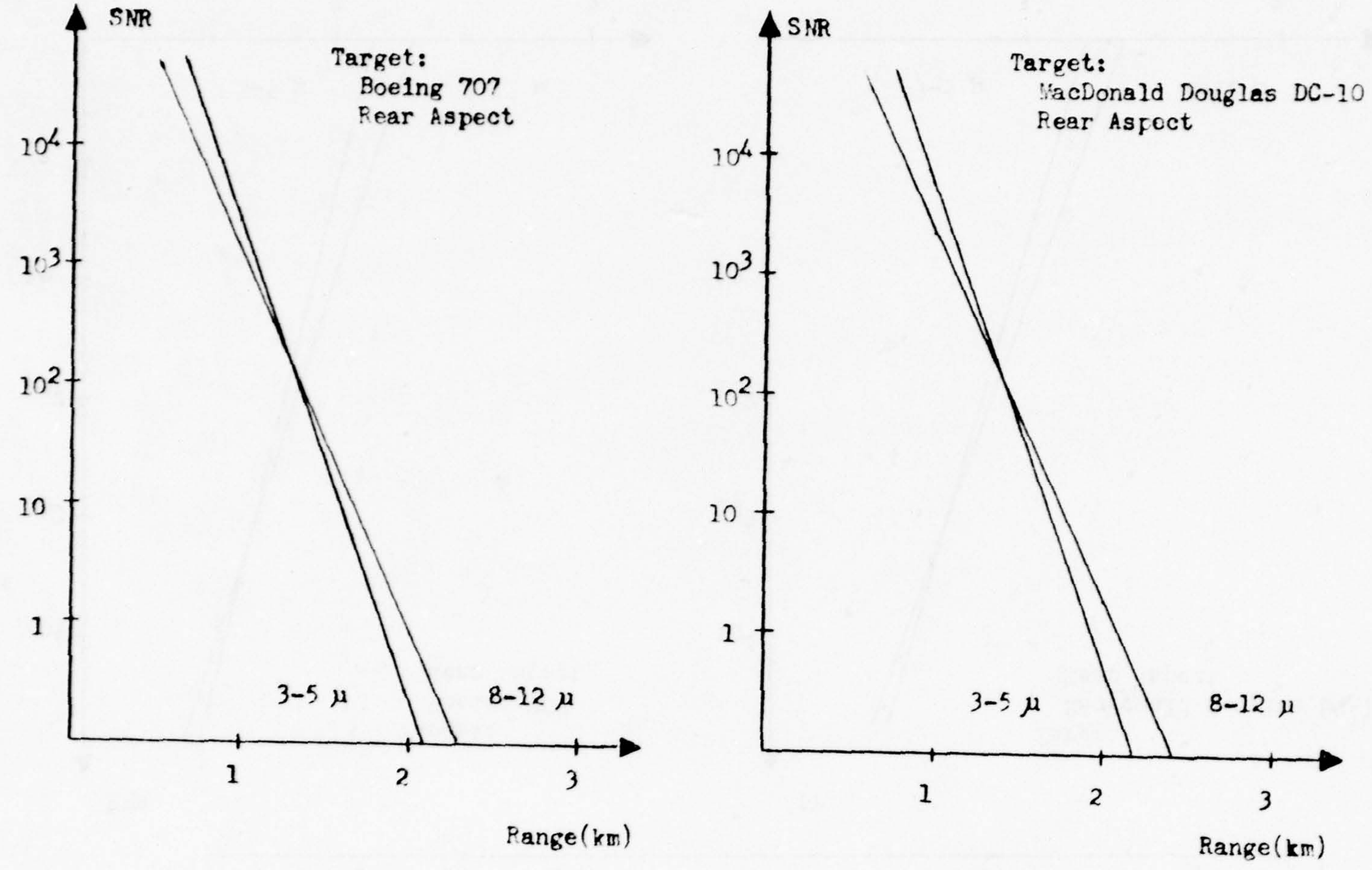


Figure 3.4 Signal-to-Noise Ratio in 1200 Foot Visibility

their respective regional means. Background variation in fog environments is a relative unknown, but indications are that effects are comparable to those found in other IR system applications.

Experiments done by Lincoln Laboratory indicate that a two-color algorithm used with the HOWLS seeker yields a reasonable probability of detection with signal-to-clutter ratios of about 1.5 - 2.0.

e. False Alarm Rate

As indicated by Figure 1.3, a runway mounted two-color IR jet engine detector would signal an alarm only when jet engines, or objects at comparable temperatures, enter the field of view. Ground vehicles would have no effect on the system. However, the requirement for adequate runway coverage without system sensitivity to off-runway activity remains difficult to achieve. The detection ranges indicated by Figures 3.3 and 3.4 imply that the large number of detectors needed for adequate runway coverage in low visibility operations could result in significant false alarm rates due to taxiway activity. It appears that this problem would be confronted at a number of major airports.

3. DISCUSSION

The passive two-color jet engine detector is a feasible approach to collision avoidance, however, it will require extensive development and may not achieve the required reliability for the following reasons.

Detection range against the rear aspect of a Boeing 707 aircraft will be from 3000 to 5000 feet dependent on visibility. A 10,000 foot detection range is the approximate actual requirement. Detection range is even lower for nose and beam aspects of an aircraft. Increasing detection range will materially increase the false alarm rate and reduce pilot confidence in the system.

In light of these problems, analysis was conducted on a second and apparently more feasible approach which utilizes a long wavelength carbon dioxide laser to detect aircraft or objects on the runway. The approach known as an IR Blanking System has the following advantages:

- Detection of hot or cold targets
- Good fog penetration
- Low path attenuation
- 10.6 micron wavelength is out of the visual range and can satisfy eye safety requirements.

The proposed IR Blanking System is described in the following paragraphs.

4. INFRARED BLANKING SYSTEM

The passive two-color IR jet engine detector that has been described utilizes the positive thermal contrast of the engine tailpipe and hot parts with the relatively cool background. Infrared detection systems may also operate on a negative contrast principle. In one approach, objects are detected when their cross sectional area interferes with background and obstructs or blanks out the nominal radiation field.

Analysis indicates that negative contrast IR can be successfully applied to runway collision avoidance if the radiation background is modified or coded by the use of a cooperative IR source at the extreme end of the runway. Such a system could utilize any IR source of sufficient power and collimation to insure adequate system range in low visibility. Although other specialized sources might be fabricated, the prime candidate from the standpoint of atmospheric transmission is an infrared laser.

a. System Concept

Figure 3.5 illustrates the basic principle of infrared blanking applied to runway collision avoidance in low visibility. An IR laser would be mounted at one end of the runway and provide a coded signal link with an infrared detector at the opposite end. Any interruption of the coded signal by an obstacle in the optical path would be automatically registered by the electronic logic of the runway collision avoidance system. Such a system could be queried directly by the pilot at takeoff (for example, with a low power VHF readout).

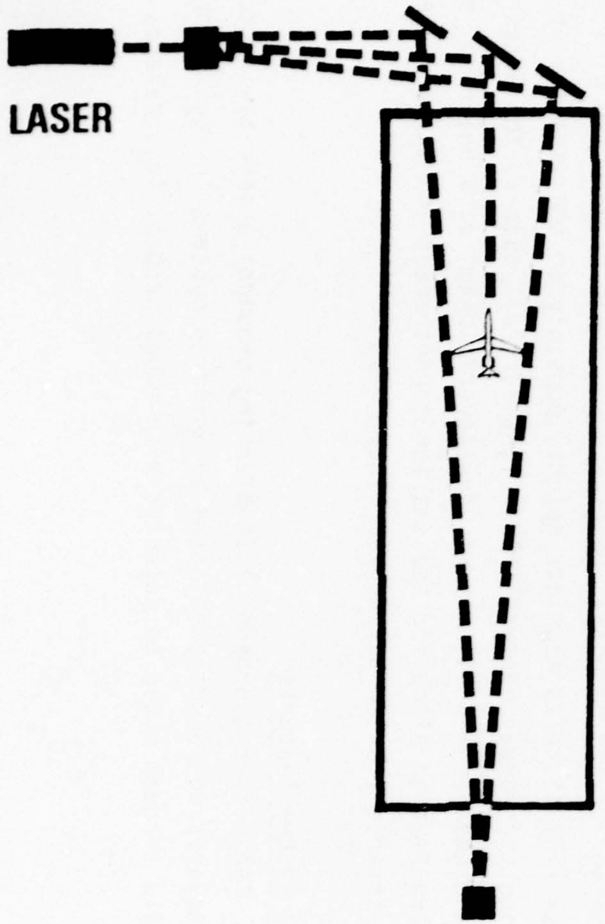
Infrared lasers, in particular CO_2 lasers (10.6 micron wavelength), have been utilized to provide continous video transmission links in a variety of weather conditions (see reference 44). All evidence indicates that optical design parameters are sufficiently flexible to insure sufficient range for runway collision avoidance operation.

b. Aircraft Target Cross Sections

Commercial aircraft target cross sections have been examined from the standpoint of geometric commonality as they would appear to an IR blanking system. It has been found that potential hazard aircraft cross sections fall into two categories. Large carriers including such aircraft as the Boeing 707 and MacDonald Douglas DC-10 could be detected by a single laser beam link of an appropriate height, possibly in the vicinity of ten feet, along the runway center line. Light aircraft such as the Gates Learjet and Cessna Cardinal may require several beams at a height of approximately five feet to allow for the smaller target areas and larger lateral takeoff variance from runway center line.

c. System Features

The direct approach of IR blanking provides a sensitivity to takeoff hazards not usually detected by infrared systems in fog. Since hot or cold targets would be detected with equal probability, hazards such



- MAINTAIN SIGNAL LINK ALONG RUNWAY CENTER
- UTILIZE CO_2 WAVEGUIDE LASER
- DETECT LIGHT PLANES AND LARGE AIRCRAFT BY SIGNAL INTERRUPTION
- CONFORM DESIGN TO EYE SAFE LEVELS
- MAINTAIN 3 KILOMETER FOG PENETRATION
- MINIMIZE HARDWARE REQUIREMENTS
- DIRECT PILOT READOUT

Figure 3.5 Basic Principle of IR Blanking as ground vehicles and light aircraft would be acquired regardless of their temperature. This multi-target sensitivity could be a major advantage over passive IR at very active airports.

The IR blanking system could offer several useful growth options. An IR blanking system might be designed to function as an aircraft runway centering device, which would notify the pilot of his plane's position relative to centerline. The concept may also have applications to airport taxiway control.

d. Basic Transmitter

Figure 3.6 is a stylized view of an infrared laser transmitter as would be utilized by an IR blanking system. A long wavelength laser (possibly CO_2 at 10.6 microns) would be utilized to insure sufficient range in fog. Use of a pulsed laser would provide large gains in signal-to-noise ratio and constitute an unmistakeable coded signal link. A signal monitor would prevent false alarm by alerting users in the event of hardware failure. Condensation of water on optical apertures could be prevented by a simple electric heater. An expendable outer window would simplify maintenance and minimize optical cleaning requirements.

e. Basic Receiver

An illustration of basic receiver components is shown in Figure 3.7. The receiver aperture would also be protected by an expendable outer window. Reflective optics would be utilized to permit maximum signal collection and an appropriate interference filter would serve as spectral passband for the laser line to improve background rejection. The modulated laser signal would be acquired by a narrowband amplifier for signal-to-noise enhancement. Logic and hazard alert components would be microprocessor based.

f. System Range

Examination of atmospheric transmission data indicates that attenuation of 10.6 micron CO_2 laser radiation by fog is described by an

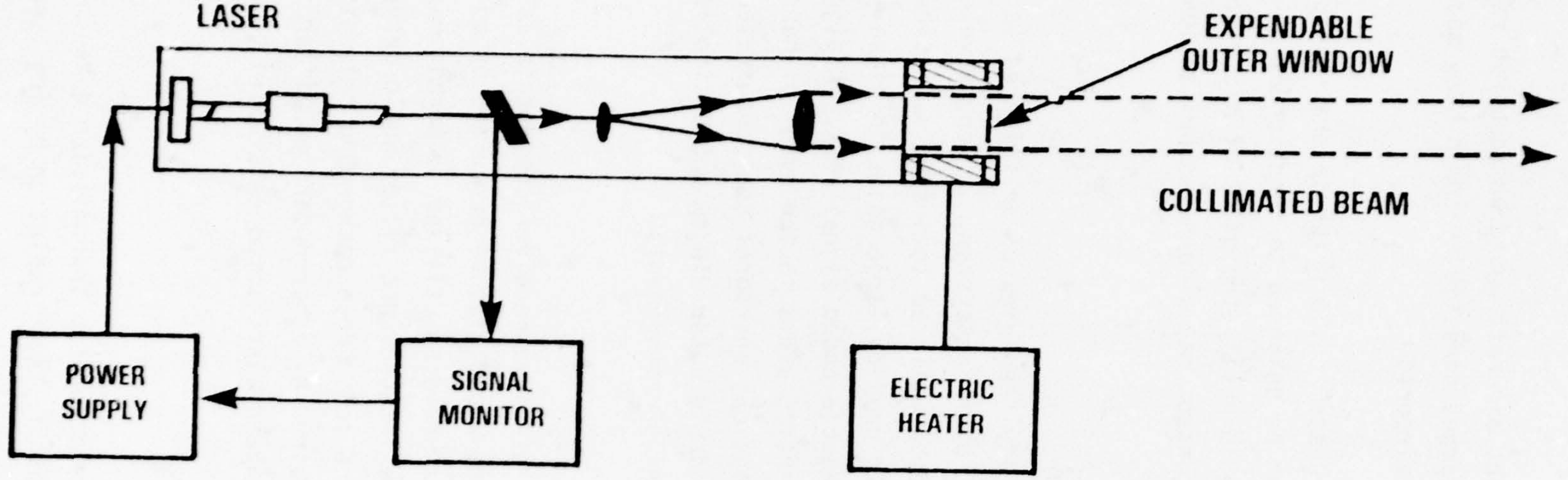


Figure 3.6 Basic Transmitter

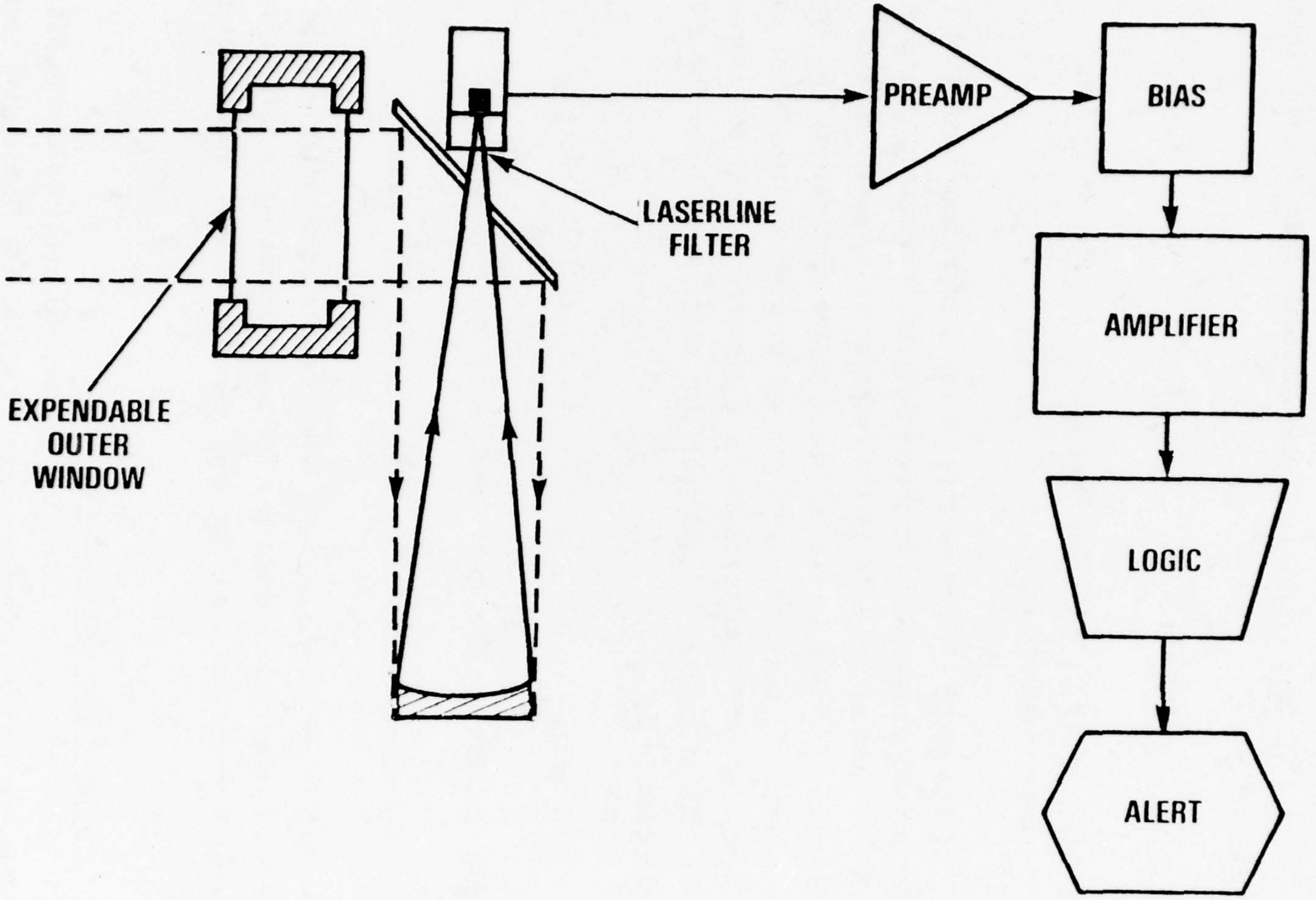


Figure 3.7 Basic Receiver

optical density of approximately 4.1 km^{-1} for 700 feet visibility and 2.3 km^{-1} for 1200 feet visibility. Corresponding transmission factors are given by

$$T(R) = 10^{-4.1R} \quad (700 \text{ feet RVR})$$

and

$$T(R) = 10^{-2.3R} \quad (1200 \text{ feet RVR})$$

where R is range in kilometers.

System range will be calculated for a continuous wave (CW) laser. Ranges for pulsed sources will be greater due to improvement in signal-to-noise ratio. Optical aperture at the receiver is taken as 15.24 cm (6 inches) diameter yielding an area of 182.4 square centimeters. An eye-safe CO_2 laser of 10.6 micron wavelength would have an intensity of about 40 milliwatts/cm^2 or 7.3 watts total for a six inch beam at the source. At a range of 3.16 kilometers (10,000 feet) the total power level for a 700 feet RVR fog would be

$$(7.3 \text{ watts}) \times 10^{-(4.1)(3.16)} = 8.1 \times 10^{-13} \text{ watts.}$$

For a 1200 feet RVR fog the power level at 10,000 feet would be

$$(7.3 \text{ watts}) \times 10^{-(2.3)(3.16)} = 3.9 \times 10^{-7} \text{ watts.}$$

Either of the above power levels should be detectable by an IR receiver. Laser beam divergence has not been considered in this calculation, but the small effect (on the order of a few milliradians) should not present difficulty.

g. System Runway Configurations

Shown in Figures 3.8 - 3.10 are several possible configurations for a runway collision avoidance system utilizing the IR blanking concept.

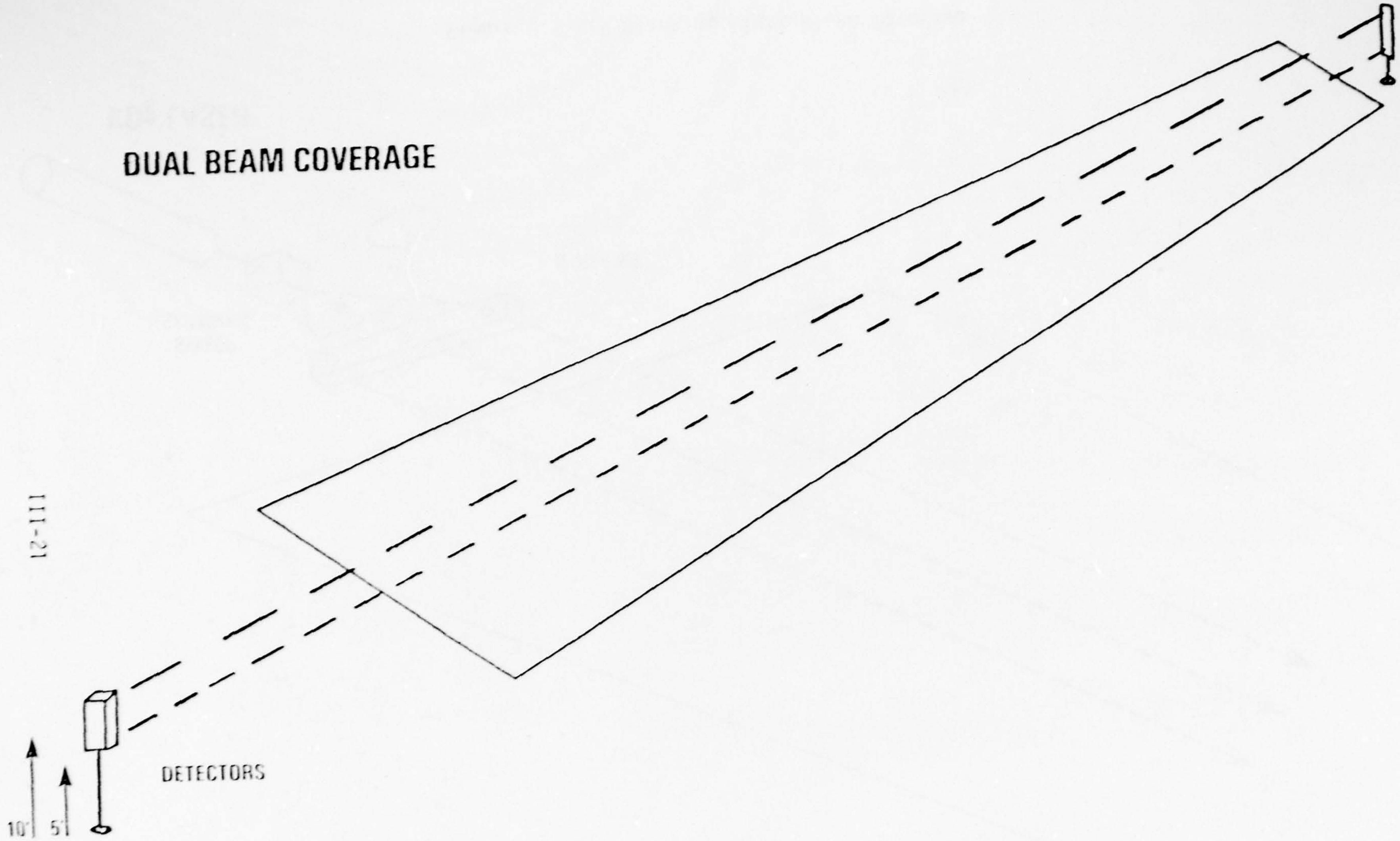


Figure 3.8 IR Blanking Minimum Mode

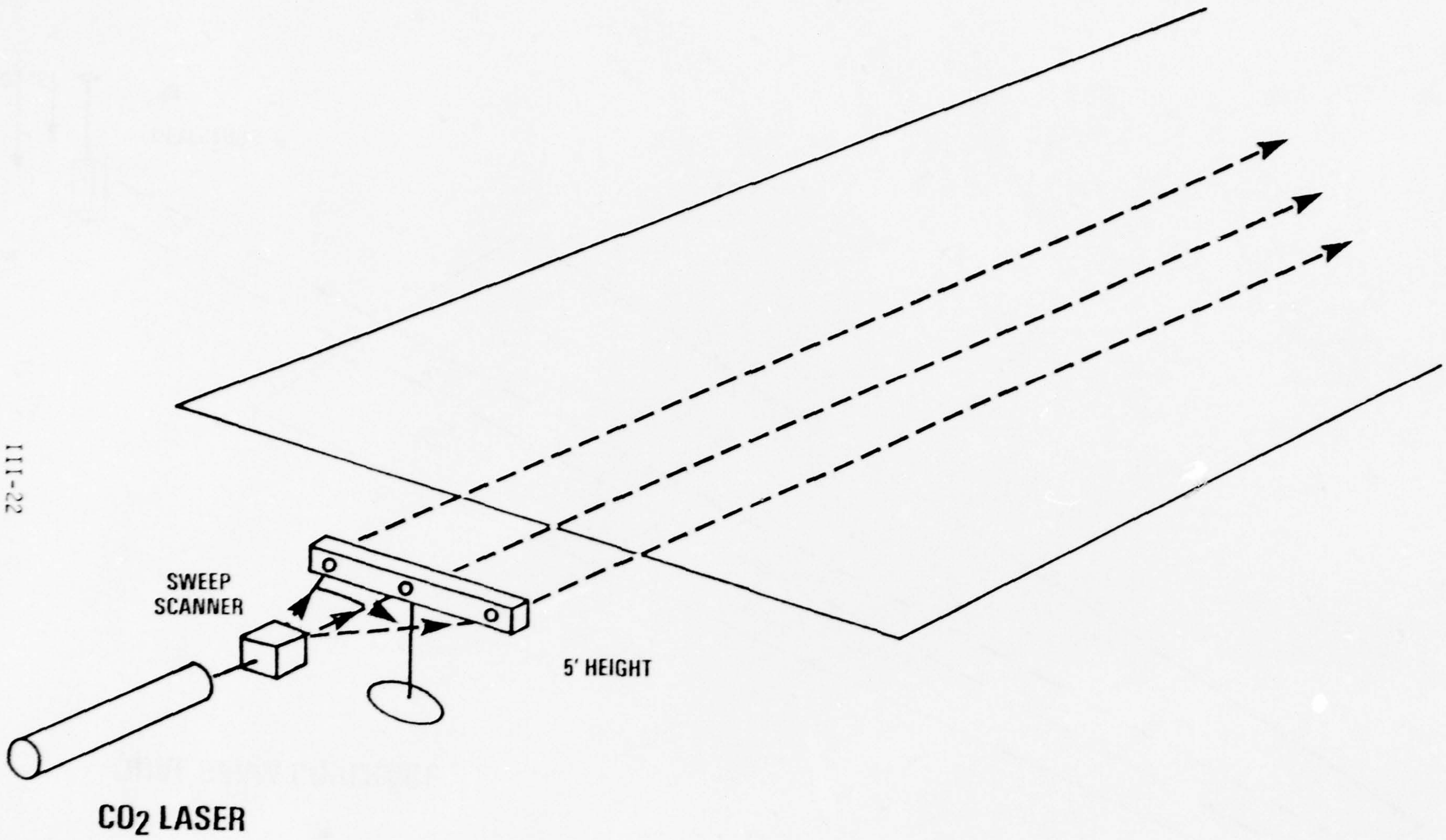


Figure 3.9 IR Blanking Light Plane Coverage

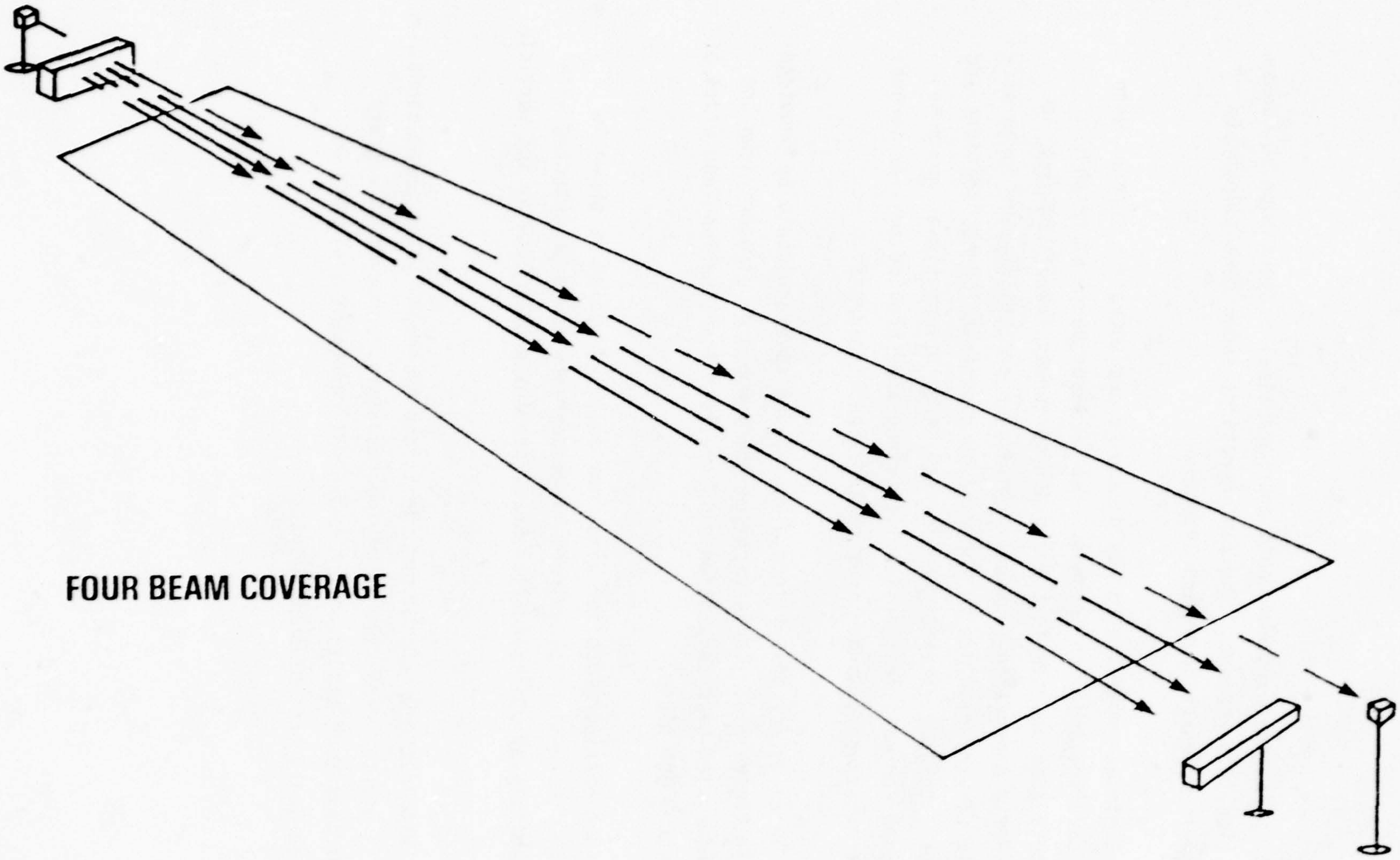


Figure 3.10 IR Blanking Maximum Coverage

Real world operational systems would take practical matters such as runway irregularities into account. The configurations shown here illustrate only the basic approach to hazard detection.

A minimum mode system would require one detection channel each for large carriers and light planes. Two IR laser beams at heights of approximately five and ten feet would detect runway takeoff hazards in a mixed traffic airport environment. Detection probability for large aircraft would be very high due to their large geometrical cross sections and small lateral takeoff variance from center line. Light planes would be detected with somewhat less reliability since they provide smaller targets and can be expected to wander from center line at takeoff.

To allow for this effect, light plane coverage could be provided as shown in Figure 3.9. Three parallel beams would be directed down the runway center with beam separation slightly less than the fuselage width of the smallest light plane.

One configuration for a maximum coverage system is shown in Figure 3.10. Both light planes and large carriers could be detected with high probability by utilizing four beams providing both lateral and verticle coverage.

Within these general considerations numerous system adaptations to specific airport requirements may be necessary. However it appears at present that such modifications would not represent a significant obstacle to deployment of such a system.

CHAPTER IV: CONCLUSIONS

The foregoing analysis shows the infrared laser blanking system to be highly promising as a runway collision avoidance device. Unlike the passive two-color IR system, it permits an unambiguous and automated determination of runway clearance with essentially a zero false alarm rate. Such an approach offers a convenient interface with existing cockpit communication systems and would facilitate direct pilot readout of runway conditions. Indeed this approach not only provides for reliable takeoff clearance in fog, but could be used as a pilot-accessed landing aid to provide a last minute check on runway clearance. In this way, the IR laser blanking system might serve as a significant instrument in expanding airport capacity as aircraft traffic densities increase.

Conversely, in the case of the passive two-color IR system, it is apparent that the short detection range limits its value as an aircraft mounted runway collision avoidance device. The maximum available range (5000 feet) of less than half the accelerate-stop distance of typical commercial carriers would not provide adequate warning of a runway takeoff hazard. Indeed this maximum range for a single aircraft mounted IR sensor holds only under 1200 foot visibility against the rear (tail-on) aspect of the largest targets (aircraft comparable to the Boeing 707 and larger). Smaller targets (general aviation aircraft), relatively cool target aspects (e.g., the frontal engine view), or more severe weather will degrade this system range to totally inadequate levels.

Essentially the same difficulties hold for a runway mounted passive device. Although adequate range and coverage of commercial carriers could be provided by increasing the number of sensors (to at least four detectors covering both takeoff directions), the problem remains with a low detection probability against frontal aspect targets. This is a particularly serious problem since the frontal (head on) aspect presents the highest danger of collision with the most severe outcome. Furthermore, the weak thermal signature of light aircraft from any aspect would render a passive system unreliable in most operational environments.

In a previous study of aircraft ground guidance techniques at airports (Reference 42), it was noted that for IR to be a significant advantage it must be shown that either (1) greater amounts of energy penetrate fog at IR wavelengths than visible light for equal ranges or (2) detectors of greater sensitivity than the human eye can be used in a practical way. The study then addressed the long wavelength fog penetration improvement from the standpoint of acquisition of hot targets by passive IR systems. The conclusion was that for passive systems neither of the criteria could be shown to be true.

For active IR systems utilizing cooperative sources (in particular, a highly collimated laser) at long wavelengths (10 microns or greater) the negative result does not apply. The first criterion (1) is found to be true. The reasons are that the per kilometer fog attenuation per watt radiated power is less at 10 microns than at shorter wavelengths, and secondly, a laser not only does not suffer from inverse square losses (since it is collimated) but its power is concentrated in a narrow spectral interval and not wasted over the entire spectrum as is the IR radiation from hot thermal sources such as jet engines.

When considering lasers (or any highly collimated beam) as a cooperative source,the use of infrared wavelengths, as opposed to the visible region, is mandated by eye safety requirements. A visible laser of sufficient power to penetrate fog at runway range would be many orders of magnitude above eye safety levels. Laser power levels acceptable for general access purposes have been established by the Bureau of Radiological Health (BRH) and the American National Standards Institute (ANSI). Such standards and regulations are subject to revision, but the general findings of each of these sources has been that more power can be utilized safely at long wavelengths far from the visible region. Examination of these standards indicates that eye safety requirements can easily be met by expanding the laser beam diameter until the intensity is sufficiently reduced. Preliminary analysis indicates that required beam diameter would be approximately six inches (fifteen centimeters). A diameter of this order has been found to be compatible with other optical design considerations.

CHAPTER V: RECOMMENDATIONS

An effective runway collision avoidance system must satisfy at least three criteria. It must be capable of real time access by the pilot. Runway clearance must be determined objectively and automatically by the physical system. The detection system should acquire targets directly and be independent of the physical state or presented aspect of the potential takeoff hazard.

The analysis presented in this report indicates the IR blanking approach meets these criteria. An examination of physical transmission data indicates ranges of 10,000 ft. should be possible under 700 foot RVR conditions, utilizing relatively simple electronics, with appropriate optical beam diameters and apertures. More sophisticated approaches, such as signal integration and/or narrowband techniques promise great improvements in signal-to-noise ratio and will be reflected in less stringent optical requirements.

Aircraft target cross sections have been examined and found to have sufficient common geometry for an IR blanking system to reliably acquire targets. In some cases difficulties may be presented by runway irregularities, but at present it appears that these can be overcome by a judicious choice of system geometry. With the exception of environmental housings and electronic logic, all hardware associated with the systems can be purchased off the shelf from various manufacturers. Areas which remain to be investigated fall into the general categories of operations and system engineering.

It is recommended the program for development of a systems specification for an operationally suitable Infrared Runway Collision Avoidance System be structured to proceed in two phases. Phase I, Preliminary Specification Development should be designed to provide workable solutions to all critical operational and systems design questions prior to proceeding with more costly efforts. A combination of system analysis, modeling and simulation, laboratory design, and controlled field testing of critical components and concepts should be used to minimize cost and ensure a high probability of success.

Phase II if necessary, would see the acquisition of a limited number of prototype systems which would be based on the preliminary specification developed in Phase I. These systems would be installed at airports selected for their type and mix of traffic, and frequency of adverse weather conditions. Pilots and ground personnel would be trained in system operations and maintenance, and requested to maintain pre-design logs and systems operations questionnaries. Periodic reviews of the documentation and personal interviews would be made over a selected time period. A complete data analysis to identify system problems and assess the contribution to airport safety would be made. The conclusion of the program would be the generation of a complete system specification, suitable for submission to qualified contractors for fabrication and installation bids.

Recommended Phase I tasks are outlined below and are priority ordered to ensure critical questions are considered early, solutions identified or concepts verified, prior to proceeding with more detailed effort. Specific subtasks for Phase II would be identified if Phase II is determined to be required.

1. Phase I - Preliminary Specification Development

The goal of Phase I is the development of a preliminary design specification which will serve to describe an Infrared Collision Avoidance System suitable for extensive field testing at selected airports. There are two tasks in this phase and 12 subtasks.

a. Concept Validation

This task would be primarily operationally oriented, with major consideration given to validation of laser weather penetration, effect of the airport environment on selected components, validation of the IR blanking concept, simulation and validation of alternative beam configurations and analysis of airport operations which could impact system design.

1) IR Blanking Target Acquisition Test

This task would be a preliminary field demonstration of the infrared approach to runway hazard detection. A CO_2 laser and IR receiver, together with appropriate laboratory equipment, would be used at the FAA NAFEC facility to validate the IR blanking concept. An IR beam would be directed over selected paths, and aircraft taxied through the beam. Readouts of receiver pulse changes, together with notations of aircraft position should validate the basic concept.

2) CO_2 Laser Propagation Test

Transmission tests with a CO_2 or suitable longer wavelength IR laser over a 3 kilometer path would be made under 700 ft RVR and 1200 ft RVR fog conditions to verify the 10,000 ft fog penetration requirement is feasible.

3) Beam Configuration Analysis and Test

A determination of beam configurations to provide the greatest runway coverage should be made and verified through ground tests. A simple computer model could be utilized to vary beam configurations, aircraft runway positions, and airport configurations. The most suitable configurations would be selected and verified by ground tests at NAFEC.

4) Evaluation of Environmental Effects

There is no doubt the components of the IR CAS system can be made to perform adequately in a laboratory. This task would take those optical components which would be exposed to the airport environment in an operational system out of the laboratory and expose them over an extended period, to dirt, dust, moisture, jet blast, severe weather, etc., in which they will be required to operate. Observations and tests would be made which will assist in the definition of a low maintenance, environmentally resistant system.

5) Operational Analysis

In order for the Infrared Runway Collision Avoidance System to be effective and useful, it should not interrupt or adversely impact routine airport operations. This task would determine the most useful system operational modes, to include communications frequencies, radio range requirements, procedure changes (if any), pilot query system, tower interface display modes, etc.

6) Airport Installation Requirements

The determination of requirements for installation of an Infrared Runway Collision Avoidance System at typical airports would be made. Items such as device siting, power available, interconnect cable distances, device hardstand design, should be considered. Cost estimates (in 1979 dollars) for system installation should be determined.

7) Systems Requirements Definition

The data and analysis gathered in the preceding six subtasks should be integrated to form the basis for an Infrared Runway Collision Avoidance System Requirements Definition. A physical description of mechanical and electronic components together with their operational modes and procedures would be included in this document.

b. Prototype Design and Laboratory Testing

This task would be primarily oriented toward system engineering and testing to complement the validation, analysis and environmental component testing previously outlined. Consideration would be given to assembly and laboratory testing of IR components and assembly and laboratory testing of a full brassboard prototype system. System signal transmission tests would be conducted, with the task culminating in a preliminary systems specification.

1) Brassboard Design

This task would identify and design system electro-optical, electronic, and electromechancial components necessary for fabrication of a prototype system. Engineering analysis using the results of the "System Definition" as a baseline would be performed. Specific engineering designs and/or descriptions would be formulated for the following subsystems:

Internal Optics
Electrical System
Mechanical System
Thermal System
Environmental System
Maintenance System
Logic
Display or Readout System

2) Component Selection and Testing

The results of "System Definition" and "Brassboard Design" can be used as a basis for selection of suitable components and/or subsystems for prototype fabrication. Individual components would be tested for defects, performance, tolerances, etc. Re-design would be carried out as warranted.

3) System Fabrication and Test

All elements of the Infrared Runway Collision Avoidance System would be integrated and tested as a system. System internal interfaces would be verified and system performance validated by laboratory tests.

4) System Validation Tests

The Infrared Runway Collision Avoidance System would be installed at the FAA NAFEC facility. Operational concepts, airport interface, and system performance would be validated.

5) Preliminary Specification Development

The following preliminary specifications which describe all facets required for purchases and installation of an Infrared Runway Collision Avoidance System would be developed:

- Beam Configuration Alternatives

- Infrared Runway Collision Avoidance Device System Specification
- Environmental Housing Requirements for an Infrared Runway Collision Avoidance System.

The preliminary nature of the specifications would be due only to the lack of an extended field operational test, the subject of Phase II of such a program.

In summary it is recommended that the infrared laser blanking approach be vigorously pursued not only with respect to its application to low visibility takeoff and landing clearance, but as a compatible and integrated multiplier of the traffic handling capabilities of existing airport instrumentation systems. The utilization of such a device in around-the-clock operations could impact substantially on future airport capabilities and at the same time afford a significant advance in runway safety.

APPENDIX A: IR TECHNOLOGY SURVEY AND CONTACT

Shown below are the professional sources utilized as part of the infrared technology survey by BDM. These contacts were established in order to obtain information on current IR technology, atmospheric optics, and infrared signatures.

I. Industrial Survey and Contact

Advanced Kinetics
AGA Corporation
Air Products
Barnes Engineering
Boeing Aircraft
Coherent Radiation
Corning Glass
CTI Cryogenics
Ford Aerospace and Communications
General Electric
General Scanning
Grimes Manufacturing
Honeywell Electro-Optic Center
Hughes Santa Barbara Research Center
Infrared Associates
Infrared Industries
ITT Electro-Optics
MacDonald Douglas
Molectron
Optoelectronics
Oriel
Pratt and Whitney
Texas Instruments
Whelan Engineering

II. Government and University Contact

Defense Advanced Research Projects Agency
Environmental Research Institute of Michigan
Environmental Sciences Research Laboratory
Federal Aviation Administration
Lincoln Laboratory (M.I.T.)
U.S. Air Force Geophysical Laboratory
U.S. Army Electronic Command
U.S. Army Night Vision Laboratory
U.S. Naval Research Laboratory
U.S. Naval Surface Weapons Center
U.S. Naval Weapons Test Center

APPENDIX B: ATMOSPHERIC MOLECULAR COMPONENTS

Constituent	Formula	Occurence (%)	Occurence (ppm)
Water Vapor⁺	H_2O	Variable	
Carbon Monoxide⁺	CO	Variable	
Nitrogen	N_2	78.084	
Oxygen	O_2	20.946	
Carbon Dioxide⁺	CO_2	0.033	
Argon	A	0.934	
Neon	Ne		18.18
Helium	He		5.24
Krypton	Kr		1.14
Xenon	Xe		0.087
Hydrogen	Hz		0.5
Methane⁺	CH_4		2
Nitrous Oxide⁺	N_2O		0.5
Ozone⁺	O_3		0.02-0.5

⁺Principle IR Absorbers

BIBLIOGRAPHY

1. Infrared System Engineering, R. D. Hudson, Jr., (Wiley & Sons, New York, 1969).
2. Handbook of Military Infrared Technology, William L. Wolfe, ed., (Office of Naval Research, 1965).
3. Infrared Radiation, Henry L. Hackforth, (McGraw-Hill Book Co., Inc., 1960).
4. Fundimentals of Infrared Technology, Holter, Nudelman, Suits, Wolfe, Zissis (The MacMillian Company, New York, 1962).
5. ABC's of Infrared, Burton Bernard (Howard W. Sams & Co., Inc., New York, 1970).
6. Elements of Infrared Technology, Kruse, McGlauchlin, and McQuiston (Wiley, New York, 1962).
7. The Detection and Measurement of Infrared Radiation, (Oxford Press, Clarendon, 1968).
8. Electrical Noise, William R. Bennett (McGraw-Hill, New York, 1960).
9. Handbook of Optics, W. G. Driscoll, ed. (McGraw-Hill, 1978).
10. Optics of the Atmosphere, Earl J. McCartney (Wiley, New York, 1976).
11. "Atmospheric Transmission," S. Passman and L. Larmore, RAND Paper P-897, Santa Monica, California, The Rand Corporation, 11 July 1956.
12. "Statistics of Global IR Atmospheric Transmission," A. P. Modica and H. Kleiman, Lincoln Laboratory Project Report TT-7, 3 March 1976.
13. "The Transmission of the Atmosphere in the Infrared - A Review," J. N. Howard and J. S. Garing, Infrared Physics, 2, 155 (1962).
14. "In Fog and Rain - Sight, IR, or Radar?" M. E. Seymour, Electronics, 33, 64 (January 29, 1960).
15. "Transmission by Haze and Fog in the Spectral Region 0.35 to 10 Microns," A. Arnulf et al., Journal of the Optical Society of America, 47, 491 (1957).
16. "Evaluation of Atmospheric Aerosol Particle Size Distribution from Scattering Measurements in the Visible and Infrared," J.A. Curcio, Journal of the Optical Society of America, 51, 548 (1961).

17. "A Method for Predicting Atmospheric Aerosol Scattering Coefficients in the Infrared," E. A. Barnhardt and J. L. Streete, *Applied Optics*, 9, 1337, June 1970.

18. "On the Nature and Size of Particles in Haze, Fog, and Stratus of the Los Angeles Region," M. Neiburger and M. G. Wurtele, *Chemical Reviews*, 44, 321 (1949).

19. "The Attenuation of Infrared Radiation by Fogs," S. W. Kurnick, R. N. Zitter, and D. B. Williams, *Journal of the Optical Society of America*, 50, 578 (1960).

20. "Parameters for Attenuation in the Atmospheric Windows for Fifteen Wavelengths," L. F. Elterman, *Applied Optics*, 3, 745 (1964).

21. "Infrared Transmission Through the Atmosphere," A. Green and M. Griggs, *Applied Optics*, 2, 561 (1963).

22. "The Scattering Cross Section of Water Drops in Visible Light," H. G. Houghton and W. R. Walker, *Journal of the Optical Society of America*, 39, 955 (1949).

23. "A Procedure for Calculation of Atmospheric Transmission of Infrared," T. L. Altshuler, General Electric Company, Ithaca, NY, Report R57ELC 15, 1 May 1957.

24. *Effect of Weather at Hannover, FRG, on Performance of Electro-Optical Imaging Systems, Part 1.*, L. M. Biberman, Institute for Defense Analysis, Paper P-1123, 1976.

25. "A Two-Color Infrared Detector," William H. Rolls, *Electro-Optical Systems Design*, November 1977.

26. "Choosing an Infrared Detector," Francis M. Lussier, *Laser Focus*, October 1976.

27. "What's New in Cooling?" W. S. Hudspeth, *Electro-Optical Systems Design*, May 1977.

28. *Infrared and Visible Equipment for Guidance and Homing of Flying Systems*, L. P. Lazarev, U.S.S.R. (in Russian).

29. "Non-Extractive Electro-Optical Measurement of Jet Engine Emissions," William F. Herget, Technical Report No. FAA-RD-78-10, January 1978, Federal Aviation Administration.

30. "A Statistical Study of Target Temperature," M. Lotman and J. Ackerman, USAF Systems Command, Technical Report No. RADC-TR-66-160, August 1966.

31. "ASD Strobe Light Evaluation," Technical Report ASD-TR-77-33, Wright Patterson Air Force Base (1976).

32. "Xenon Arc Lamps for Modulation," J. K. Buckley, Illuminating Engineering, 58, 365 (1963).

33. "The Carbon Arc as an Infrared Source," C. S. Rupert and J. Strong, Journal of the Optical Society of America, 40, 455 (1950).

34. "Light Sources for Optical Communication," N. C. Beese, Infrared Physics, 1, 5 (1961).

35. "Radiating Characteristics of Tungsten and Tungsten Lamps," W. E. Forsythe and E. Q. Adams, Journal of the Optical Society of America, 35, 108 (1945).

36. "Lock-In Amplifiers Obtain Measurements Even if There's More Noise Than Signal," E. H. Fisher, Laser Focus, November 1977.

37. "Dual Lane Runway Study," Technical Report FAA-RD-73-60, Lincoln Laboratory, May 1973.

38. "A Preliminary Requirements Analysis for Airport Surface Traffic Control," Technical Report FAA-RD-73-6, Federal Aviation Administration, January 1973.

39. "Tables of Runway Visual Range Values as a Function of Transmittance and Various Values of Pilot's Illuminance Threshold and Light Targets," Technical Report FAA-RD-70-58, Federal Aviation Administration, August 1970.

40. "Another Look at Acceleration-Stop Criteria," T. G. Foxworth and H. F. Marthinsen, American Institute of Aeronautics and Astronautics Paper No. 69-772, AIAA Aircraft Design and Operations Meeting, July 1969.

41. "Airborne Proximity Warning Instrument Laboratory Tests," Technical Report FAA-RD-77-5, Federal Aviation Administration, January 1977.

42. "Analysis of Techniques for Aircraft Ground Guidance at Airports," SRDS FAA Report No. 65-34, Airborne Instruments Laboratory, April 1965.

43. "Parametric Study of a 10.6-μ Laser Radar," R. A. Brandewie and W. C. Davis, Applied Optics, 11, 1526, July 1972.

44. "A 10.6 μm Terrestrial Communications Link," T. A. Nassmeier, F. E. Goodwin, and J. E. Zavin, IEEE Journal of Quantum Electronics, QE-10, 230, February 1974.

45. "Comparative Studies of Extinction and Backscattering by Aerosols, Fog, and Rain at 10.6μ and 0.63μ , D. B. Rensch and R. K. Long, Applied Optics, 9, 1563, July 1970.

46. "Scattering and Polarization Properties of Water, Clouds, and Hazes in the Visible and Infrared," D. Deirmendjian, Applied Optics, 3, 187, February 1964.

47. "DARPA Research in Surveillance and Target Acquisition," G. H. Sigman, Jr., Signal, October 1978.