COMMERCIAL AIR TRANSPORT

HAZARD WARNING AND AVOIDANCE SYSTEM

(Final Report)

VOLUME II - REQUIREMENTS STUDIES

by: E. Bolz, G Casserly, W. Polhemus,
D. Richardson, T. G. Thorne, L. Ursel

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Burlington, Vermont
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for: Electronics Research Center
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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FOREWORD

The work described in this three volume report was performed by Polhemus Navigation Sciences, Inc., for the Electronics Research Center, Cambridge, Massachusetts, of the National Aeronautics and Space Administration, under Contract NAS - 12-2108. The study was oriented towards the development of a Commercial Air Transport Hazard Warning and Avoidance System with particular emphasis on alleviating the problem of aircraft all-weather landing. The NASA Technical Monitor for the Aircraft Hazard Avoidance Programs office during the initial phase of the study was Mr. Richard J. Miner. During the final portion of the study Mr. Harold Decker was the NASA Technical Monitor.

ABSTRACT

Analysis of the operational requirements for a Commercial Air Transport Hazard Warning and Avoidance System was performed in conjunction with a study of the available sensor technology suited to such a system. Particular emphasis was placed on the problem of low visibility landings through a comprehensive investigation into such factors as meteorological and visibility data, aircraft accident statistics, airline-related economic benefits, current and future landing aids, and present operating procedures. The technology study was concentrated primarily in the area of microwave sensors at frequencies in the X, Ka, Ku, and V bands, with some additional analysis of electro-optical and infra-red sensors. Operational requirements were studied for landings in visibility conditions down to and including Category IIIC.

Requirements for Independent Approach and Landing Monitor (IALM), High Ground Avoidance (HGA), and Roll-out and Taxi Aid (ROTA) functions were developed. Several possible system configurations were postulated as they applied to the overall operational and functional performance requirements.

Volume I of this report is a summary volume, containing an overview of the conclusions and recommendations of the study. The main body of the report, the operational requirements, technology analysis, and system analysis is contained in Volume II. Volume III is devoted to a detailed set of Radar Performance Studies which provide the technical background for the study.

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1.0 INTRODUCTION

This report presents results of a study of Hazard Warning and Avoidance System concepts for commercial aircraft. Using documented safety statistics as a primary study input, three major hazard avoidance functions are distinguished. These functions, which dominate the technical discussion, are:

1. Independent Approach and Landing Monitor (IALM)
2. Roll Out and Taxi Aid (ROTA), and
3. High Ground Avoidance (HGA).

An important aim of the study was the attempt to find a sensor which could provide all of these functions in a single, integrated, on-board system. The on-board location was desired in order to best cope with the unique needs of individual aircraft and to cultivate pilot confidence. The major effort in sensor technology was directed toward an in-depth search of radar capability at X, Ku, Ka and V bands. Electro-optical and infra-red sensors were also considered, but in somewhat less detail.

Economic considerations were deemed to be a crucial element of any decision to implement a hazard avoidance system. The economic justification of such a system is explored from the standpoint of cost penalties, and therefore, possible savings, associated with aircraft delays and diversions and flight cancellations.

1.1 Background

This project was initially motivated by a careful consideration of aircraft accident characteristics. While the current record of airline safety is indeed an impressive one, it was believed that significant numbers of past accidents possessed similar characteristics.

Specifically, it was believed that a substantial percentage of all fatal jet transport accidents were related to inadvertent contact with the ground during periods of reduced visibility, as a consequence of either striking high ground between top of descent and start of final approach, or hitting short during final approach and landing. Furthermore, it was noted that these events occurred even in areas where VHF navigation and ILS approach aids were operational. This suggested the need for an all-weather hazard warning system capable of monitoring the region ahead of the flight path of the aircraft for some specified distance.

The military services, particularly the U.S. Air Force's Strategic Air Command, have been singularly successful at avoiding this class of accident through utilization of airborne radar. However, their solution of the problem necessitates the use of a highly skilled radar specialist and a complex of expensive and sophisticated electronic equipment.

It was also believed that the development of Radar and display technology had progressed to the point where it was practical to attempt the development of equipment suited to the commercial transport environment. The result of any development work along these lines should provide a pilot-operable hazard avoidance system which is reasonable in cost, reliability and complexity.

1.2 The Study

In the course of the study a comprehensive view of the operational environment related to approach and landing was assembled. This comprehensive view included consideration of the aircraft, airports, airline operating practices, and meteorology. Aircraft performance characteristics are important in determining the maneuvering capability available to avoid hazards and to align the flight path with the runway. Important airport and operational characteristics are: runway size and construction material, which affect runway sensing; and landing aids and aircraft handling rates, which are required to calculate aircraft delay data. Meteorology manifests itself in both the visibility statistics, which contribute to delays, and the attenuation of signal transmissions associated with the sensing function. Airline operating practices are assumed and used in the development of the cost penalties associated with delay and diversion, and in estimating cost benefits that accrue from improved landing capability.

1.3 The Report

The report has been configured to provide a logical flow of information and development of an expanding data base in order to present a broad picture of the overall hazard avoidance problem and the quantitative evaluation of candidate solutions. Each section of the report deals with specific areas of interest as they pertain to the general subject of aircraft hazard avoidance. Particular emphasis is placed on problem solution as applied to commercial air carriers. Some sections are quite detailed and technical in nature, while others are necessarily qualitative. However, it is felt that as the reader progresses from one section to the next, the development of the subject material from the separate viewpoints of operational and technical considerations will provide a meaningful summary of the subjects studied and the conclusions drawn during the conduct of the study.

Section 2 establishes the frame of reference for quantifying the effect of poor visibility on commercial transport operations. The frequency and duration of various atmospheric conditions such as rain, fog and snow which affect visibility are introduced and discussed for a number of geographic locations. The visibility statistics are then related to the statistics of delay and diversion caused by the period of poor visibility. The additional delay caused by traffic congestion is considered in Section 3. Statistics of fatal aircraft accidents are then presented and analyzed to identify those phases of flight in which the functions of a hazard warning and avoidance system would contribute significantly to flight safety.

Once the general character of the low visibility landing problem has been defined, Section 3 examines this data from the point of view of establishing what user benefit would accrue from a solution to this problem. It carries the economic benefit analysis to the point of defining the economic impact on scheduled airline operations of the availability of some categorical systems which would permit safe operation in a variety of visibility conditions (down to Category IIIC). The economic benefit analysis has been confined to the subject of delay and diversion considerations, since the economic effects of aircraft accidents is not readily quantifiable.

Section 4 defines categories of functional problems for the purposes of this study. Major emphasis was placed on the function of an Independent Approach and Landing Monitor (IALM). The corollary functions of Roll-Out and Taxi Aid (ROTA) and High Ground Avoidance (HGA) are each defined, as are the very basic ground rules and constraints as they apply to equipment characteristics and operational features. The operational environment in which the system must function is then treated in some detail. Particular emphasis was placed on a study and preliminary definition of several sets of system requirements. These include pilot information requirements, system performance requirements and system functional requirements.

Section 5 contains a summary of available and anticipated landing aids. The advantages and disadvantages of currently operational landing aids are discussed, and these are used as a basis to present a strong case for an additional landing aid in the form of an Independent Landing Monitor.

Section 6 presents an in-depth analysis of sensor technology which was performed during this study. In this analysis, by far the major effort was concentrated on an investigation of radar sensors within the range of frequencies from X band (10 GHz) on the low end of the spectrum to V band (70 GHz) on the high end. Electro-optical and infrared sensors were also included to a lesser degree in the analysis. A comprehensive evaluation of sensor performance under a variety of weather conditions, target signatures (including enhancement), frequencies, antenna sizes, and operating conditions was performed in order to define, in quantitative terms, the performance of all of the candidate sensors. This section contains the bulk of the technical performance data which must be used to define a system concept and technical configuration. This background of technical data regarding sensor performance was then used in the consideration of an optimum sensor for the combined functions of IALM and HGA. The design concepts investigated included both a separate IALM/HGA radar system, and a combined IALM/HGA/weather radar system. Recommendations were made as to the optimum sensor configuration in each case.

Section 7 presents a series of candidate system configurations. These are introduced for the purpose of identifying, from an overall integrated system standpoint, some possible combinations of the primary hardware elements of sensor, computer and display. The capability of the various system elements/configurations to provide the required functional performance of IALM/HGA/ROTA is also included.

Section 8 contains a summary of the conclusions which have been reached in the course of the study. The conclusions from earlier sections are collected, unified and discussed in the context of the project as a whole.

The final section in this report, Section 9, contains a series of recommendations for further development, particularly in the area of necessary tests. In particular, early ground-based sensor tests at low grazing angles and display simulation tests are recommended as required first steps in the development of an effective operational system. An overall technical program plan is presented as an identification of the necessary task elements.

2.0 HAZARDS TO AIRCRAFT DURING APPROACH AND LANDING

2.1 Introduction

In the most general of terms, it can be stated that one of the most serious hazards to aircraft flight is that of collision. Frequently of a major or catastrophic nature, the inclusive term of "collision" includes a number of different categories. For example, considering the approach and landing phase, an aircraft might strike high ground, it might inadvertently hit either long or short of the runway, or it might strike another aircraft. Collision with another aircraft could occur either in the air or on the ground. In all of these cases, the usual method of determining the existence of a hazardous situation, and the necessary corrective action, is based on visual observations, primarily outside the cockpit.

Conditions of reduced or degraded visibility due to atmospheric or meteorological effects will, of necessity, seriously compound the difficulty of avoiding the several hazards previously identified. In addition to making the basic problem of hazard detection and avoidance more difficult, poor visibility further aggravates the overall situation by introducing added complexities to the normal traffic flow in the terminal area due to either a slowdown or stoppage of landing operations. Added to their effect on the paramount issue of flight safety is the reflection that these adverse conditions have as operational and economic penalties, due to delays, diversions, traffic build-up and separation problems.

In the following paragraphs the meteorological conditions which affect visibility are discussed. Fog, rain, snow and smog are considered in terms of both the degree to which they can impair visibility and the frequency of their occurrence. Accident statistics are then presented and reviewed for the purpose of determining their possible relationship to poor visibility. They are also studied in a broader sense to determine what system functions and what performance criteria are important in a hazard warning and avoidance system.

2.2 Effects of Meteorological Conditions On Visibility

2.2.1 Fog. - The main meteorological condition that adversely affects aircraft landing is fog. It reduces the range at which the runway is seen through direct attenuation of the visible radiation from the runway and approach lights and through an increase in the background light level produced by scatter from other lights and, during the day, from the sun. The total effect fog has on airline operations depends upon the following parameters:

. Amount by which visibility range is reduced, ie, density of fog.

Duration of Fog

. Frequency of occurrence.

Fog consists of particles of water varying in size from 0.5 to over 60 microns, the number of particles per unit volume and the distribution of sizes varying with different types of fog. But as far as airports are concerned, fog is classified in terms of meteorological visibility or runway visual range, irrespective of the type of fog.

Meteorological visibility is obtained by an observer judging the distance at which various objects can be seen. Runway Visual Range (RVR) may be obtained by an observer counting the number of lights visible along the runway. More accurate information is obtained by measuring the actual attenuation over a fixed path alongside the runway and converting this to give RVR. For purposes of defining visibility conditions in order to establish legal compliance with established minimums at a given airport, the measurement of attenuation is typically made with a transmissometer.

Low cloud along the approach path also reduces visibility in the same way as fog thus, in order to determine whether this will affect landing aircraft, the height of the cloud base above the airport is measured. This height is known as the decision height (DH). The important visibility parameter is, of course, the slant visual range along the approach path which is a function of the horizontal RVR and DH.

The visibility conditions associated with approach and landing are normally described in terms of categories which are composites of RVR and DH. Each category has a minimum value for RVR and for DH. The currently established minimum values for each category are shown in Table II-1.

TABLE II-1. APPROACH MINIMA

Category	RVR	DH (Approach Minima)
Cat I	2400 ft	200 ft
(Interim) Cat II a	1600 ft	150 ft
Cat II	1200 ft	100 ft
Cat III a	700 ft	0 ft
Cat III b	150 ft	0 ft
Cat III c	0 ft	0 ft

The serious effect fog has on airline operations can be shown through evaluation of the meteorological visibility statistics for various airports. For example, at Kennedy International Airport, the records for the past 18 years indicate that the visibility is less than 1/2 mile for an average of 153 hours per year and less than 1/4 mile for an average of 94 hours per year. The figures include poor visibility conditions due to rain and snow. However, the contribution from these phenomena is small.

The performance of approach and landing sensors is affected by the attenuation at the wavelength of the radiation being used. In the case of optical sensors, the level of the background illumination caused by scatter from approach lights and sun light is also important.

It is usual to give the attenuation of fog in terms of its water content, to relate this to meteorological visibility, it is necessary to know the relation between the two. A number of empirical formulae have been given to relate the two; a recent one by Eldrige is as follows (Ref. 1):

$$M = 950/d^{1.54}$$

where M = average moisture content in gm/m^3

d = visibility in feet

Barhydt (Ref.2) and Chu and Hogg (Ref.3) give the following theoretical values for the attenuation through fog at optical wavelengths:

Visible Band (0.5 microns)	$3000 dB/km/gm/m^3$
Far infrared (10 microns)	$450 dB/km/gm/m^3$

Using the above information, the attenuation through fog of various visibilities has been calculated and the results listed in Table II-2. For comparison, the attenuation at four microwave wavelengths is also listed.

The significance of this table is the extreme increase in the attenuation as the wavelength decreases. As shown later on, this severely restricts the range of optical systems in dense fog.

TABLE II-2. ATTENUATION IN FOG (dB/km)

Visible Range (ft)	ILS Category (gm/m^3)	Water Content (gm/m^3)	Radar				Optical	
			X 10 GHz	Ku 16 GHz	Ka 35 GHz	V 70 GHz	10 microns	0.5 micror
2400	I	0.006	very small values				2.7	18
1200	II	0.016	very small values				7.2	48
700	III a	0.04	0.002	0.005	0.025	0.095	18.0	120
150	III b	0.41	0.02	0.051	0.26	0.96	180.0	1210
100		0.80	0.039	0.1	0.51	1.88	360.0	2400

2.2.2 Rain. - Rainfall has to be extremely heavy before the optical visibility through it is reduced to such an extent as to prevent a landing. The rainfall density-visibility relationship has been investigated by a number of workers (Ref.4) and the range of values derived from their empirical formulae are listed below.

TABLE II-3. VISIBILITY IN RAIN

Rainfall Rate (mm/hr)	Visibility Range (ft)
1	38,000 - 42,600
4	15,000 - 15,300
16	5,500 - 5,750
40	2,600 - 3,550
100	1,400 - 1,920

In practice the visibility can be somewhat less than those listed above in the event that windshield clearing mechanisms are either not available or inoperative.

Since the rainfall density has to be relatively high before visibility is seriously affected, it could be argued that it is not essential for a landing aid to operate in rain. This deduction may be valid for those cases wherein the aircraft pass through rain but not cloud (or fog) during the approach and landing phase. However, the pilot will not see the runway when the aircraft is descending through low lying precipitating clouds. For these occasions a sensor which will perform in rain is required. It is the thesis of this study that it is essential for high ground to be detected through rainfall as well; or, if this is not possible, for a climb signal to be generated by the rain itself.

Rainfall produces both attenuation and signal backscatter effects on sensor performance. These are discussed in Volume II, Section 6 and Volume III, Sections 3 and 4 for the microwave frequencies listed below in Table II-4. This table also includes consideration of optical frequencies.

TABLE II.4. ATTENUATION IN RAIN (dB/km)

Rainfall Rate, mm/hr	X	Ku	Ka	V	10μ	0.5μ
1	0.01	0.07	0.3	0.8	1.3	0.8
4	0.05	0.25	1.1	2.4	4.2	2.5
16	0.26	1.3	4.1	7.3	8.6	5.2
40	1.15	3.2	10	16	14	8.5
100	3.24	9.0	20	30	28	17

TABLE II.5. RADAR CROSS SECTION OF RAIN AT 18°C (m^2/m^3)
(Backscatter Effect)

Rainfall Rate, mm/hr	X	Ku	Ka	V
1	1.3×10^{-7}	1.3×10^{-6}	1.8×10^{-5}	2.6×10^{-4}
4	1.0×10^{-6}	1.1×10^{-5}	1.3×10^{-4}	1.9×10^{-3}
16	9.0×10^{-6}	6.0×10^{-5}	6.0×10^{-4}	8.7×10^{-3}
40	4.0×10^{-5}	2.9×10^{-4}	1.3×10^{-3}	1.8×10^{-2}
100	1.8×10^{-4}	9.8×10^{-4}	3.3×10^{-3}	3.6×10^{-2}

The tables show that the attenuation of rain and the backscatter from rain are dependent upon both the rainfall rate and the operating frequency. Both attenuation and backscatter increase with increasing rainfall and with increasing frequency. Thus, the minimum values occur in light rainfall at X band frequencies and the maximum value occurs in heavy rain at V band. The effect of frequency is discussed further in detail in Section 6 (this volume). But in assessing the overall effect on airline operations, it is also necessary to know something of the statistics of rainfall frequency, duration and area of coverage.

The most important factor is the amount of time the rainfall rate exceeds a given value. Other factors of interest are the duration of rainfall of various intensities and the linear extent of various intensities.

A review of typical rainfall statistics shows, for worst case U.S. and worldwide conditions, that rainfall rates can exceed by a significant amount the levels used in present design criteria, i.e., greater than 16 mm/hr. For example, the maximum recorded rainfalls in the U.S. show, for a storm occupying an area of 10 sq. miles, a rainfall of 250 mm in one hour. But these storms occur very infrequently and, as shown in Table II-6, are of short duration. In order to obtain a realistic estimate of the effect rainfall has on airline operations, average rather than extreme statistics have been used.

TABLE II-6. EXPECTED EXTREME RAINFALL RATES FOR VARIOUS DURATIONS (Ref. 5)

Duration (mins)	Rainfall Rate - mm/hr.	
	Gulf Coast	World Wide
1	380	480
5	181	230
10	152	190
30	113	140
60	81	100

From rainfall statistics averaged over a number of years, the total time during which rainfall exceeded the specified rates has been derived for several typical locations and listed in Table II-7, below.

TABLE II-7. RAINFALL DURATION (HOURS PER YEAR)
(From Refs. 5,6)

Rainfall Rate Exceeds (mm/hr)	Miami	Washington	Bedford England	New Orleans
4	--	63	--	90
10	--	11	0.4	--
16	25	--	0.2	37
40	9	--	0.05	17
100	1.7	--	--	--

Table II-7 shows that the duration of rainfall rates greater than 16mm/hr is small, even in places with high annual rainfall such as Miami. In the domestic U.S., localities would not appear to experience rates higher than 16mm/hr for other than relatively short periods of time.

In tropical areas, however, long periods of heavy rainfall occur during the monsoon season. For example, Bombay's rainfall for July, which is the peak of monsoon season, averages 700mm. But if we assume that the rainfall pattern is the same as Miami's then, on the average it exceeds 16 mm/hr in July for only 12 hours. The corresponding figure for 40 mm/hr would be four hours.

This analysis shows that on the average the amount of time per year the rainfall rate exceeds 16 mm/hr is generally quite small, even in areas of heavy rainfall. In addition, the duration of any one period of heavy rainfall tends to be short which further minimizes the effect rainfall has on airline operations except for those cases where an aircraft is terminating its flight following a long overwater leg, has limited reserves and must utilize an alternate which is also in equatorial regions. Consequently, this study considered sensor performance only for rainfall rates of up to 16 mm/hr.

2.2.3 Snow. - Visibility is affected by heavy snowfall and empirical formulae relating visibility range to snowfall rate, expressed by its melted water content, have been given by various researchers. The range of values of snowfall corresponding to optical visibility in feet, together with related attenuation values for pertinent frequencies, are listed in Table II-8. The value of 11dB/km/mm/hr has been assumed for 0.5 micron; (Ref.7) the values given by Gunn and East (Ref.8) have been adopted for the microwave frequencies.

TABLE II-8. SNOWFALL VISIBILITY AND ATTENUATION (dB/km)

Snowfall Rate Melted mm/hr	Optical Visibility ft.	Radar				Optical
		X	Ku	Ka	V	0.5µ
1	1600-3060	8×10^{-4}	2×10^{-3}	9×10^{-3}	1×10^{-1}	11
4	510-760	3×10^{-3}	7×10^{-3}	7×10^{-2}	9×10^{-1}	44
16	170-190	2×10^{-2}	4×10^{-2}	6×10^{-1}	8	176

The other factor which affects sensor performance in the presence of snow is the radar cross section of the snow. Dry snow consists of ice crystals and, because ice has a lower dielectric constant than water, its radar cross section is below that of rain of equivalent precipitation rate.

The maximum rate of snowfall is, typically, much less than the maximum rate of rainfall. Measurements by Warner and Gunn (Ref.7) show a maximum rate of fall in Montreal of about 5mm/hr (melted) and Wisler and Brater (Ref.9) say in urban areas it rarely exceeds 2.5 mm/hr (melted).

The mean seasonal duration of snowfall exceeding particular rates was determined for this study. However, assuming that half the total fall will be at a rate of greater than 2.5 mm/hr, then during the winter months the amount of time with a significant reduction in visibility is of the order of 20 hours at typical northern latitudes.

Snow does not affect the performance of a microwave sensor as much as does rain of an equivalent rate of precipitation because it has lower attenuation and scattering coefficients. As a general rule it can be assumed that performance in snow (disregarding the effects of snow cover on the ground) will be better than that estimated for 4 mm/hr rain.

2.2.4 Smog. - With stable atmospheric conditions the results of combustion produce a concentration of aerosols in the atmosphere above large urban areas. The necessary stable atmospheric condition is a radiation inversion. This phenomenon typically occurs in Los Angeles during the day; in London it occurs during winter nights. The resulting dense haze is known as smog.

Smog consists of particles 0.01 to 2 microns in diameter. On occasions the concentration can be high enough to reduce optical visibility to below half a mile. Since the particle size distribution is comparable with that of fog, there is a corresponding improvement in relative visibility at the longer infrared wavelengths.

Typically dense smog has an attenuation of up to 17 dB/km at 0.6 microns (Ref.10) which is assumed to fall to 2.5 dB/km at 10 microns. At microwave frequencies attenuation and scattering affects are negligible. Thus smog is very similar to fog of 2400 ft. visibility and, hence, an equipment that operates satisfactorily in this environment operates satisfactorily in dense smog.

2.3 Characteristics of Accidents

2.3.1 Accident Statistics. - Early in 1969, in recognition of the extreme importance a proper interpretation of aircraft accident statistics could have to this project, PNSI subcontracted such an analysis to the Flight Safety Foundation. The basic data contained in the FSF report (Ref.11) to PNSI was previously reported in Ref. 12.

Table II-9 presents one aspect of the statistical evaluation, that of determining just where in the overall flight domain the accidents occurred which might be avoided through hazard warning and avoidance systems. Of the 820 accidents which occurred to certificated air carriers during the period 1958 through 1967, approximately 110 of these were placed in an "applicable" category meaning that the existence of an airborne hazard warning and avoidance system could have significantly contributed to the avoidance of these accidents. The 110 "applicable" accidents were then subjected to further analysis.

As a basis for categorizing accidents by flight phase, six phases of the flight profile were identified in accordance with National Transportation Safety Board (NTSB) practices as follows:

I Takeoff climb - that period from the time the wheels leave runway to the time when the aircraft is configured for climbing to cruise altitude.

II Climb to cruise - that period from the time the aircraft is configured for climb and is ascending to cruise altitude.

III Cruise and inflight descending - includes periods of both cruise and en route descent for the purpose of landing or to change altitude, during which the aircraft is configured for normal cruising.

IV Let-down/initial approach - that period during which aircraft undergoes changes in altitude for the purpose of landing and which takes the aircraft within 10 miles of the airport with the intent of landing.

V Final approach - that phase of the flight profile from 10 miles out from the airport to one and one/half miles from end of runway prior to landing.

VI Landing - from 1 1/2 miles out to touchdown.

TABLE II-9. DISTRIBUTION OF ACCIDENTS -- DOMESTIC AIR CARRIERS (by type of accident and flight phase)

FLIGHT PHASE	MID AIR COLLISION	NEAR MISS	COLLISION WITH GROUND	UNDERSHOT LANDING	THUNDER STORM	TOTALS
PHASE I TAKE-OFF CLIMB	0	0	1	0	0	1
PHASE II CLIMB TO CRUISE	1	4	1	0	0	6
PHASE III CRUISE & INFLIGHT DESCENDING	6	13	6	0	5	30
PHASE IV LET-DOWN/INITIAL APPROACH	1	1	2	0	0	4
PHASE V FINAL APPROACH	4	0	22	0	0	26
PHASE VI LANDING	0	0	1	42	0	43
TOTALS	12	18	33	42	5	110

Types of accidents applicable to the use of airborne radar were defined for the purpose of this study as:

1. Mid Air Collision.

2. Near Miss - flight occurrence where personal injury due to evasive action was sufficient to classify as an accident.

3. Collision with Ground - an accident involving ground contact during flight other than during the landing phase.

4. Undershoot - any accident occurring during the landing where ground contact is made prior to reaching the end of the runway.

5. Thunderstorm related turbulence - an inflight occurrence, where turbulent air conditions in or near thunderstorms caused personal injuries or aircraft damage sufficient to classify as an accident.

Some of the logical questions that could be asked, given a data base of this nature, are:

1. Is there any identifiable group of commercial carrier accidents which, in general, exhibit similar characteristics?

2. What equipment(s) does it appear would be beneficial in preventing more of these accidents?

3. Can we further identify some of the required characteristics of these equipments?

The set of 110 applicable accidents accounted for 37% of all of the human fatalities sustained by domestic air carriers during the 1958-1967 time period. Further, 63% of the applicable accidents occurred during the final approach and landing phases of flight. In the final approach phase the major cause cited was collision with the ground. In the landing phase the major cause cited was undershooting the runway. Tables II-10 and II-11 present a relatively detailed matrix of the approach and landing accident survey, along with some notations concerning the circumstances regarding each accident.

It can be reasoned from an examination of these data that an additional sensing and display device could play an important and critical role in assisting the pilot to avoid high ground and to avoid undershooting the runway. According to the ground rules laid down as regards definition of flight phases, accidents classified as "final approach" (from 10 miles out to 1 1/2 miles from the end of the runway) represented 24% of the 110 applicable cases.

This indicates a definite necessity for a system providing capability for detection of either high ground or runway orientation at ranges up to 10 miles. Extension of the flight phase back beyond 10 miles up to start of let-down only includes 4 additional accidents or 4% of the total. Complete data was not available concerning the weather conditions during all of these incidents, but Table II-10 does indicate the relatively high percentage of accidents reporting either IFR or specific conditions of degraded visibility. The need does exist for some form of sensor/display which could give the pilot, under instrument flight conditions, some warning of the existence of an obstruction to his flight ahead of him along his current velocity vector.

An additional level of performance requirements can be generated from an interpretation of Table II-11 in which landing accidents (from 1 1/2 miles out to the end of the runway) are detailed. These 43 accidents comprise 39% of all of the accidents categorized as applicable to this study. Two aspects of the problem become evident. First, the data available in quantification of the undershoot or hit-short distance indicates the predominance of accidents in which relatively close-in misjudgments were made. In the majority of cases cited, the aircraft struck the ground closer than 400' from the end of the runway. Pilot misjudgment of distance from touchdown represented the most common factor quoted in the accident analysis.

TABLE II-10. APPROACH PHASE, ACCIDENT SURVEY MATRIX

AIRFIELD	AIRCRAFT	OCCURRENCE	CIRCUMSTANCE	PILOT MISJUDGEMENT	WEATHER	DAY/DUSK/NIGHT	LANDING AID
Final Approach							
Constance, Ky.	CV880	Coll Gnd	10k Short			Night	
Gt. Falls, Mont.	CV340	Coll Wires/Poles		Alt Err Dist Alt	Low Ceil., Snow		
Saigon, Viet Nam	L1049	MAC					
San Antonio, Texas	DC6	Coll Gnd					
Tourane, Viet Nam	CL44	Coll Gnd					
Newbern, N.C.	M404	Coll Trees	Dark, Unlit				
Constance, Ky.	B-727	Coll Hillside		Failed to Monitor Alt	Visual		
Knob Noster, Mo.	DC-6	Coll Trees	During Maneuver to	Desc. Below Gl. Sl.	Adverse		ILS
Detroit	C-46	Coll Gnd	Align w/Runway, below				
Miles City, Mont.	DC-3	Coll Gnd	Runway Altitude				
Morgantown, W. Va.	DC-3	Coll Gnd					
Peoria, Ill.	DC-3	Coll Gnd	Turbulence		Thund'stm		
Moses Pt., Alaska	Beech D-18	Coll Gnd	Altimeter Lag		VFR		
Bristol, Tenn.	DC-3	Coll Gnd	Mountain	Lost Position Info.			
Detroit, Michigan	DC-8	Coll Gnd			IFR/VFR, Rain/Glare		
Stuttgard, Germany	DC-7	Coll Gnd		Passed Below Minimum	IFR		
Denver, Colo.	DC-6/Beech 35	MAC					
Missoula, Mont.	DC-4	Coll Gnd		Tried VFR Appr.	IFR		
Sacramento, Cal.	C-46	MAC	Struck by another A/C				
Hickory, N.C.	F-27	MAC	Struck by another A/C		Deteriorating		
Providence, R.I.	DC-4	Coll Gnd	Trees (during go-ar'nd)	Below Minimum	3rd Attempt		
Williamsport, Pa.	M-202	Coll Gnd	Mountain	Didnt Find Head'g	Snow Shower		
Chicago, Ill.	L-1049	Coll Gnd		Rtn. to AP, Tite Mnvr.	Marginal, Low Ceil		
Charlottesville, Va.	DC-3	Coll Gnd		Not in proper	IFR		
Freeland, Michigan	V-700	Coll Gnd	Stall	IFR appr. area	Restricted Vision		ILS
Chicago, Ill.	CV-240	Coll Gnd	Off Course				Back Course

TABLE II-11. LANDING PHASE, ACCIDENT SURVEY MATRIX

Landing							
Kansas City, Mo.	DC-6	Undershoot		Dist/Alt		Day	
San Juan, P.R.	CV-640	Undershoot	ATC gave incorrect	Dist/Alt		Day	
Flushing, N.Y.	B-727	Undershoot	Alt. setting	Dist/Alt	Rain, low		
New Orleans, La.	DC-8	Undershoot	Poor Planning, excessive	Dist/Sp/Alt	Ceiling	Day	
Salt Lake City, Utah	B-727	Undershoot	Descent Rate			Dusk	
Charlotte, N.C.	DC-7	Undershoot		Dist/Sp/Alt		Day	
Stevens Pt., Wis.	DC-3	Undershoot	Below Minima (235' low)				VOR
Ponce, P.R.	CV-340	Undershoot		Dist/Alt		Day	
Weyers Cave, Va.	M-404	Undershoot		Dist/Alt		Day	
Sacramento, Cal.	B-720	Undershoot		Dist/Sp/Alt	Clear	Day	
Kansas City, Mo.	B-707	Undershoot		Dist	VFR	Day	
Richmond, Va.	DC-7	Undershoot		Dist/Alt		Dusk	
LaGuardia, N.Y.	DC-6	Undershoot	Failure to Plan &				VASI
Karluk, Alaska	G-44	Undershoot	Execute	Dist/Speed		Day	
Calgary, Canada	F-27	Undershoot	No Data				
Indianapolis, Inc.	DC-6	Undershoot		Dist.	Gusty	Day	
San Francisco, Cal.	L-1049	Undershoot	Below Minima		Marg, fog		ILS
Grand Island, Nebr.	CV-340	Undershoot		Fail. to Monitor Alt.	Fog, instr app	Night	
Pow "B" Rdr St., Alaska	C-18	Undershoot		Dist.	600 ft, 7mi vis	Day	
New Orleans, La.	B-720	Undershoot		Dist.	5mph wind	Day	
Rocky Mt., N.C.	M-404	Undershoot		Dist/Speed		Day	
Manila, P.I.	B-707	Undershoot		Dist	"normal"	Day	
Wake Island	CL-44	Undershoot		Dist		Night	
Adak, Alaska	L-1049	Undershoot	Ignored Warnings	Dist/Alt	Above min	Night	PAR
Ft. Lauderdale, Fla.	B-720	Undershoot		Dist		Day	
Jacksonville, Fla.	DC-7	Undershoot	Improper Instru. App'ch.		Gnd fog, smk		
Shemya, Alaska	DC-6	Undershoot	Runway Lights Out		At minimum	Night	GCA, Inadeq.
Bismark, N.D.	DC-3	Undershoot		Dist.	Visual&dry	Day	info to pilot
St. Louis, Mo.	B-707	Undershoot	Inadequate Airspeed	Flare		Day	
Houston, Texas	B-720	Undershoot	Inadequate Supervis'n	Approach		Night	
Pittsburgh Pa.	Viscount	Undershoot	by C'ptn.	Landing		Day	
LaGuardia, N.Y.	L-188	Undershoot	Badly Planned Approach			Day	
Houston, Texas	DC-7	Undershoot				Day	
New York, N.Y.	DC-7	Undershoot	Too Low Failed to			Day	
Wash. D.C.	DC-7	Undershoot	Correct in Time.		Clear		
Riverhead	B-707	Undershoot	Hit Localizer Shack			Day	
Juneau, Alaska	B-377	Undershoot				Day	
Kotzbue, Alaska	C-46	Undershoot					ADF
Chicago, Ill.	B-707	Undershoot			35-40kts crosswind	Day	
LaGuardia, N.Y.	L-188	Undershoot					ILS Bk Crs, A/P eng.
New Orleans, La.	DC-7	Coll Gnd	Tried Go-Ar'nd		Fog		ILS
Columbus, Ohio	M-404	Undershoot	Snow on Runway			Day	
Nantucket, Mass.	CV-240	Undershoot	Fld. to Abandon. 1/8 Mile Vis		Adverse		ILS

Of the 43 landing accidents, 25 occurred in what was termed "daytime" conditions. The conditions of visibility were not further qualified. If this categorization could be interpreted as VFR conditions, then the suggestion could certainly be advanced that the pilot undershot the runway even though he was looking at it. The display then, must provide more than just a pictorial representation of the runway, it must provide in great measure a flight director representation of the real-time deviation from the prescribed horizontal and vertical flight paths.

The general conclusion to be drawn from this brief resume of the existing accident statistics is to verify the requirement for a system whose hazard warning functions encompass both final approach and landing phases of flight back as far as 10 miles from the end of the runway. As many as 63% of the applicable accidents studied in this investigation could have been avoided by the proper application of an airborne system which provided both high ground avoidance and runway approach and landing guidance.

2.4 Summary

2.4.1 Meteorological Effects. - The meteorological data provides the following indications with regard to hazard warning and avoidance systems.

1. Dense fog severely restricts optical visibility.
   - It is necessary that the IALM operate through heavy fog.
2. Heavy rain does not seriously degrade optical visibility unless accompanied by fog or low clouds.
   - When heavy rain accompanies fog, it is necessary that the IALM operate through both.
   - It is necessary that the high-ground avoidance mode operate reliably in heavy rain.
3. Rainfall of 16 mm/hr is taken as a reasonable maximum value for this study. Much heavier rains do occur but with small probability of occurrence and short durations.
4. The attenuation of falling snow is less than for rainfall of equivalent water content. Heavy snow has a water content equal to only a few mm/hr of rainfall. A reasonable attenuation for snow is somewhat less than that of 4 mm/hr of rain.
5. Smog is similar to fog with a visibility of 2400 ft.
   - Smog should not be a factor in either Cat II or Cat III operations.

2.4.2 Accident Statistics. -

1. 820 accidents occurred to certified air carriers during the period of 1958 to 1967.

2. 110 of these accidents were "applicable" to the concept of hazard avoidance through the use of airborne sensors.

   These 110 accidents accounted for 37% of all of the human fatalities sustained in the 820 accidents.

3. 63% of the applicable accidents occurred during the final approach and landing phases of flight.

4. 24% of the applicable accidents occurred in final approach (10 mi to 1 1/2 mi from the runway) and typically in poor visibility.

   There is a need for detection of either high-ground or runway orientation at ranges up to 10 miles. Few accidents occur beyond 10 miles.

5. 43 of the applicable accidents occurred in the landing phase of flight. Of these, 25 occurred in "daytime" conditions with misjudgment being cited as the major cause.

   Assuming that "daytime" implied that the pilot could see the runway, it follows that seeing the runway is not enough. Further, in conditions of poor visibility, a pictorial presentation of the runway would also be inadequate.

   It is concluded that a situation display is required as a reasonable minimum level of information. Further, to avoid adding workload, it would be necessary to sense the situation and thus display some form of command information to the pilot.

3.0 ECONOMIC BENEFIT OF IMPROVED LANDING CAPABILITY

3.1 Introduction

Section 2 provided an identification of the meteorological conditions which contribute to poor visibility. This section considers an analysis of the subsequent effect of poor visibility on airline operations. Operationally, poor visibility leads to delays, diversions and attendant cost penalties. The inclusion of equipment to provide added landing capability (ability to operate a lower minimums) presents a potential way to avoid some of these penalties. The intent of this section is to evaluate the cost benefit of improved landing capability and to provide the basis by which the cost of the additional equipment may be weighed against the cost benefit of this added capability in the sense of economic justification. The emphasis is placed upon the evaluation of the saving associated with improvement in terms of visibility increments. The magnitude of the saving is related to airline operating procedures and to the unique visibility characteristics of individual airports.

The effect of hazard warning and avoidance upon flight safety is neither small nor unimportant but it does have subjective facets which make a meaningful quantitative dollar evaluation difficult. Therefore, no effort is made either to quantify safety in terms of dollars or to include a safety value in the following analysis.

3.2 Poor Visibility and Operational Delays

Poor visibility has an adverse effect upon flight operations. It creates delays in landing and diversion to alternate airports because of inability to land. This section will present the recorded visibility statistics for a number of U.S. airports and use them to estimate the average delaytime and diversion probability for an aircraft attempting to land at a specific airport. The aircraft is characterized as having the capability to loiter near its destination for a specified maximum time before having to divert. Loiter capabilities of 30, 60, and 120 minutes are considered in the analysis.

The visibility statistics for the analvsis were taken from the Climatological Summaries (Ref. 13). Data in a series of tables for each of 31 airports were used. These tables listed the total number of occurrences of visibilities at or below certain levels for a period of ten years. The number of occurrences were given in columns according to the duration of the occurrence. A part of these tables, for Stapleton International Airport at Denver, Colorado, is shown below.

TOTAL TIME AT OR BELOW EACH VISIBILITY CLASSED AS ONE INCIDENT
TABLE VI. (IRRESPECTIVE OF CEILING).

(mi)	DURATION IN MINUTES									
VISIBILITY	1-15	16-30	31-45	46-60	61-90	91-120	121-180	181-240	241-360	361-480	481+
3/8	43	34	23	27	27	15	21	11	4	1	
5/16	32	22	25	19	26	15	16	9	4	1	
1/4	32	21	25	20	25	15	16	9	4	1	
3/16	14	13	10	12	9	5	11	3	3		
1/8	11	11	10	10	10	5	10	4	2		
1/16	2	6	6	5	1	3	6	3			
0	4	1			1	2	3	2			

The occurrences are cumulative. The total duration of visibility at or below a specific level is considered as one occurrence. For example, if the visibility were 1/4 mile for 25 minutes and 3/16 mile for five minutes during the period of interest, it would be classified as four occurrences. There would be three entries under 16-30 minutes duration, at 3/8, 5/16 and 1/4 mile, and a fourth entry under 1-15 minutes at 3/16 mile. The values for the 1/2 mile visibility entries were developed by extrapolation from the data in Climatological Summaries.

The objective of the analysis was to yield typical delay times and diversion probabilities using actual visibility conditions and typical loiter capabilities for large, medium and small transport aircraft. The equations used in the analysis are derived in the first part of Appendix A. Generally speaking, they describe three situations which contribute to aircraft delay and diversion. First, if the aircraft loiter capability is greater than the duration of poor visibility, the aircraft simply waits for the weather to clear and lands. Second, if the aircraft loiter capability is less than the duration of poor visibility, then there is a finite probability that the aircraft, after waiting as long as it can, will have to divert. Third, under the same conditions, there is a finite probability that the aircraft can successfully wait until the weather clears. The last two alternatives depend upon when, during the period of poor visibility, the aircraft encounters it. At each airport, three separate loiter capability times of 30, 60 and 120 minutes are used. The mean delay times per landing and the probability of diversion calculated for visibilities at or below the seven listed values: 1/2, 3/8, 1/4, 3/16, 1/8, 1/16, and 0 miles. All calculations were carried out on a digital computer.

Note that the delay times and diversion probabilities presented in this form correspond only to the times spent in weather below the landing minimum. They do not include the additional delays which are created by traffic accumulation during periods of poor visibility. These additional delays created by the queuing effect are taken into account in the latter part of Appendix A and in the analysis of the following subsection.

The mathematical background and the tabular results of this work are shown in Appendix A. Equations 1 through 4 of that Appendix, are the basis for the results shown in the Tables. The tables present the basic visibility data which was taken from the Climatological Summaries. The tables also present the mean delay time per landing and the probability of diversion for each of the assumed loiter capabilities and for visibility conditions at or below each of the seven listed values. The results of this work will not be discussed here because the inclusion of operating rules, delay and diversion costs, and the compounding delay due to the traffic congestion lead to a much more meaningful result. These factors are added to the analysis in the next subsections.

3.3 Cost of Delays, Diversions and Cancellations

The effect of poor visibility in creating delays and diversions was introduced above. In this section, the typical dollar cost of delay, diversions and cancellations are briefly stated. These cost figures are later used in the evaluation of cost penalties associated with assumed route structures and specific airports.

The cost figures presented below are typical of three different types of aircraft which are used on different route structures:

Aircraft #1:	A large four-engine jet,
Routes:	transcontinental, intercontinental,
Flight Plan:	may delay for two hours; diverts after a 2-hour delay
Aircraft #2:	A medium two or three-engine jet,
Routes:	regional,
Flight Plan:	May delay for one hour; diverts after a one-hour delay; cancels flight if a delay longer than two hours is anticipated
Aircraft #3:	Heavy twin turbo-prop,
Routes:	commuter
Flight Plan:	May delay up to 1/2 hour; delay takeoff for anticipated delay up to one hour; cancel flight if a delay of longer than one hour is expected.

The cost figures below are taken from Reference 14. The costs of diversions and cancellations were estimated from average figures given in the reference. The cancellation figure for Aircraft #3 was not available explicitly, but it was estimated from figures that pertained to Aircraft #2. In addition, all of the cost figures were adjusted upward to account for a five year passage of time.

The Figures in Table II-12, following, representing the cost of delays, range from \$ 250/hr for the small aircraft (#3) to \$ 870/hr for the large aircraft (#1).

TABLE II-12. COSTS OF DELAY, DIVERSION, AND CANCELLATION.

Aircraft Number:	1	2	3
Delay	$14.50/min.	$10.20/min.	$4.10/min.
Diversion	$1700	$1460	———
Delayed Takeoff	———	———	$0.41/min.
Cancellation	———	$1300	$1150

3.4 Method of Computation

The cost benefits of improved landing capability are obtained by combining the visibility data with the delay and diversion cost figures. The visibility data and the evaluation of it, which is contained above, assumes that the landing may be accomplished as soon as the weather clears. In reality, the delay may be further propagated because of accumulated traffic. An analysis of delays and diversions and the inclusion of traffic buildup is contained in the Appendix A. The accumulated traffic affects the original delay figures in two ways. First, it lengthens the delay time for aircraft which arrived in bad weather. This effect can also produce additional diversions. Second, it creates delays for those aircraft which arrive shortly after the weather clears. In the analysis of Section 3.2, this delay was not considered.

The objective here is to find the cost penalties related to the inability to land in individual intervals of visibility. The intervals used are assumed to be consistent with the visibility intervals in which the visibility data is presented in Appendix A.

The average delays and the diversion probabilities are computed for maximum aircraft loiter capabilities of 30, 60 and 120 minutes. These delays and diversion values are computed from the visibility data and the traffic arrival and landing rates for a particular airport. The landing rate for a finite number of specific airports is determined by the FAA specifying a maximum hourly rate of operations during IFR conditions. For other airports, an estimate of the rate of operations can be made from the IFR runway configuration and landing rates stated in Reference 14. The value of the landing rate, r_o, for an airport is determined by assuming that if several aircraft have been waiting to land, 80% of the operations will be landings until the overload is cleared.

The aircraft arrival rate, r_i, for a given terminal area is determined from the annual number of operations at that airport. The hourly arrival rate is assumed to be half the total number of operations divided by 365x16 since traffic pattern studies have shown that nearly all operations occur during a 16 hour period of the day.

So, arrival rate, $r_i = \frac{NO}{11680}$

where NO = the number of annual operations. The values of arrival rate developed in this manner are sixteen hour averages, so the values of delays derived from them reflect only an average value, and not the peak value, which could be much higher. In some cases the arrival rate exceeds the landing rate during peak hours, resulting in a build-up of waiting aircraft rather than a decrease.

The table (II-13) below lists the annual operations, the peak IFR operations, and the values of landing rate and arrival rate for eight airports in the years 1967 and 1970. The annual operations for 1967 are from Reference 15 and the figures for 1970 are estimates.

TABLE II-13. TYPICAL AIRPORT OPERATIONS

Airport	Thousands of Operations		Peak IFR Operations (per hr)	Landing Rate (per hr)	Arrival Rate (per hr)	
	1967	1970			1967	1970
JFK	481.5	580.0	80R	64.0	41.2	49.6
Newark	260.0	308.0	60R	48.0	22.3	26.4
Baltimore	208.0	260.0	52	41.6	17.8	22.3
Miami	446.9	537.0	81	64.8	38.3	46.0
O'Hare	643.8	819.0	135R	108.0	55.1	70.2
Los Angeles	482.8	602.0	94	75.2	41.3	51.6
Atlanta	362.6	508.0	90	72.0	31.1	43.5
Cleveland	318.6	426.0	71	56.8	27.3	36.5

(R means explicitly stated values. The remaining values of IFR Ops are estimates.)

The costs of delays and diversions are calculated in the following manner. The reader is referred to Appendix A, for a more thorough discussion of the analysis. The important variables are:

W — The length of time where the visibility is below the minimum required for landing.

L — The loiter capability (maximum delay) of the aircraft.

The following four variables refer to a specific category of visibility:

P(D) — Probability of diversion where the duration of bad weather exceeds the loiter capability.

D_s — Average delay per landing where the loiter capability exceeds the bad weather duration.

D_e — Average delay per landing where the aircraft arrives near the end of a long period of bad weather and is able to wait long enough to land.

D_d — Average delay per attempted landing spent before diverting ($W > L$). (Note that D_d is not contained in D_e).

Additional subscripts, such as D_{s120}, indicates that D_s is to be evaluated at $L = 120$ minutes.

The following variables relate to costs:

CDL — Cost of a delay/minute.

CDV — Cost of a diversion.

CCL — Cost of a cancellation.

CHT — Cost of delaying takeoff/minute.

The numerical values for these cost elements were presented in Table II-12.

In this analysis and in the computations for this section, three typical route structures and operating guidelines are assumed.

Assumed Route Structure 1.

Stage lengths: 3600nm, transcontinental, intercontinental

Aircraft: large, four-engine jet

Landings/Year: 600

Flight Plan: Delay up to two hours, divert if delay lasts beyond two hours (L = 120 minutes)

Delay Cost per Flight $= (D_{s120} + D_{e120})$ CDL

Diversion Cost per Flight $= P(D)_{120}$ CDV $+ D_{d120}$ CDL

Assumed Route Structure 2.

Stage length: 600nm, regional carrier

Aircraft: medium, 2-3 engine jet

Landings/Year: 2400

Flight Plan: Delay up to one hour. Divert if delay lasts beyond one hour. Cancel flight if delay will last beyond two hours (L = 60).

Delay Cost per Flight $= (D_{s60} + D_{e60})$ CDL

Diversion Cost per Flight $= (P(D)_{60} - P(D)_{120})$ CDV $+ (D_{d120} - D_{d60})$ CDL

Cancellation Cost per Flight $= P(D)_{120}$ CCL

Add to get the total cost per flight.

Multiply by 2400 flights to get the total cost per year.

Assumed Route Structure 3.

Stage Length: 200 nm, Commuter

Aircraft: Heavy twin turbo-prop

Landings/Year: 3000

Flight Plan: Delay up to one/half hour. Delay takeoff one/half hour if delay will last up to one hour. Cancel flight if delay will last beyond one hour.

Delay Cost per Flight $= (D_{s30} + D_{e30})$ CDL

Delayed Takeoff Cost per Flight $= (P(D)_{30} - P(D)_{60})$ 30CHT $+((D_{s60} + D_{e60}) - (D_{s30} + D_{e30}))$ CDL

Cancellation Cost per flight $= P(D)_{60}$ CCL

Add to get the total cost per flight.

Multiply by 3000 flights to get the total cost per year.

Once the computations have been made for each visibility category, they are summed to get the total costs due to visibilities below one/half mile.

3.5 Results of Low Visibility Cost Computations

The results of cost computations for eight airports and three route structures and the six visibility categories appear in Appendix A. They are organized so that all of the results for a given airport for one year appear on one page. There are five tables of data on a page. The first is a listing of the source visibility data taken from the tabular data of the Climatological Summaries (Ref. 13), with the addition of the estimated 1/2 mile data mentioned earlier. It should be noted that the methods used to determine 1/2 mile data were very conservative, and so the resulting dollar figures associated with Category I are also conservative estimates. Following this are the values associated with delay propagation, unique to that airport and year. The second table lists mean delays per landing and probabilities of diversion corresponding to total allowable delays of 30, 60 and 120 minutes, computed in accordance with equations 9 through 12 in Appendix A. The mean delay per landing stated is the total mean delay ($D_s + D_e + D_d$). The contributions to delay and diversion probability of each individual category are not shown. The three remaining tables correspond to the three route structures defined above. For each route structure and for each visibility category, the contributions to total cost of delays, diversions, cancellations and delayed takeoff (where applicable) are shown. These figures are calculated on a per flight basis. The per flight totals are multiplied by the number of flights per year to get the total costs per year.

3.6 Conclusions: Benefits of Specific Improvements in Capability

It is apparent from these cost computations that the yearly losses due to poor visibility vary widely depending on the airport and route structure. The variation between airports is certainly to be expected because of the different visibility statistics and different ways in which traffic congestion propagates delays. The variations between route structures is relatively consistent from airport to airport, however. Route structure One always has the lowest total yearly cost and route structure Two has the highest. This is caused primarily by the variations in basic operating costs and the number of landings per year. Route structure One has the highest operating costs but there are relatively few landings made per year. Route structure Two has somewhat lower costs but four times as many landings. Route structure Three has significantly lower operating costs, but due to the high cost of cancellations and the large number of landings per year, this route has total losses that are nearly as high as those of route structure Two.

The best way to determine the benefits of a particular improvement in landing capability is to pick a route structure and an airport (or an average for a combination of airports), that represent a particular air carrier's situation. Then add together the total losses corresponding to the visibility ranges in which landings could be made with the improved system. This figure can be compared to the yearly cost of purchasing and maintaining such a system. For example, let us assume route structure Two with landings in Baltimore as projected for the year 1970 and equipment that would allow landings in visibilities down to one-quarter mile. The yearly benefit of such a system would be $2365 + $5187 = $7552. If we assume five year depreciation plus five percent of purchase cost per year for maintaining etc., this would pay for $30,000 worth of equipment. (Note that this is a simple computation and does not reflect interest charges, present value of the money or other considerations). Again, examining the Baltimore table, we see that capability down to 3/16 mile could increase the benefit by another $10,423 to a total of $17,975. This yearly amount would pay for $72,000 worth of equipment.

One of the most interesting results of the data on these tables is the distinct lack of correlation between the benefits derivable from a small increase in capability and the benefits of a system with capability down to zero visibility. Compare, for example, route structure Two at Baltimore and Newark. The total of the costs per year at Baltimore is nearly twice the total at Newark. But the total of the benefits down to 1/4 mile are of the same order of magnitude. The totals for Los Angeles and New York JFK are roughly equal, but the benefits of a system good to 3/16 mile at JFK is twice as great at Los Angeles. These results are caused by a wide variation in the way the visibility occurrence data is distributed. It can also be affected by the methods used for observing and reporting visibility data. Note that at JFK the number occurrences of higher visibility is very high, and the occurrences of low visibility is very low. At Los Angeles the changes in occurrences with changes in visibility are not nearly so great.

The most significant result of these computations is the demonstrated fact that the cost benefit of having improved capability increases when the length of the route, and therefore the size and cost of the aircraft decreases. This fact directly contradicts the usual practice of spending a fixed per cent of the cost of the aircraft on avionic systems. Quite obviously, this effect is directly caused by the assumptions made in generating the cost model. For example, a large cost of diversion would tend to stress the importance of individual landings. This subsequently relates the greatest cost benefit to the aircraft making the greatest number of landings regardless of the type of aircraft.

Using the figures for Baltimore, let us calculate the ratio of cost of low visibility to total revenue per flight.

TABLE II-14. RELATIONSHIP OF LOW-VISIBILITY COST TO TOTAL REVENUE ON A PER-FLIGHT BASIS.

	Assumed Route Structure		
	1	2	3
Average # Passengers	100	60	35
One-Way Fare	$225	$50	$30
Total Revenue	$ 22.5K	$ 3K	$ 1.05K
Low Visibility Cost	$ 35.04	$19.25	$12.82
% of Total Revenue	0.16%	0.64%	1.22%

In this case, the percent of total revenue per flight lost due to the inability to land in visibilities less than 1/2 mile is nearly ten times as great for the twin turboprop aircraft as it is for the large four-engine jet. Indeed, the loss to smaller aircraft is a very significant portion of the profit margin of the aircraft. An increase of landing capability to 3/16 mile for a turboprop landing at Baltimore would reduce costs by 0.5% of gross revenues. If the cost of the equipment required to give this capability were less than $60,000, the result would be a net increase in profits.

In general, the supporting data in this analysis leads to the qualified conclusion that the IALM function is most cost effective to the regional carriers - or stated another way, the carrier whose combination of operating cost per hour and number of landings per year results in the largest cost benefit appears to be the hypothetical route structure Two operation. Certainly, a modification of the arbitrarily chosen ground rules for the analysis will change the numerical results somewhat, but the logic of the system benefits will tend to keep the ultimate conclusions similar to those shown in this section.

The preceding discussion does not take into account the obvious benefits of lives and aircraft saved due to the reduction in ground collision accidents, nor the economic benefit from any reduction in insurance rates.

3.7 Summary

In this section visibility statistics, costs of individual delays and diversions, aircraft loiter capability, and airline operating practices have been combined to develop the cost penalties associated with various intervals of visibility. It is noted here that the treatment in this particular analysis was limited to visibilities of one/half mile and less. There is an additional benefit which is available in providing for the full exploitation of capability down to one/half mile visibility. The fact that landing minimums at some airports are limited to visibilities above one/half mile is established in Section 4.

To summarize the dollar cost savings which are available, the data from the tables of Appendix A is retabulated here. The dollar savings available from a full exploitation of Category II are presented for several airports and the assumed route structures which were used in the analysis above. The summary table is shown below.

TABLE II-15. ANNUAL COSTS ASSOCIATED WITH THE VISIBILITY INTERVAL 3/16 MILE TO 1/2 MILE.

Airport	Assumed Route Structure		
	1	2	3
Atlanta	$ 8,004	$ 16,951	$ 14,736
Baltimore	8,176	17,975	14,981
Chicago (O'Hare)	4,719	10,042	8,333
Cleveland	4,273	8,972	7,587
Los Angeles	6,417	13,218	11,303
Miami	1,551	3,528	2,610
Newark	5,553	12,004	10,485
New York (JFK)	13,022	26,688	21,241

The figure must be weighted with aircraft usage of individual airports to arrive at a true picture of the cost per aircraft. For example, if a medium range aircraft (route structure Two) were assigned to fly back and forth between New York (JFK) and Chicago (O'Hare) with half the total landings being made at each of these airports, the dollar saving of reducing the visibility limit from 1/2 mile down to 3/16 mile is the average of the two values in the table; that is, $18,365. If an intermediate stop were included in Cleveland, the saving would change to a new value. Assuming the same number of landings per year as before, which may be conservative, the potential savings become $13,668 annually. This saving should be sufficient to justify equipment costs on the order of $50,000.

4.0 DESIRED CHARACTERISTICS HAZARD WARNING AND AVOIDANCE SYSTEM

4.1 Introduction

Section 2 has introduced some of the operational aspects of the hazard warning and avoidance problems. From the standpoints of both economics and safety, there are basic solutions required. Investigation of the different aspects of the situation leads to an initial conclusion that three broad categories of functional capabilities are required as candidate solutions to the overall low visibility landing situation.

For the purposes of this study, primary emphasis has been placed on the investigation of an airborne solution to the problem. Recognition is made of the fact that alternative, ground-based, solutions to each of the major functional requirements do offer promise. Indeed, additional study and development effort along these lines should be encouraged. However, as the overall spectrum of requirements was analyzed, one immediate, if not rigorous, assumption has been made, that of providing one single integrated system that provides all of the required functions. For this reason, and considering the various phases of flight to which the system must be applied, an airborne self-contained solution was selected to be investigated.

There are three main system functions that need to be provided, each for a variety of reasons. Hereafter in this report, these three functions will be referred to in the following context. The necessity of protecting the aircraft from colliding with high ground or other unusual obstructions to flight, normally during cruising or descending flight, defines a requirement for the capability for High Ground Avoidance (HGA). This requirement manifests itself primarily as a flight safety motivation - to avoid the large percentage of fatal jet accidents directly attributable to hitting high ground.

A combination of flight safety and economic reasons dictate the requirements ascribed to an Independent Approach and Landing Monitor (IALM) whose primary function is to provide acquisition, identification and guidance to a runway approach and landing in visibility conditions including Category IIIC. Intended primarily as a monitor of the performance of the existing ILS equipment in the aircraft, a major system requirement is to reduce the number of accidents categorized as "hit short" or "premature contact with the ground" as identified in Section 2. A secondary but important consideration is the effect on operating economics afforded by the ability of an IALM to reduce delays and diversions caused by low visibility, particularly if such a system could be certified by the FAA to conditions approaching Category II for airports currently restricted to Category I minima.

Any consideration of Category IIIC operations must include provisions for guiding the aircraft to the ramp under conditions of zero visibility. The system or function which provides this capability has been designated as a Roll-Out and Taxi Aid (ROTA).

Table II-16 summarizes these system functions and their economic and/or safety motiviations.

As a general study ground rule, it can be stated that the requirement for these system capabilities is independent of the existence of an instrument approach system at any given airport. To define the requirement for the system in greater detail, an operationally-oriented study has been performed which defined the:

- Present and probable future operational requirement.
- Information requirements applicable to each system configuration.
- Performance requirements.
- Characteristics of acceptable system(s).

The context in which the study documented herein was performed was:

- The system(s) under consideration is to be an independent source of guidance data for the approach and landing phase of operation.
- It is to provide a terrain warning facility.
- Weather avoidance capability is to be provided in an ultimate integrated system.

  Pilot manipulation requirement is to be minimized in order to assure no significant workload increase during the terminal phase of operation.

  Data display is to be compatible with current systems.
- The objective of the system design is to allow CAT II operation as a minimum, with operation to CAT III weather conditions desirable, including the provision of ROTA (Roll Out and Taxi Aid) capability.

TABLE II-16. FACTORS AFFECTING SYSTEM FUNCTIONAL REQUIREMENTS

Function	Safety Factor	Economic Factor
High Ground Avoidance (HGA)	Prevent accidents caused by striking high ground or other physical obstructions to flight such as buildings, towers, trees, etc., Possible application as proximity warning aid.	Reduce cost of repair or replacement of aircraft due to damage, possible reduction of insurance costs.
Independent Approach and Landing Monitor (IALM)	Prevent accidents caused by premature contact with ground during landing (hit short) or due to misalignment or disorientation with runway.	Reduce aircraft operating cost losses caused by delays or diversions due to low visibility. Reduce cost of repair or replacement of aircraft due to damage, possible reduction of insurance costs. *
Roll-Out and Taxi Aid (ROTA)	Prevent accidents caused by striking ground objects while taxiing (trucks, structures, etc.) or caused by inadvertent leaving of runway or taxiiway.	Reduce aircraft operating cost losses caused by Category IIIC visibility conditions. Reduce cost of repair or replacement of aircraft due to damage while taxiing. *

* In both the IALM and ROTA functions, a primary requirement must be the capability to maintain current IFR landing acceptance rates.

4.2 Operational Environment

The operational environment in which an independent airborne hazard warning and avoidance system must function is discussed in the following paragraphs. In particular, the following aspects of the environment are examined.

- Airports and runway characteristics.
- Aircraft characteristics.
- Cockpit operating procedures.

These data will be utilized in assessing the information and performance requirement for the hazard warning and avoidance system.

4.2.1 Airport Characteristics. - Airport characteristics vary widely from one airport to another. Factors such as the number of runways; how they are configured; their length, width and material and the landing aids which are provided, all form a part of the environment for approach and landing operations. They affect the rates at which aircraft can be handled, the weather in which operations may be conducted and the characteristics which should be required of an additional aid such as the IALM function of the hazard avoidance system.

The current airport environment is typified by the route system of a regional carrier which is shown in Table II-17. This particular route system stretches throughout the northeastern region of the United States. The table was constructed by indicating the best approach aid which a given airport has, and also, those runways on which that aid is available. The runways vary in material content but most are 5000 ft or more in length and 150 ft or more in width. ILS systems are available at many of these airports, but in a number of cases they do not furnish approach capability in conditions corresponding to Category I minima. Category II capability is available at only two of the airports. At the other end of the spectrum one finds a 100'-wide runway shorter than 5000 ft in length, with only an ADF approach capability.

The potential place for the IALM function is clear. It would be valuable if it could help in the further expansion of Category II capability. This was the basis of the economic analysis in Section 3 (this Volume). In addition to that potential, there are additional needs to fully expand ILS capability to the minima of Category I and to develop additional capability for the air carrier to land at airports where no ILS exists. This is the situation as it exists today.

TABLE II-17. TYPICAL REGIONAL AIRLINE SYSTEM - RUNWAYS AND LANDING AIDS

TYPICAL REGIONAL AIRLINE SYSTEM .... RUNWAYS & LANDING AIDS ....

CITY	DATE/INFO	Rwy	Length	Width	Material	Aid	Vis	DH	
Albany, N.Y.	9/68	19	6000	150	Asphalt	ILS	3/4	300	
Binghamton N.Y.	10/69	34	6300	150	Asphalt	ILS	3/4	250	
Boston, Mass	10/69	4R	10000	150	Bitum-Concr	ILS	1/2	200	
	9/69	33L	10100	150	Bitum-Concr	ILS	1/2	200	
Bridgeport, Conn.	3/68	6	4700	150	Asphalt Concr	VOR			
Buffalo, N.Y.	6/69	5	8100	150	Concrete	ILS	3/4	300	
	1/69	23				ILS	1/2	200	
Burlington, Vt.	10/68	15	7800	150	Bituminous	ILS	1/2	200	
Cleveland, O.	11/68	5R	9000	150	Concrete	ILS	1/2	200	
	11/68	5L	6200	200	Asphalt	ILS	1/2	200	
	9/69	27R	6000	150	Concrete	ILS	3/4	300	
Detroit, Mich.	8/69	3L	10500	200	Concrete	ILS	1/2	200	CAT II RVR 16 (150')
	8/69	21R				ILS	1/2	200	
	8/69	3R	8500	200	Concrete	ILS	1/2	200	
Elmira-Corning, N.Y.	10/69	24	5600	150	Asph Concr	ILS	1	502	
Erie, Pa.	10/69	6	6000	150	Bituminous	ILS	3/4	250	
Glens Falls, N.Y.	12/68	19	5000	150	Macadam	VOR			
Hartford (Windsor Locks), Conn.	9/69	6	9500	220	Bitum-Concr	ILS	1/2	200	
Islip, N.Y.	8/68	6	6000	150	Asphalt	ILS	3/4	250	
Ithica-Cortland, N.Y.	3/69	14	5800	150	Blacktop	VOR			
Jamestown, N.Y.	8/68	25	5300	100	Bituminous	ILS	3/4	300	
Keene, N.H.	6/68	2	5500	150	Bituminous	VOR			
Lebanon(Wht.Rvr.Jct., Vt.)N.H.	2/68	25	5500	150	Bitum-Concr	VOR			
Manchester, N.H.	9/69	35	7000	150	Bitum-Concr	ILS	1	500	
Massena, N.Y.	1/69	5/23	5000	150	Asphalt	VOR			
Minneapolis, Minn.	4/65	29L	10000	200	Concrete	ILS	3/4	300	
	5/65	4	7250	150	Concrete	ILS	1/2	200	
Montpelier, Vt.	6/68	35	4500	150	Macadam	VOR			
New York, N.Y. (Kennedy)	12/68	4R	8400	150	Concrete	ILS	1/2	200	
	12/68	22L				ILS	1/2	200	
	9/68	31R	10000	150	Concrete	ILS	3/4	300	
(LaGuardia)	9/69	4	7000	150	Asphalt	ILS	3/4	400	
	9/69	22				ILS	1/2	200	
	9/69	13	7000	150	Asphalt	ILS	1	600	
(Newark, N.J.)	9/69	4	7000	200	Asphalt	ILS	1/2	200	
	9/69	22				ILS	1/2	200	
Ogdensburg, N.Y.	5/68	27	5200	150	Bituminous	ADF			
Olean, N.Y.	12/68	22	4700	100	Blacktop	ADF			
Philadelphia, Pa.	6/69	9	9500	150	Bituminous	ILS	1/2	200	
Pittsburgh, Pa.	8/69	27	5500	150	Concrete	ILS	1/2	300	
Plattsburg, N.Y.	7/68	1/10/14	5000	150	Asphalt	VOR			
Poughkeepsie, N.Y.	3/69	24	4000	100	Paved	VOR			
Providence, R.I.	8/68	5R	6500	200	Concrete	ILS	1/2	200	
Rochester, N.Y.	10/69	4	8000	150	Concr & Bit.	ILS	3/4	250	
	10/69	28	5500	150	Bituminous	ILS	1	250	
Rutland, Vt.	1/68	1/19	5000	150	Asphalt	ADF			
Saranac Lake, N.Y.	1/68	5	5000	100	Bituminous	VOR			
Sullivan County, N.Y. (Liberty-Monticello)	8/69	33	6300	150	Asphalt	ADF			
Syracuse, N.Y.	9/69	28	9000	150	Asphalt	ILS	1/2	200	
Utica-Rome, N.Y.	11/68	33	6000	150	Macadam	ILS	1/2	200	
Washington (National), D.C.	9/68	36	6900	200	Asphalt	ILS	1/2	200	CAT II RVR 16 (150')
Watertown, N.Y.	10/69	6	5000	150	Asphalt	VOR			
White Plains, N.Y.	10/69	16	6500	150	Concr & Blacktop	ILS	1/2	200	
Worcester, Mass.	8/69	11	7000	150	Bitum. Concr.	ILS	1	360	

- Airports

Airport characteristics can be expected to change in the future due to increased traffic and the introduction of new types of aircraft. These factors will introduce special problems when designing a new multiple sensor hazard warning system. In particular, the characteristics which will change are:

- More parallel runways will be introduced.
- Special purpose runways and operating areas will be provided for VTOL and STOL aircraft, including helicopters.

  High speed turnoffs fur use at speeds of up to 60 knots will probably be introduced.
- There will be an increase in the simultaneous use of runway facilities.

The problems resulting from these expected changes are:

- The runway identification problem will become more difficult.
- Lateral and vertical guidance accuracy will need improvement.
- The introduction of high speed turnoffs will require more sophisticated roll out and taxi guidance.

- Runway Characteristics

Runway construction practices will continue to be much as they are at present. The combined use of a variety of surface materials is foreseen. Buildup of adjacent hangers, terminals, air-freight and other facilities will continue. There will almost certainly be an increase in the number of multiple land surface traffic arteries which will complicate identification of runways from extreme ranges. In addition to the conglomerate of airfield buildings and surface arteries, the system must be capable of distinguishing among single, crossed multiple, parallel adjacent, parallel staggered, uncrossed multiple and special purpose runways. A problem in some areas (Denver for example) is the location of two airports within two miles of one another.

Runway dimensions can vary as follows:

- Width - 150' to 300'
- Length - 5000' to 15000'

ICAO specified a minimum width of 150 ft which should be used as a design criterion.

Approach paths to the runway are, in general, over terrain which is not level. Ref. (16) specifies the approach terrain model shown in Figure II-1 which should be considered in design of the sensor system.

Other factors in need of definition and for which little data is available relate to typical obstructions in the vicinity of approach trajectories. It is safe to assume that obstructions with heights of up to 1000' can be located on the approach path at the extreme ranges (10 miles). Other obstacles in the form of high ground displaced laterally from the final approach path (from 5 miles in) exist. Approaches at Denver and San Francisco illustrate this problem. The system must locate these obstructions and provide warning data if the threat of impact exists.

4.2.2 Aircraft Characteristics. - The system must be designed ultimately to be used (perhaps in modular form) in a variety of aircraft. The definition given in Ref.(17). for four of these classes are given below:

Class I - Final approach speeds from 60-100 KIAS with descent approach angles from 2-9 degrees.

Class II - Final approach speeds from 101-135 KIAS Approach angles from 2-9 degrees.

Class III - Final approach speed from 136-165 knots Descent angle from 2-6 degrees.

Class IV - Final approach speed from 165 knots upward.

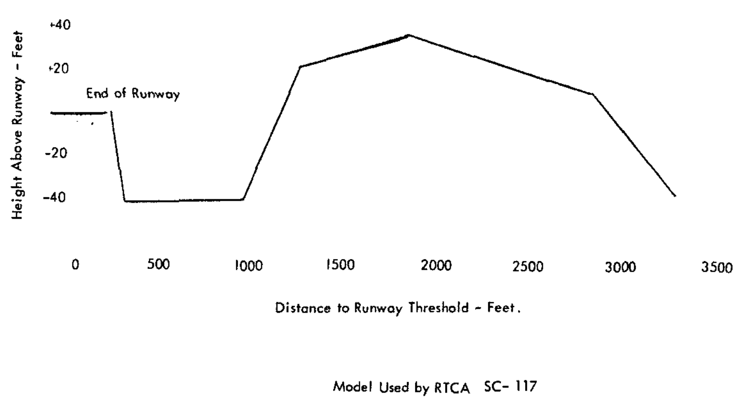

Figure II-1. Standard Elevation Terrain

The study will concentrate on Class III aircraft. Figure II-2 shows the landing approach speeds for a representative set of commercial aircraft.

4.2.3 Operating Procedures used with Present Systems. - In order to provide first hand information concerning current operational ILS techniques, a number of ILS approaches were flown with United Air Lines, with PNSI personnel acting as flight deck observers. Approaches were flown at Chicago (ORD), Reno, San Francisco, Los Angeles and Detroit. The several flight observations were correlated and used to construct an operational scenario and perform the basis for a functional analysis. The particular purpose of this analysis was to identify in general terms the crew functions, workload, and information requirements. For the purpose of this study, an instrument approach to Runway 14R at Chicago's O'Hare Airport was used to construct the model.

- Aircraft Equipment

The aircraft contains the following navigation and related approach guidance equipment.

- Twin VHF Comm/Nav Sets (includes VOR/DME, ILS and communications equipment).

  Twin 4096 ATC Transponders.

  Twin Collins FD109A Flight Director Computers with Attitude Director and Horizontal Situation Displays.

  Autopilot/Flight Director Computer Coupling which can be engaged one channel at a time.

- Approach and Landing Pattern

The operational sequence begins with the aircraft in a holding pattern at Lakewood intersection. The racetrack is executed on an inbound heading of 158°. The aircraft is stepped down in the stack at five minute intervals until it reaches 8,000 ft upon which a radar vectored approach to the ILS is initiated by ATC. The aircraft is simultaneously caused to descendto 4,000 ft and later to 2,200 ft, the altitude required inbound at the outer marker. Normal ATC transponder identification methods are used.

During holding, the aircraft is flown at 230 knots IAS. Final descents are executed using 1500 fpm. During the inbound vectoring, the aircraft is slowed to gear speed and initial approach descent checks are executed. After reaching 2200 ft the prelanding check is completed.

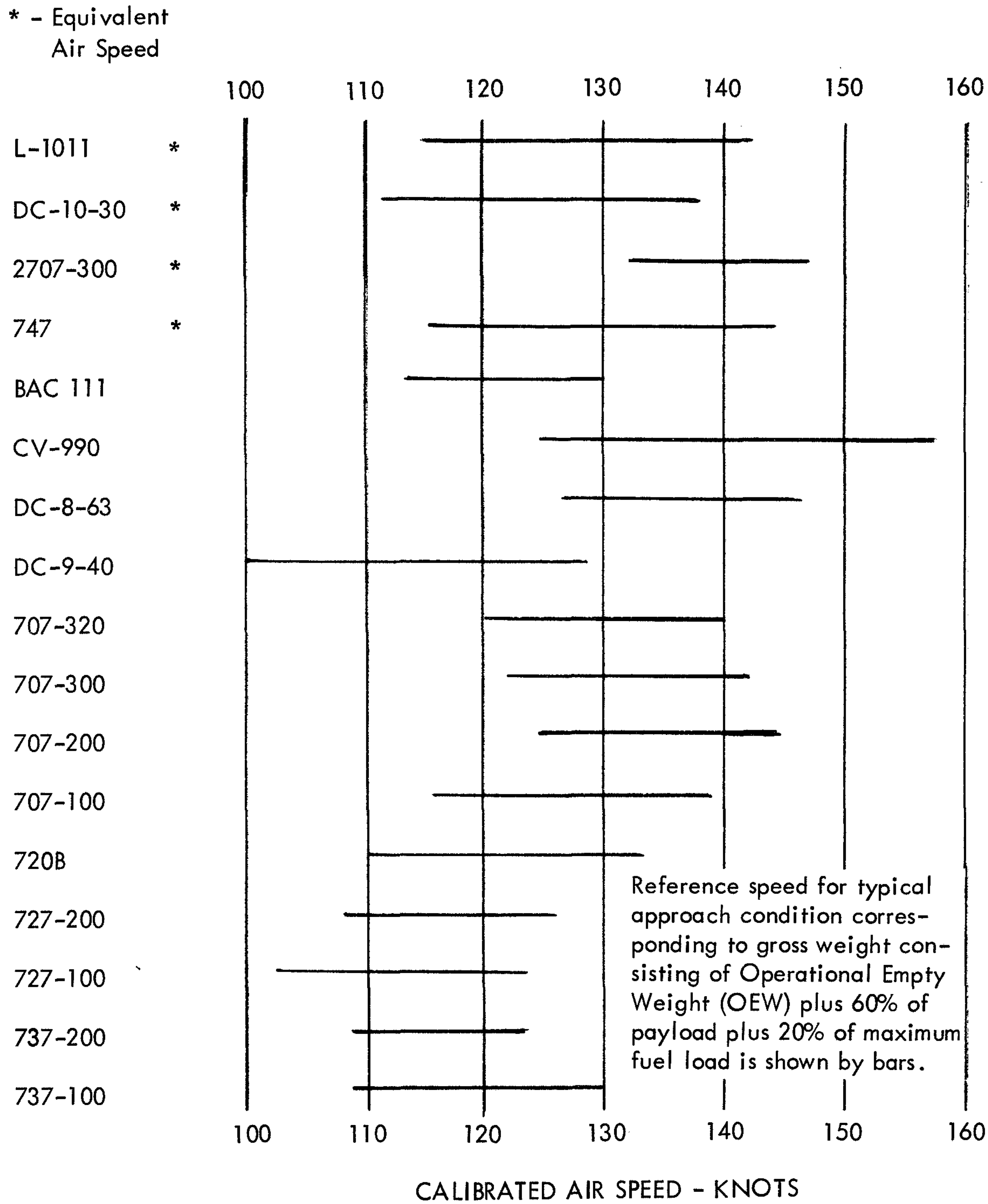

Figure II-2 Reference Speeds for Landing Weights from (OEW + Reserves) to Maximum Landing Weight

The VOR/DME at Northbrook and that at Naperville are used as references during holding. Upon initiating approach, both ILS sets are tuned to IORD and the crew cross checks FD109 indications. An ILS to Runway 14R is executed in coupled mode. If upon reaching minima the aircraft is still in fog, a missed approach sequence is executed. VOR #1 is tuned to DPA (DuPage VOR) for guidance to that point and missed approach guidance is followed.

The approach profiles are shown in Figures II-3 and II-4 together with aircraft speed and other configuration data.

- Timing Sequence

The holding pattern is assumed to start at 31,000 ft. Three steps down the stack are required. Elapsed time in the hold is 15 minutes. Inbound Lakewood to LOM requires approximately 6 minutes. ILS approach from LOM to Missed Approach requires 2.3 minutes.

The total time for approach and landing sequence is approximately 9 minutes. Total time for all equipment set up, landing checks, ATC communications, etc. is 24 minutes. If the holding pattern is not executed, this total time will be significantly reduced.

It will be observed that the flight operation can be divided into four segments. They are:

- Holding.
- Initial descent to 8,000 ft and descent to initial ILS inbound altitude.
- Instrument Approach.
- Missed Approach segment.

4.3 General System Requirements

4.3.1 Requirements for an Independent Approach and Landing Monitor (IALM). - In order that a pilot be able to safely land an aircraft under conditions of poor visibility, the information he normally obtains by direct visual reference to the ground must be replaced with information supplied from some other source. In general terms, during the actual landing phase, the IALM should be able to center the runway in the field of view of a display at a scale suitable to allow the pilot to positively confirm that what he is seeing is exactly the airfield and runway he wants. Ideally, the system should or could track the desired touch-down point and concurrently show an extrapolation of the existing velocity vector, or

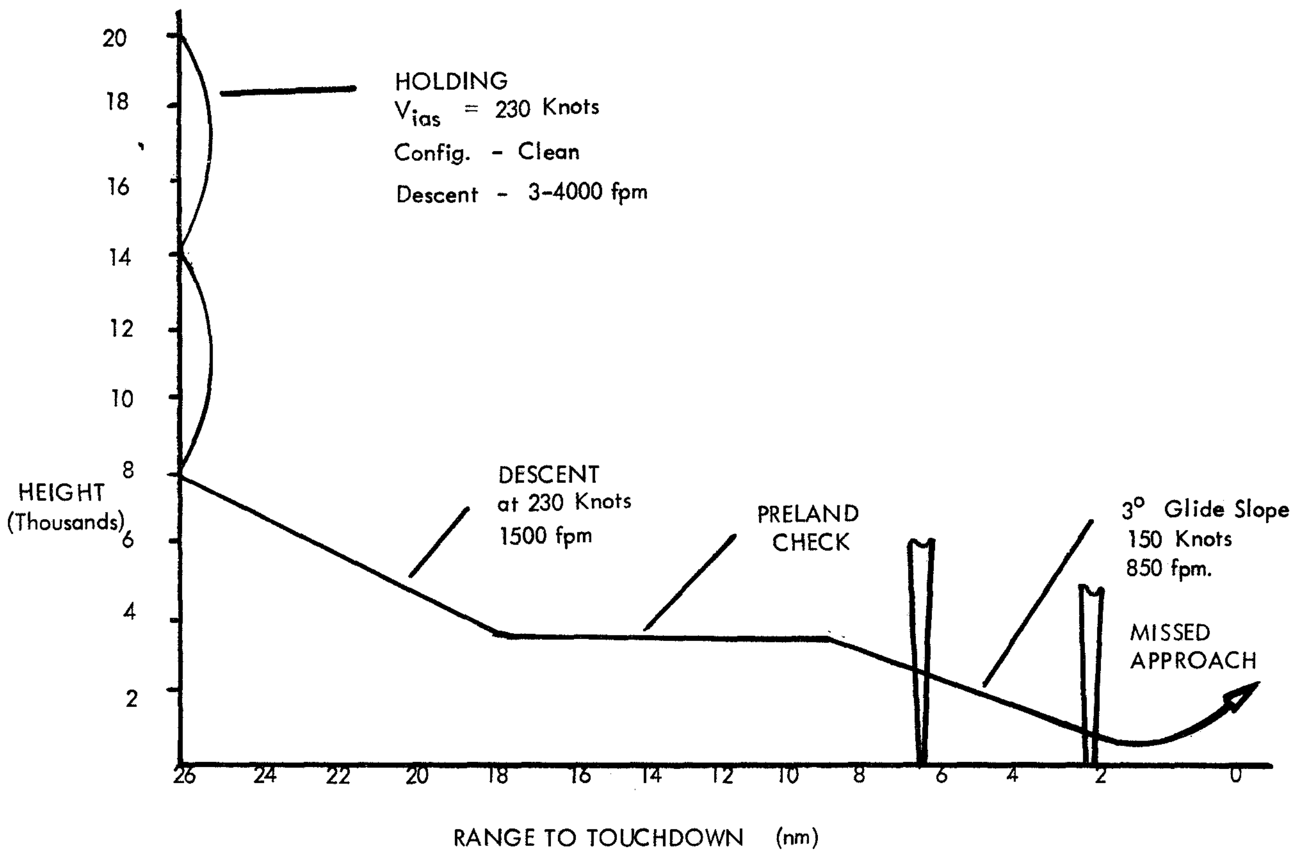

Figure II-3. Vertical Profile

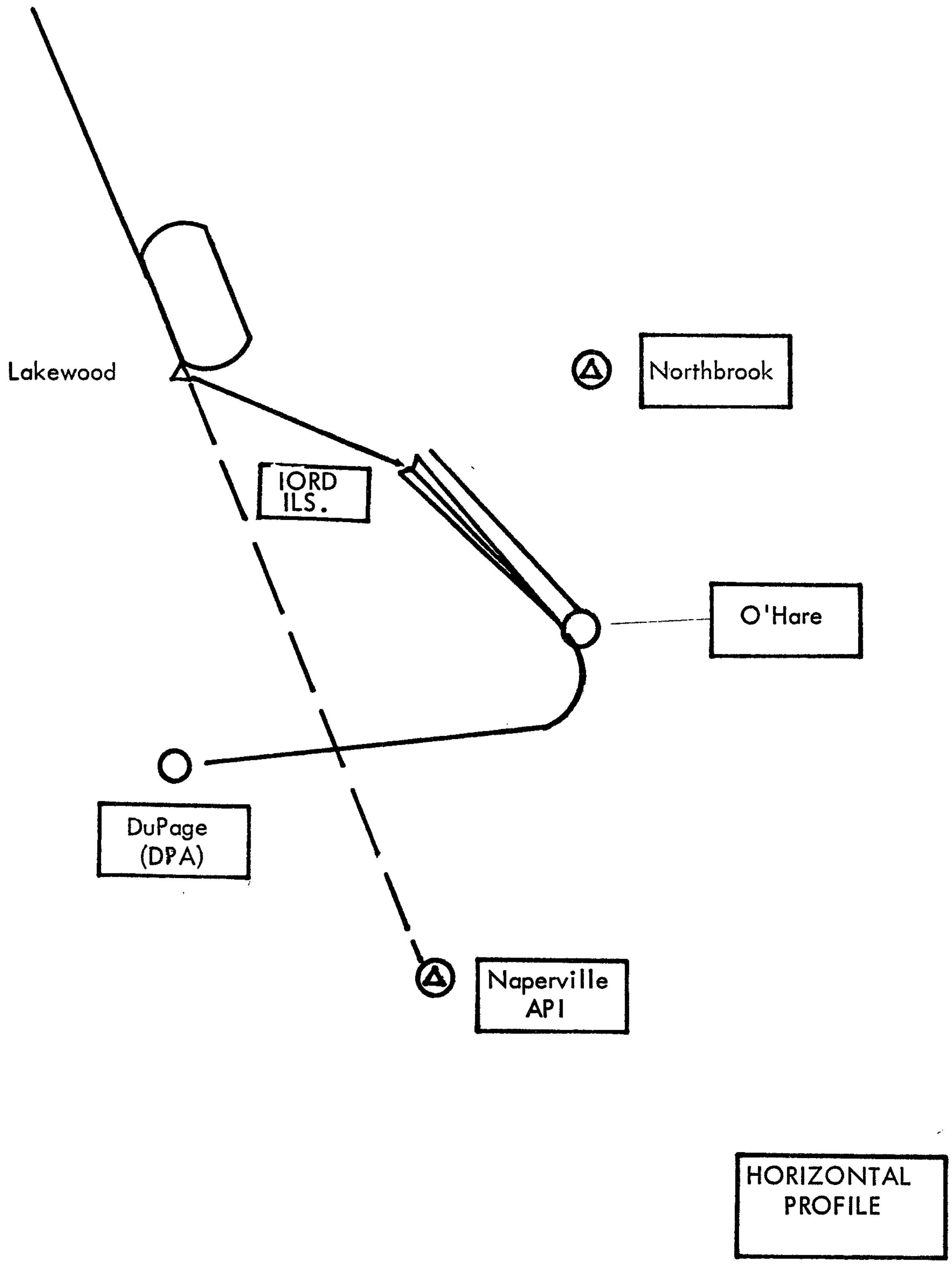

Figure II-4. Horizontal Profile

conversely give the position and attitude of the aircraft with respect to the correct approach path. Another desirable feature of a possible sensor system is the ability to detect other aircraft in the vicinity of the approach path or on the runway.

Possible sensors applicable to this function can be classified into the following two broad types depending upon the type of display they have.

- Sensors providing a pictorial display which is a direct or symbolic representation of what the pilot would see if there were no visibility limitations.
- Sensors providing a director type display showing the distances from the correct approach path in two planes and the range to touchdown.

A pictorial display can be obtained from the following sensor types:

- TV camera with its electron optics chosen to maximize its range in poor visibility conditions.
- Forward looking IR Scanning equipment.
- Ground mapping radar, possibly with reflectors or transponder beacons on the ground to enhance the runway.
- At some later date, the selection of a head-up vs. head-down display concept must be made. At this point in the system development, no conclusions can be drawn concerning relative benefits of either concept.

For a director type display a radar or other suitable sensor is required which measures the range and angular position of a reflector or transponder beacon placed at, or near, the touchdown point.

The suitability of the various sensor types depends upon their performance in poor visibility conditions. Section 6 contains an in-depth analysis of the candidate sensors over a wide range of operating conditions.

Another factor that affects the choice and design of a sensor is the overall system requirements since the sensor is part of a system that includes the pilot and the aircraft.

4.3.2 Requirements for a Roll-Out and Taxi Aid. - After the pilot has landed, he has to roll out, locate the runway exit, and follow the taxiway to the ramp. In poor visibility conditions on the ground, the taxi speed has to be reduced, and this increases the time it takes for the aircraft to clear the runway. This, in turn, reduces the maximum landing rate at the airport and, at busy airports, aggravates the delays due to poor visibility.

This delay can be reduced by providing the aircraft with a sensor that indicates the center line of the runway, the exit points and the center line of the taxiway leading to the ramp. The greater the distance out in front of the aircraft the sensor can "see", the higher is the safe taxi speed. Another desirable feature of this sensor is the ability to detect obstacles in the path of the aircraft such as airport vehicles and other aircraft. This sensor is called a Roll-Out and Taxi Aid (ROTA).

Possible sensor types are, as for the IALM:

- TV camera with its electro-optics chosen to maximize its range in poor visibility.
- Forward looking IR scanning equipment.
- Ground mapping radar, possibly with reflectors on the ground to enhance the route to be followed.

The performance of possible ROTA sensors is given in Section 6.

4.3.3 Requirements for a High Ground Avoidance Aid. - The pilot must be provided with information which warns him of any high-ground threat or other obstruction to flight in time to allow him to take corrective action. It may be claimed that with the navigation aids now fitted to commercial aircraft, collision with high ground should not occur, either enroute or during the approach and landing phase. The records show that this is not the case. In fact, the number of fatalities from this cause is far greater than those from any other type of accident. It is interesting to note that the majority of these accidents occur during the final approach phase in conditions of poor visibility.

Accidents of this type may be prevented by fitting the aircraft with a sensor which detects ground in the path of the aircraft in sufficient time for the pilot to carry out an avoidance maneuver. Such a sensor is known as a High Ground Avoidance equipment (HGA).

The HGA sensor is typically a radar equipment which measures the range and angular position of the terrain with respect to the flight vector. There are two basic types:

Vertical Profile Type. This sensor determines the profile of the ground along the flight vector by vertical scanning or by interferometer techniques. When high ground intrudes inside a predetermined profile with respect to this flight vector, a warning is given and the pilot climbs to prevent a collision. A turn under these circumstances could

could be dangerous since there is no indication given about the height of the terrain on either side of the flight vector. In its simplest form the sensor measures the range to the terrain along a line which is at a predetermined angle below the flight vector. A warning is given to the pilot when the range is less than a certain value.

Terrain Clearance Plane Type. This sensor scans a horizontal sector in front of the aircraft and terrain above a plane a predetermined distance below the flight vector as shown on a horizontal situation display. A warning is given when high ground along the flight vector could be a hazard to the aircraft. The pilot can decide from the information shown on the display whether to climb or turn in order to get out of danger.

The sensor should be capable of detecting high ground at the maximum required range in all possible weather conditions. If the attenuation in heavy rainfall makes it impossible to detect ground at the maximum required range, the signal back-scattered from the rain should be above the warning threshold. In this circumstance the aircraft would fly above the rain storm. The performance in rain and fog is affected by the wave-length of the radar, and this is discussed in Section 6.

4.4 System Information Requirements

Information requirements for approach and landing, missed approach and terrain avoidance are described below. These requirements are discussed in terms of the services to be provided and the resulting system data requirements. These data are presented in the context of an IALM system which is generating complete guidance data. Several lesser degrees of sophistication are also possible, which would naturally result in less stringent data requirements.

4.4.1 Lateral Guidance - Approach and Landing. - The basic lateral guidance requirements are:

- Definition of the required approach ground track.
- Definition of linear and angular displacement from required ground track.
- Definition of distance to go to touchdown.
- Roll Command.

The information requirements in terms of current aircraft situation should be available in a sector with an angular dimension of up to 45° from the runway centerline. (Lateral guidance should be available in a sector up to ± 10° and within a range of 10 nautical miles). It is necessary to provide the data shown during approach and up to the ILS reference datum as discussed in Section 5.

The system must also contain Runway Designation (L,R), Runway Length, Runway End Location in XY or Latitude/Longitude Coordinates, and Runway Width.

4.4.2 Vertical Guidance - Approach and Landing. - The vertical guidance information requirements comprise:

- Required Approach Angle and flare pattern (if any).
- Linear and Angular displacement from the required approach path and the rates of departure.
- Definition of required descent rate.
- Runway Elevation.
- Marker Locations.

In addition to these basic data, the system must generate pitch command signals to enable pilot or autopilot control. The pitch command data will be based on displacement and displacement rate (angular or linear from the required glide slope).

4.4.3 Missed Approach Guidance. - Vertical and lateral services must be provided during the missed approach. Of these, vertical guidance is mandatory. The data requirements are:

- Missed approach profile.
- Pitch Command data to missed approach height.
- Obstacle data (height and lateral extent and location).

Other terrain and obstacle avoidance parameters are defined in subsequent paragraphs.

4.4.4 Roll-Out and Taxi Service. - Roll out services should be sufficient to interface with a taxi system if Cat. III operation is feasible. Full taxi services with a self-contained system appear to be difficult to provide since:

Airport runway and taxi patterns are not standardized and therefore to provide guidance with respect to them, using range and azimuth data, would require the storage of a large number of random track coordinates and directions.

- Self-contained sensors in the cluttered airport area will probably not be useful.

Accordingly, it is reasonable as an initial assumption to provide turn off cues after touchdown and obstacle avoidance. Turn off cues can be provided if the on-board sensor measures range from the stop end of the runway.

Requirements are:

- A/C position with respect to runway end point and runway periphery.
- Turn off position with respect to runway end point.
- Turn off track with respect to runway.

4.4.5 Terrain and Obstacle Avoidance Information Requirements. - Terrain and obstacle avoidance data requirements are:

- Range to obstacle or terrain hazard.
- Height of hazard (relative to a/c flight vector).
- Minimum safe altitude above terrain.
- Pitch command to achieve desired clearance.

Aircraft parameters are Configuration, True Airspeed, Placard Limit data (Roll & Pitch Angle limits and maximum acceleration data) and Angle of Attack. Lateral dimensions of the hazard may be provided if turn avoidance is considered. Active pilot participation in the decision process is implicit in such an approach.

4.5 System Performance Requirements

The system performance requirements to acheive both terrain avoidance and Cat. III landing operation are defined below. The pertinent information requirements previously defined are analyzed in detail. The general approach is to define range of variation and subsequently to define accuracies. Data rates are defined on the basis of accuracy and system dynamic requirements.

4.5.1 Range Performance. - A preliminary estimate of the radar detection ranges required for high ground avoidance was obtained by considering aircraft maneuver limits, system time lags and lateral obstacle dimensions. Two cases were considered - obstacle avoidance using a turn maneuver and a pitch maneuver.

The required detection range is made up of two elements: R_d, the minimum range assuming instantaneous aircraft response and R_i, the range increment attributable to system, pilot and aircraft response lags. In the case of a turn maneuver, the value of minimum range is dependent upon the aircraft velocity, permissible load factor during the maneuver, and the desired obstacle clearance or miss distance. The required detection range when using a pitch maneuver is dependent upon the aircraft turn speed, the available climb rate, the vertical extent of the obstacle and the miss distance. Nominal load factors of 1.15 for turn maneuvers and 2.0 for pitch maneuvers were used in this analysis.

The response time lag consists of the three elements of system time lag, aircraft response, and pilot response. System time lag is related to sensor scan rate and the number of detections required prior to determination that an obstacle is present. A typical value of one second was used for this factor. Aircraft response time lag is the time between control application and aircraft response. In the turn case for a large commercial transport, this time lag is typically 1.5 to 2 seconds for establishing a 30° bank angle. For the pitch up case, the response time lag is a function of the time required to establish a flight path angle change and this (assuming no power limitation) is defined by pitch rate. For a load factor of 2, the values of pitch rate are 7.25°/sec at 300 knots and 4.36°/sec at 500 knots. Engine response lag also affects this parameter but it is of the same order of magnitude. Pilot response time is the most unpredictable parameter since it can vary from a minimum of one second to a practical maximum of 15 seconds. This has a substantial effect on detection range requirements. From an analysis of these conditions, the practical design point appears to be pitch avoidance of a 2000' obstacle at 250 knots with a total time lag (τt) of 8 seconds. The minimum detection range requirement then is approximately 30,000' or 5.0 nautical miles. A detection range of somewhat higher order (10 nm) would be desirable.

If a detection range of 5.0 nm is achieved, then this is adequate for worst case turn avoidance at 300 knots ($\tau t = 8$) for an obstacle dimension of 8000' laterally and will allow avoidance of a 3000' obstacle at 500 knots (worst case). Pitch avoidance of a 1300' obstacle at 180 knots is also possible (worst case). With time lags of 8 seconds, obstacles of 6000' can be avoided with turn avoidance at 500 knots and obstacles 1500' high can be avoided with pitch maneuver at 180 knots.

The approach and land case requires detection capability of a higher order. More precisely, it is required that the aircrew be able to establish the system in a normal tracking and monitoring function at least one minute prior to reaching the outer marker whose range is typically 4 nm from touchdown. The time required to execute these functions is estimated to be two minutes, which for a Class III aircraft results in a detection range requirement of 10 nautical miles. If the detection range achievable is much less than 10 nm, then this implies pilot monitoring of raw sensor data during the final two minutes of the approach which is considered impractical in view of the work loading at that time.

4.5.2 Range Accuracy. - Range accuracy for the terrain avoidance case is set by the magnitude of the safety factor desired. The system can be configured to provide initial warnings at large ranges, hence a low accuracy can be tolerated. (150' will be assumed).

Range accuracy for the landing approach will be established in subsequent analysis.

Height accuracy is set by the clearance height which is to be maintained, which, in turn, determines elevation angle accuracy. A clearance height accuracy of 300 ft at a detection range of 4.8 nm implies an elevation angle accuracy of 0.6°.

4.5.3 Angular Coverage. - The detection range requirements, together with lateral or vertical obstacle dimension, were used to establish the curves shown in Figure II-5. These curves are plots of lateral angle vs. obstacle dimension. The angle (ψ) is determined by assuming that the system must scan an angle whose magnitude is defined by the obstacle dimension and detection range. (The minimum detection range, R_d, was used). From these curves it is seen that if a combined obstacle dimension of 8000' is the maximum, then a lateral angle of $\pm 26^{\circ}$ is adequate. An angular coverage of $\pm 30^{\circ}$ would allow scanning $\pm$ 15,000' laterally when the required minimum detection range is 25,350'.* The vertical coverage required is obtained using the same relationship and adding to this the angle of attack (approximately 10°). This results in vertical coverage requirement of -15°. Coverage in the positive segment is indeterminate but need not be more than $+5^{\circ}$.** (This does not imply that a radar beam angle of $\pm 30^{\circ}$ is required. It implies that data must be provided within these angular limits).

4.5.4 Approach Flight Path. - The approach flight path coverage as specified by Ref. 17, is shown in Figure II-6 (a) & (b).. Class III aircraft will be making use of the 40° approach sector and if segmented linear approach paths are used in horizontal plane, then coverage of $\pm 30^{\circ}$ allows seeing the whole runway width to within 130' of touchdown.

Vertical sector coverage of + 5 and - 15 degrees is required for glide paths of 3°, which is the maximum for Class III aircraft.

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* This would also allow look ahead during turns.

** A stabilized antenna system or a mathematical method for roll angle correction must be provided.

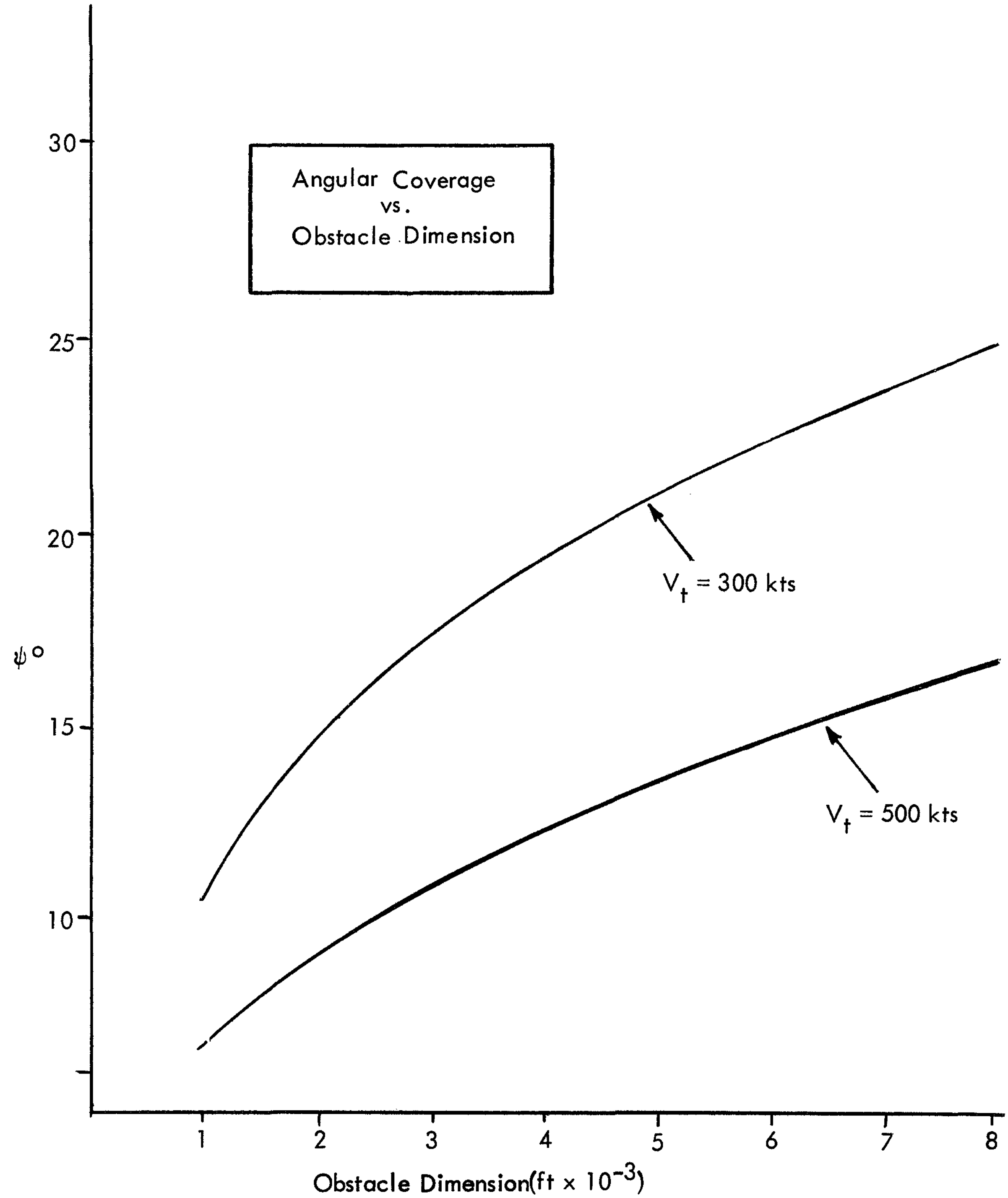
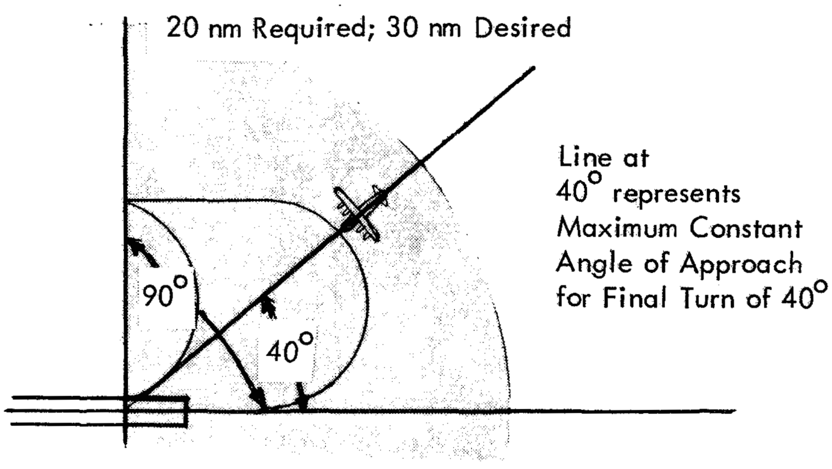
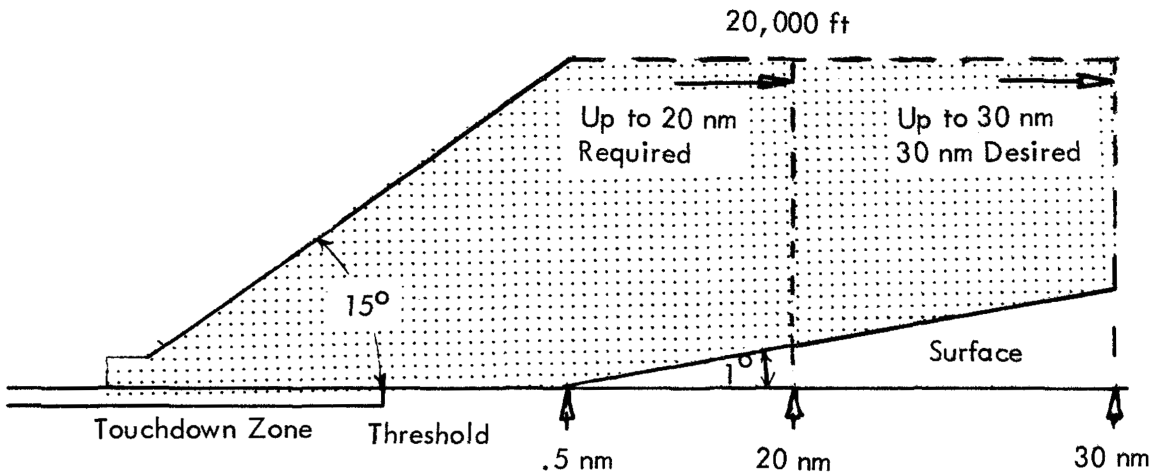


Figure II-5. Angular Coverage vs. Obstacle Dimension



(a) Plan View



(b) Side View

Figure II-6. Approach Flight Path - Plan View and Side View

4.5.5 Accuracy Requirements - Approach and Landing. - The accuracy requirements for glide slope and localizer guidance are discussed below:

- Glide Slope

Guidance accuracy in the vertical plane is determined by the required touchdown accuracy. The geometry of present ILS systems, the performance characteristics of Class III aircraft and typical runway lengths indicate that a touchdown dispersion of $\pm$ 750 feet is tolerable (I.E., in the worst case with a 3^{o} glide slope and nominal height at threshold of 50 feet, 1500' of runway can be wasted). The sources of inaccuracy in touchdown are:

- Height Error at Threshold.
- Speed Error at Threshold.

Speed error at threshold will not be considered since, at present, this function is not included in the system. Height error at threshold results from errors in sensing height and in piloting the aircraft. It will be assumed that a piloting error of 12-15 feet occurs. The total allowable error in height contributed by the system is therefore of the order of 10 ft for the nominal conditions considered. It is not considered beneficial to reduce this error significantly in the presence of a piloting error of 12-15 feet. The method of determination of the difference between actual height and required height is to measure slant range and actual height, or to derive height from slant range and radar look angle.

The height above the runway can be obtained from the equation:

$$h = R_s \sin \gamma_l \approx R_s \gamma_l ; \text{ for small } \gamma_l$$

where R_s is the radar slant range

and γ_l is the depression angle of the radar below local horizontal.

Taking differentials:

$$dh = dR_s \gamma_l + R_s d\gamma_l$$

and dividing:

$$\frac{dh}{h} = \frac{dR_s}{R_s} + \frac{d\gamma_l}{\gamma_l}$$

The last equation shows us that the percentage error in height is equal to the sum of the percentage errors in the range and the angle. Applying statistical methods, we can proceed as follows for the conditions:

R_s = 1500 ft

h = 50 ft

γ_I = 3^o

and dh = 10 ft, 3σ value.

$\frac{dh}{h} = \frac{10}{50} = 0.2$ or 20% error.

Then we can allocate 14% error to each of the range and angular errors (3σ). Therefore, for 1500' range, the allowable error is 210 ft and for the 3^o angle, the allowable error is 0.42^o.

At this point in the analysis, the sensor is assumed to be one of three major error sources. Therefore, from a statistical standpoint, the sensor can be attributed with maximum errors which are 60% of the total system error. On this basis, the sensor errors are estimated to be 130 ft in range and 0.25^o in elevation angle.

- Lateral Guidance

The accuracy requirements in the horizontal plane are discussed below. The factors which introduce errors in achieving a given touchdown accuracy are:

- Landing System Accuracy.
- Aircraft Crab Angle.
- Piloting Error.

Aircraft crab angle occurs as a consequence of the necessity to compensate for cross winds during the approach. This angle may reach a magnitude of 10^o with a resultant wheel displacement of 13' for a typical transport (Ref. 18). Piloting error according to FAA AC-120-20 may reach a value of 97' (3σ). A sidestep maneuver may be used to reduce the piloting error. The magnitude of the correction achievable is 20 ft. A total allowable system error of 40 ft will be used. The displacement to left or right of centerline (ΔL) is given by the expression:

$$\Delta L = R_s \sin \Delta\psi \approx R_s \Delta\psi$$

where R_s is the slant range and the angle $\Delta\psi$ is the angular difference between the runway heading and the location of the aircraft.

In a manner which is completely analogous to the analysis of the preceding section.

$$\frac{d\,(\Delta\, L)}{\Delta L} = \frac{dR_s}{R_s} + \frac{d(\Delta\, \psi\,)}{\Delta\, \psi}$$

The statistical sum of piloting and system errors in 105 ft (3σ). Using this value for ΔL and 40 ft for the value of d(Δ L), we obtain a percentage error of 38%. This can be budgeted, by statistical means, to 27% errors in each of range and azimuth angle. For a range of 1500 ft and a maximum azimuth error of 3°, the $3\,\sigma$ errors in range and azimuth are 405 ft and 0.81 degrees.

Estimating the magnitude of sensor errors to be 60% of the overall system errors, the sensor errors are 240 ft in range and 0.5° in azimuth.

- Data Rates

The data rates are determined by examination of accuracy requirements and the dynamics of the case being considered. They are discussed below for glide slope and localizer cases. The frequency at which a solution for a particular quantity must be obtained is given by the relationships:

$$\Delta t = \frac{\delta}{R}$$

δ - is required accuracy

R - rate of change of variable

This relationship must be altered somewhat to determine sampling rate if a significant processing delay occurs. The processing delay can, in general, be made insignificant and will, therefore, be ignored in this case.

- Glide Slope Data Rates - The parameters being computed are:

  Height Error

  Pitch Angle Error

The height error and pitch error, as we have seen are related. The accuracy requirements in each case are:

Height Error – 10 feet

Glide Path Angle Error – 0.4° nominal

The sampling rate is then given by the rate of change of height and the rate of change of pitch angle.

- Height Rates

$\gamma = 2^{\circ} \quad \frac{dh}{dt} = 9.4$ fps

for V_T = 160 knots

$\gamma = 3^{\circ} \quad \frac{dh}{dt} = 14.1$ fps

and resultant solution rates for the height channel are:

$\gamma = 2^{\circ}$ - 1 solution every 1.1 seconds

$\gamma = 3^{\circ}$ - 1 solution every 0.71 seconds

based on the necessity of keeping the height error less than 10 feet (solution rate = $\frac{10'}{\text{height rate}}$)

- Lateral Data Rates

Lateral solution rates are set by lateral displacement accuracy, and the rate of change of this parameter.

Lateral displacement rate is set by the velocity and the angle at which the localizer path is being intercepted. This angle can approach 20°.

Therefore, the lateral rate $= 268 \times \text{Sin } 20^{\circ}$

$= 91$ fps

Lateral Accuracy Requirement is 40'

Then, solution rate required is 2.3 per second.

4.6 Summary

4.6.1 Basic System Functions. - The basic functions to be performed by the system are:

Terrain Warning (High Ground Avoidance)

Generation of Approach and Landing and Missed Approach Guidance Data.

- Roll-Out and Taxi Aid.

In order to perform these tasks the system must process sensor and command data inputs to provide relevant usable outputs to the aircrew. The system must, there, provide both guidance and warning data in each operating mode.* In addition, the system computer can assist the aircrew in sensor selection and control and it can also provide data outputs which will enhance runway acquisition.

- Operating Modes.

The analysis of the operation of the aircraft has shown that at least three major flight operating modes are required in addition to the ground function of roll-out and taxi aid. They are:

- Terrain Warning.
- Approach Mode.
- Missed Approach Mode.

4.6.2 Equipment Constraints. - Each of the three primary system functions, IALM, ROTA, and HGA requires sensors that are essentially forward looking. This dictates an installation somewhere in the nose section of the aircraft, and in the case of a radar sensor, also requires an antenna which must fit within the physical cross section dimensions pertinent to that area of the fuselage. As in any aircraft installation, size and weight are always at a minimum, but there is no particular absolute restriction on either of these parameters for this application.

* Note that the system configuration descriptions which follow in Section 7 assume that the system is generating command data. The system configurations which will be defined will allow the use of the system in a mode which provides situation "monitoring" only if that is desired.

Considering the continuing requirement and excellent performance of currently available weather radar hardware, this equipment function must be retained. The relatively low cost of components and their proven reliability lend additional emphasis to this goal. Considering the variety of functions and requirements for the overall hazard warning and avoidance system, if each additional function required a separate set of hardware elements, then an extremely demanding installation and cost problem would arise. In the case of the majority of commercial airlines, ARINC installation and interconnection standards are used to specify avionic equipment characteristics. Under these conditions, the overall size and weight of a federated system concept (separate units for separate functions) forces serious consideration of a single multi-function system, perhaps sharing most, if not all, of the basic hardware elements. Further effort therefore should be spent, both in this study, and possibly in future programs, in establishing the feasibility of combining the weather radar function with the IALM, ROTA, and HGA functions into one integrated set of hardware.

The situation regarding the display is even more demanding as regards physical size. Independent of the additional functional capability it can provide, cockpit panel space is at a premium in every aircraft ever built. Careful consideration must be given to the effective combination of software and hardware design techniques for the purpose of providing a multi-sensor multi-function display that occupies the smallest practical, but useful panel space. If possible, some functions of existing or planned instruments should be combined into the IALM, etc. display, preferably eliminating some existing displays.

As will be brought out in considerable detail elsewhere in this report, the economics of any system are of extreme importance, both from a reduction in aircraft operating costs and from the point of view of initial and continued acquisition costs. It therefore is mandatory that minimization of overall system costs be considered in any economic benefit study. This is particularly true for those system configurations aimed at the retrofit market.

Obviously, from the standpoint of reliability, certain well understood system design practices must be followed. A failure in any element of the IALM, ROTA, and HGA systems must not adversely affect safe operation of the primary aircraft systems. At the same time, since the IALM is designed to function as a monitor of the ILS equipment, the IALM equipment must have a reliability at least as good as the equipment being monitored. Provision for system self-test to be performed and displayed must also be an integral part of any proposed set of airborne equipments.

4.6.3 Operational Constraints. - Any system whose functions are as integral to flight safety as are the IALM and HGA must provide operationally significant outputs and/or displays which can be readily utilized by the pilot. Any proposed sensor/processing/ display system must provide instant hazard recognition with no required interpretation, particularly considering some of the real-time tasks already being performed by the crew during a low visibility landing situation. The sensor/processing/display concept must not require specialized training or proficiencies such as radar scope interpretation in order to be useful. If possible, command information should be generated rather than situation data only.

Pilot workload is another serious concern to the system designer. System functions must be organized in such a fashion as to even out the pilot workload peaks and valleys. Extensive operation action, intervention and interpretation are to be avoided as a design criterion.

As mentioned previously, not only must the equipment meet stringent reliability requirements both inherently and through careful system design; it also must contain the capability of detection of misleading signals or information. This self-test ability must include real-time automation annunciation of the existence of any faults within the entire system logical chain. Particularly in the case of the HGA system, it is also important to reduce to a minimum the number of false alarms (or false warnings) related to high ground. These false alarms may arise from either radar scintillations or receiver noise, and although they are not directly hazardous, frequent unnecessary avoidance maneuvers would not be operationally acceptable. Obviously, the system must also be configured so as not to miss or ignore any real or actual hazards.

4.6.4 System Characteristics. - The following Table (II-18) is included as a summary of some of the pertinent characteristics and/or requirements which have been developed in this section. Naturally these characteristics are not necessarily firm, but they do reflect the general character of the performance required of candidate systems.

TABLE II-18. DESIRED SYSTEM CHARACTERISTICS

Glide Slope Angle	2° - 10° *
Maximum Range Requirement	
High Ground Avoidance	5-10 miles
Approach and Landing Monitor	7-10 miles
Azimuth Coverage	$\pm 30^\circ$
Azimuth Error	0.8°
Elevation Coverage	$+ 5^\circ$ $- 15^\circ$
Elevation Error	0.4°
Offset Error at Threshold	$\pm$ 40'
Scan Rate	
Azimuth	2.3 per second
Elevation	1.4 per second
Cross Wind Component	22-28 knots (10° crab angle - Class III aircraft)
Primary System Goal	Independent source of landing approach guidance data. Secondary system goal - high ground avoidance.

* 10° glide slope is an estimate of the requirement for STOL approach procedure requirements.

5.0 APPROACH AND LANDING AIDS

5.1 Introduction

The purpose of this section is to examine approach and landing systems used today, and the relationship of these systems to the need for aircraft operations in low-visibility conditions.

This will be done by:

(1) Explaining the operation of the system as an approach and landing aid.

(2) Establishing the operational limits of the system and why these limits exist.

(3) Pointing out inherent difficulties in modifying the system to achieve low-visibility capability.

Aircraft landings may take place under two basic flight regulations; visual flight rules (VFR) when meteorological ceiling exceeds 1000 feet and instrument flight rules (IFR) when ceiling is below 1000 ft. The lower limits for IFR landings are established by Federal Regulations and based upon such factors as aircraft and ground equipment capabilities, runway lengths and lighting and surrounding terrain.

Table II-19 gives the meteorological definition and decision heights associated with categories of landing limits as well as the present-day authorization of various approach and landing aids.

TABLE II-19. PRESENT DAY AUTHORIZATION OF LANDING SYSTEMS AT LEVELING CATEGORY LIMITS

Definition				Federal Authorization			
Category	RVR (ft)	Met. Visibility	DH (ft)	ILS	VOR/ DME	GCA/ PAR	Automatic Landing Systems
I	2400	1/2 mi	200	Yes	No	Yes	Yes
IIA	1600	1 4 mi	150	Yes (few airports)	No	Yes (military only)	Yes
IIB	1200	3/16 mi	100	Yes (few airports)	No	Yes (military only)	Yes
IIIA	700	1/8 mi	-	No	No	No	No
IIIB	150	1/16 mi	-	No	No	No	No
IIIC	-	-	-	No	No	No	No

No System today is authorized for Cat III.

5.2 The Mechanics of Landing

A general understanding of the mechanics of landing is critical to realizing why a landing aid may or may not be capable of guiding aircraft in low-visibility conditions. Generally speaking, an aircraft transitions from an initial approach condition using perhaps VOR/DME or approach control radar (ACR) fixes, to a final approach ILS or precision approach radar (PAR) fixing system at 8-15 miles from the runway. The aircraft continues inbound to the runway at the minimum enroute altitude for the particular terminal maneuvering area (TMA) say (1000-1500 ft approx.) until a glide slope or start descent point is encountered where a controlled rate of descent (glide-slope follow) is commenced. This condition is maintained until either the minimum altitude (based on category and local terrain) is encountered or the runway is sighted.

At present Cat I limitations, the aircraft has sufficient time to level out at the minimum altitude and continue in-bound attempting to gain visual contact with the runway, before going into a landing phase. If no visual contact is gained, a missed approach procedure must be initiated.

If lower categories of visibility are to be used, the aircraft will be required to transition into a landing phase of operation prior to encountering the specified minimum altitude. The landing phase requires several precise operations on the part of the pilot/aircraft system. Consider an aircraft descending with a sink rate of 480-900 ft/min, an airspeed of 130 kts (typical jet transport aircraft), 600 ft above runway*, 2 miles from the touch down point, possibly in a "crab" due to wind and not exactly on the centerline extension due to inaccuracies in the approach/landing system. This situation progresses assuming no runway alignment side-step is necessary, until approximately 75 ft altitude* and 500 ft from the threshold the "flare decision" is made. At 50 ft altitude*, and over the threshold, the flare is initiated. The flare continues until landing some 2000 ft along the runway. During flare the sink rate is reduced parabolically to approximately 2/ft/sec, airspeed is reduced to approximately 105 kts. touchdown speed and at 20 ft altitude* the decrab maneuver is executed. If during an IFR landing of this type the aircraft encounters the minimum altitude restriction, based on visibility category criteria and terrain, without visually sighting the runway, the pilot is required to abandon the landing and execute a missed approach.

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* Defined as the altitude between the extended landing gear and the runway, typically measured by the altimeter system in the aircraft, calibrated as zero when the aircraft is on the runway, gear down.

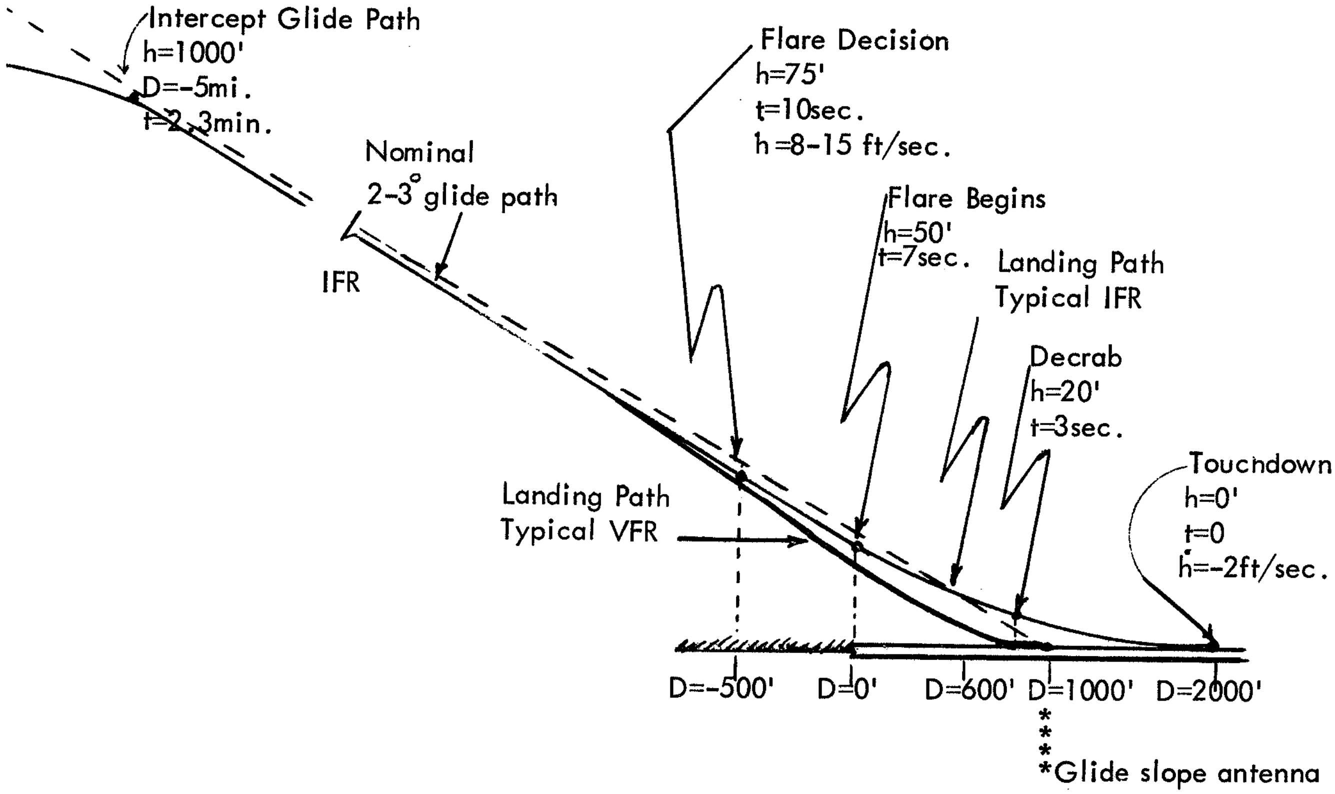


Figure II-7. Typical IFR and VFR Landing Paths.

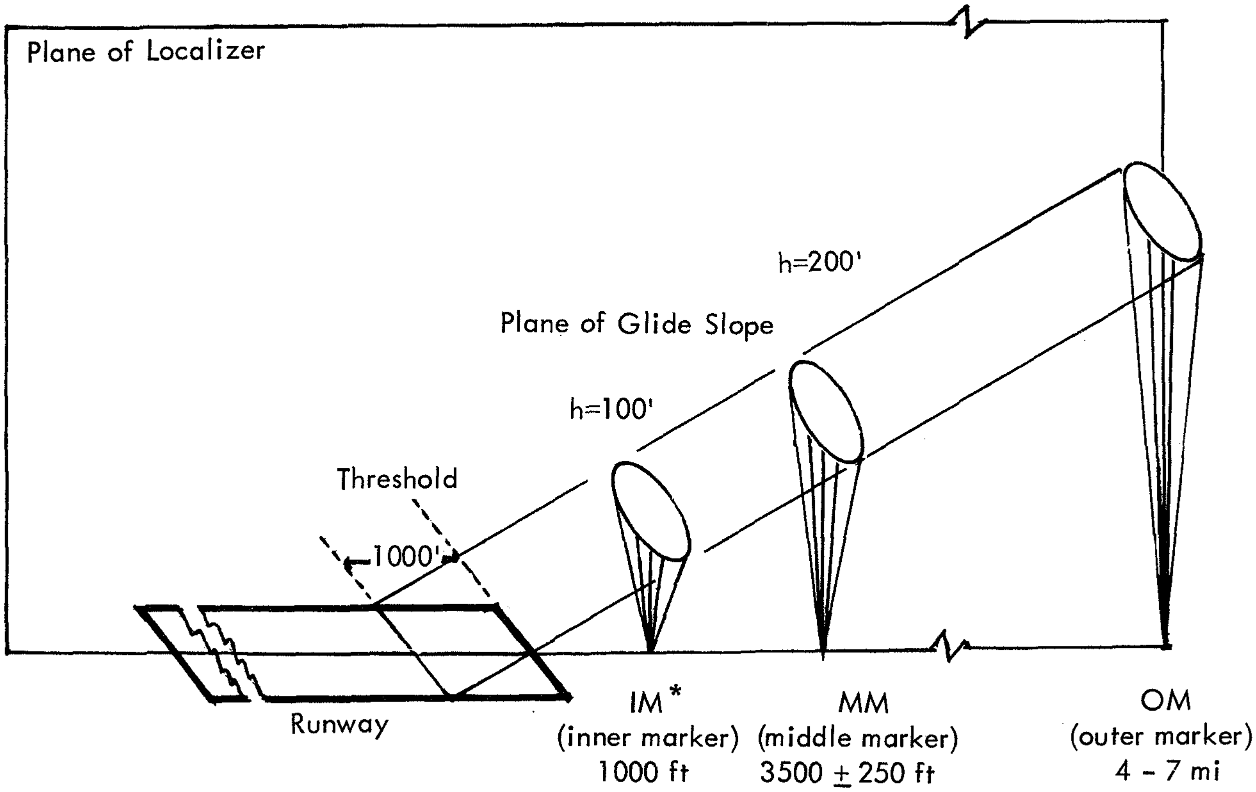
Note. . . All measurements are approximate.

The foregoing discussion represents a generalized picture of the landing envelope. Aircraft performance and optimal approach requirements vary considerably over this envelope. But, any system capable of operation down to Cat III conditions must be able to interface with the pilot/aircraft to the extent of facilitating the flare, decrab and overshoot decisions. In addition, system accuracy along the runway extension must minimize side-step maneuvers at low and unsafe altitudes. An additional capability for complying with missed approach procedures and accuracy requirements must be provided.

5.3 Characteristics of Instrument Landing Systems

The performance of present ILS systems is summarized in the following paragraphs. The data presented has been extracted from (Ref.19). Since (Ref.19) states system performance in a non-standard format, the approach outlined in (Ref.18) has been followed, i.e., performance requirements have been stated at the 3 σ probability level.

5.3.1 General Description (ILS). - The standard instrument landing system (ILS) consists of a glide-slope beam for vertical steering, a localizer beam for lateral guidance and two or three marker beacons to provide positional (distance from the end of runway) checks. Figure II-8 shows an idealized picture of the two beams and their intersection in relation to the runway.



* Inner Marker (IM) is not present at all airports.

Figure II-8. CAT II Runway Configuration of ILS

The Glide Slope. - Twenty glide slope channels are used in the U.S. separated by 0.3MHz. in the frequency band of 329.3 to 335.0 MHz. Each glide slope channel is paired with a localizer channel so that both receivers can be tuned simultaneously.

Normal acquisition range is 15 nm at approximately 1000 ft. The glide slope carrier is modulated at both 90 and 150 Hz in a pattern such that predominance of the 150 Hz signal causes a fly-up indication to the pilot, the predominance of the 90 Hz signal causes a fly-down indication. The glide slope signal path is linear, while the nominal aircraft glide path is a hyperbola whose asymptote flares out near the runway, never touching the ground. (15 to 30 ft above runway, near the antenna) Therefore, the glide slope cannot be used as a "touchdown" guidance aid.

The glide slope transmissions are subject to multipath effects because of reflections to the aircraft from surface irregularities and nearby objects. This causes apparent bending and distortion of the nominal glide path signal.

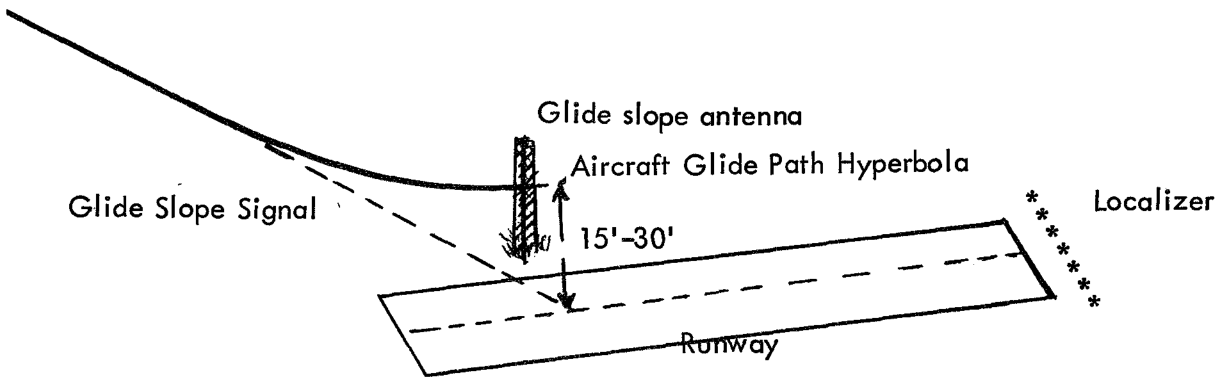


Figure II-9. Optimal Glide Path and ILS Glide Slope.

To achieve Cat II the glide path must be free of these distortions down to 50 ft. Airport sites not having flat runway approach areas must use special, higher-cost, antenna arrays to fulfill Cat II requirements.

The Localizer. - Twenty localizer channels with 0.2 MHz separation from 108.1 to 111.9 MHz, are paired with a glide slope channel. The localizer is aligned with the projected runway centerline and again the carrier is modulated at 90 and 150 Hz. Predomination of the 90 Hz modulation generates a "fly-right" indication to the pilot and conversely a "fly-left" indication occurs when the 150 Hz modulation is predominant. The localizer antenna is located several hundred feet beyond the "stop" end of the runway.

Again, multipath effects cause apparent bending or scalloping in the localizer pattern. These irregularities may be reduced by special, albeit higher cost, two array configurations.

Marker Beacons. - The 75 MHz marker beacons are used as spot distance checks from the runway and have the following configurations.

(a) Outer Marker - (OM) - 4-7 miles from threshold (generally 4.5 miles)
- 400 Hz modulation, 2 dashes/sec. audio
- lights purple light in pilot's panel
- glide slope interception point.

(b) Middle Marker - (MM) - glide slope 200 ft above runway
- approx. 3500 ft from threshold
- 1300 Hz modulation
- dash dot audio presentation
- lights amber light on pilot's panel
- Cat I decision point.

(c) Inner Marker - (IM) - Required only at Certified Cat II airports
- glide slope 100 ft above runway
- approx. 1000 ft from threshold
- 3000 Hz modulations
- 6 dots/sec. audio
- light white light on pilot's panel
- Cat II decision point.

5.3.2 General Performance Requirements. - The frame of reference for the landing approach path which has been adopted by ICAO is shown in Figures (II-10&11). It is to be observed that this specification is anchored to threshold ILS reference point and developed in reverse sequence from there. ILS system performance requirements are referred to this diagram. The standard refers only to the last four miles of the approach. A flat overrun of 200' is specified, however, more recent documents (Ref.16) contain a terrain model which illustrates the degree of variation which can be expected during the last mile.

As discussed previously, the basic requirements for an ILS system comprise:

VHF glide path and localizer equipment, associated monitor system and indicator equipment.

. VHF marker beacons, monitors, remote control and indicator equipment.

There are other requirements related to the location of control points, monitoring standards, frequency interlock, etc., which while of interest generally do not affect the performance criteria which are relevant to this study.

• Localizer and Associated Performance Requirements

The performance of the ILS Localizer equipment is specified in terms of coverage and guidance accuracy for the three categories of operation.

The coverage requirements for the localizer state that coverage shall extend from the center of the antenna system to distances of:

25 nautical miles within ± 10° of the front course.

17 nautical miles between 10° and 35° from the front course line.

. 10 nautical miles outside of ± 35°.

If alternative navigation facilities are available, the coverage requirement may be reduced to 18° instead of 35°. The signals must be received at the distances specified and above a height of 2000' above the threshold or 1000' above the elevation of the highest point.

Localizer Course widths at threshold and ICAO Point B are shown in Figure II-11. The widths shown define the point at which maximum deviation of the localizer needle occurs. Localizer angular sensitivity is varied for long and short runways to achieve the ± 350' course width at threshold.

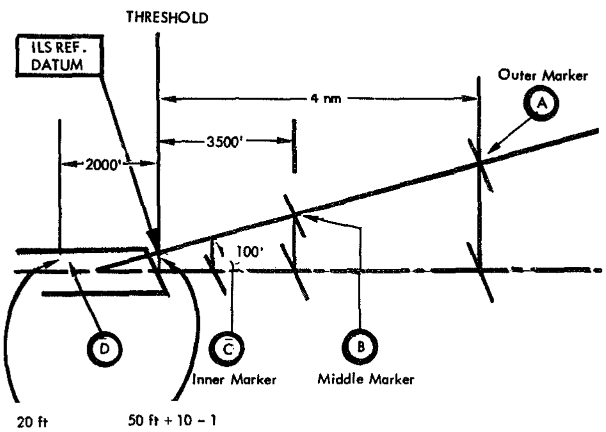


Figure II-10. ICAO/ILS Reference Points

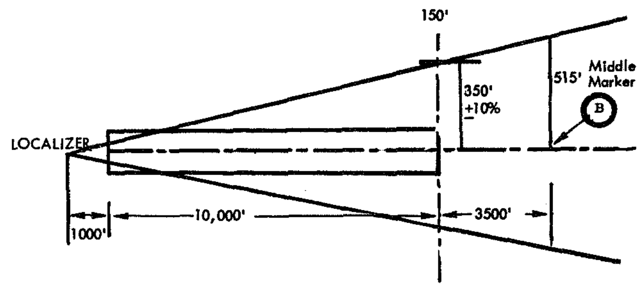


Figure II-11. ICAO/ILS Localized Course Width at Threshold and Point B

Accuracy requirements for ILS localizer are shown in Table II-20. The ICAO standards have been stated at the 3σ level. Note that, excluding flight errors, worst case errors are 84 ft, 93 ft and 111 ft at threshold points C & B respectively. RSS errors at the same points are 50 ft, 56 ft and 66 ft respectively. It is significant to note that total ground equipment error contribution is of the same order of magnitude as airborne equipment.

- Glide Slope Performance Requirements

The glide slope provides a straight line descent path in the vertical plane containing the center line of the runway. θ is the angle used to denote the nominal path angle. It is a recommendation that this angle be made variable from 2 to 4 degrees. The operationally preferred glide path angle is 2.5 degrees for Class III aircraft. An angle in excess of 3° is to be used only if obstruction clearance demands it.

The glide path angle shall be adjusted and maintained within:

- $0.075\ \theta$ for Cat I & II
- $0.04\ \theta$ for Cat III

The ILS reference datum shall be:

- 50' ± 10' for Cat I
- 50' + 10' - 0' for Cat II and III

TABLE II-20. CAT II - LOCALIZER PERFORMANCE

Parameter	ICAO Ref.	ICAO Cat. II Amount	3σ Value at threshold	3σ Value at Point C	3σ Value at Point B
Sector width with 10%	3.1.1	700'± 70'	750'±20'	775'±75'	935'±95'
Centerline Monitor	3.1.4.5.4	±25 ft threshold ±15' recommended	25 ft.	28 ft.	33 ft.
Course Bends	2.1.4	±5 microamps (2σ)	20 ft.	22ft.	26 ft.
Receiver Centering (airborne)	2.2.4.1	±5 microamps ($1\ \sigma$)	39 ft.	43 ft.	52 ft.
All flight errors FAA/AC 120-20 (crab angle wind shear. normal tracking poor heading)		±25 microamps or 1/6 full scale (1σ level)	97 ft.	104 ft.	127 ft.

TABLE II-21. ILS LOCALIZER PERFORMANCE REQUIREMENTS FOR CAT I, CAT II & CAT III AT POINT B (ft)

	Cat I	Cat II	Cat III
Alignment	35	33	10
Coursebends	127.5	26	25
Receiver Centering	72	52	-
Worst Case Error	234	111	35
RSS	± 150	± 66.8	± 27

The 3 σ values of the 100' point are given in Table II-22.

TABLE II-22. 3σ VALUES OF THE 100-FT. POINT

Error	ICAO Ref.	ICAO Spec.	3σ
Course Shift	3.1.4.6.1	0.2°	8'
Beam Bends	2.1.5	20$\mu\alpha$ at 2σ	5'
Receiver Centering	2.2.5.1	27$\mu\alpha$	5'
Linearity Flight Error	3.1.4.5.4.7	(20%)	12'

The variation in glide path angle and path height over threshold for Cat II is shown in Figure II-12.

The variation in Point C (the 100' height point) with glide slope errors is shown in Figure II-13 for a nominal 2.5° glide slope. It is to be observed that at the 3 σ level the distance to the 100' altitude point is from 740' to 1660'.

Glide path errors over typical thresholds added to ICAO variation in path height are shown in Figure II-14.

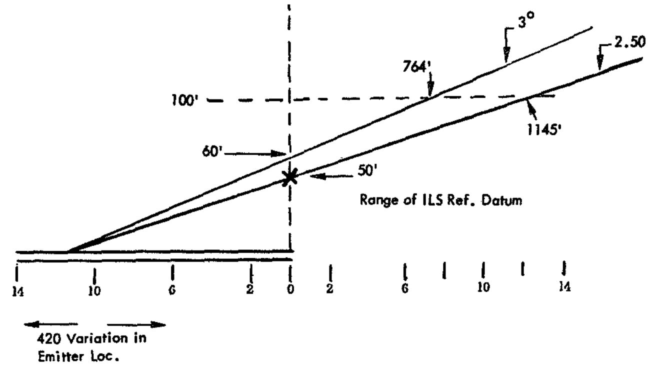


Figure II-12.
Variation in Glide Path Angle and Path Height for Cat II and Cat III

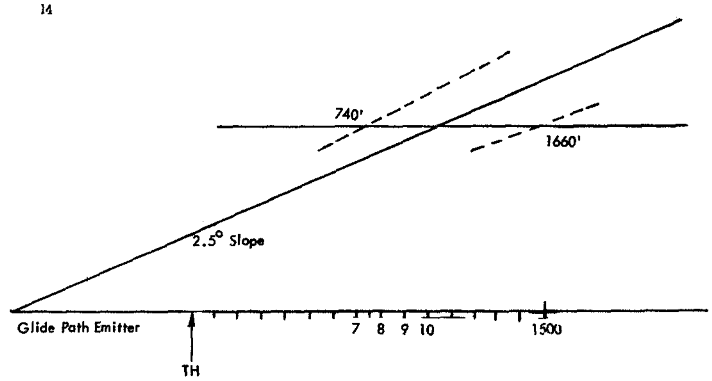


Figure II-13.
Variation in Point C with Glide Slope Errors

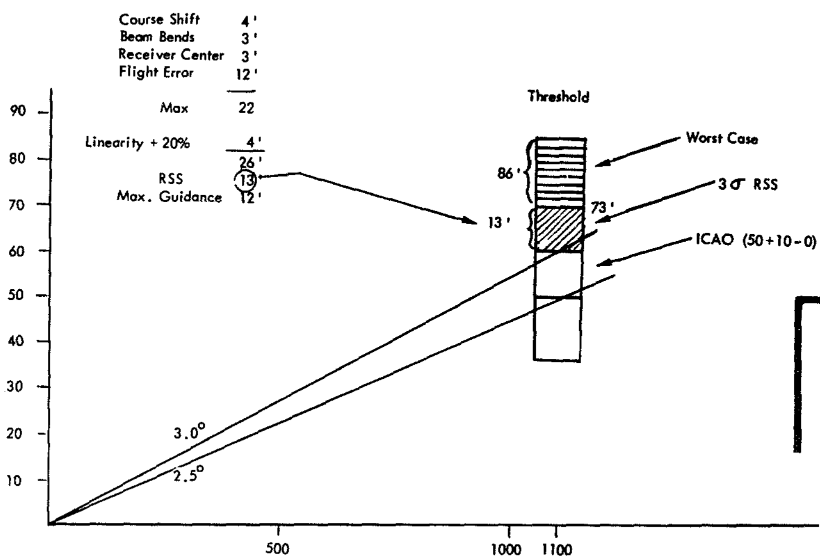


Figure II-14.
Glide Path Errors Over Typical Thresholds Added to ICAO Variation in Path Height

- Combined Performance Requirements

The lateral and vertical performance tolerances (including Piloting Error) are combined and shown in Figure

The 3σerror window is:

280' by 90' at Point B

235' by 50' at Point C

- Other Performance Requirements

Other performance requirements relate to the location of marker beacons, equipment siting, monitoring of system performance and identification. These are summarized below. They are included only to indicate the type of performance and functions which are currently provided in the existing ILS. Further detailed system analysis is required to define a compatible set of functions in this detail for an IALM System.

. Marker Beacons

Two marker beacons must be provided in each system, (a third beacon may be added if necessary). The beacons shall indicate predetermined distance from the threshold along the ILS glide path. The beacons shall provide visual indications for 3 seconds (± 1 sec.), 6 seconds (± 2 secs.) and 12 seconds (± 4 secs.) at the inner, middle and outer markers. Each marker carries identification data in the form of 6 dots per second, alternate dots and dashes and dashes (2/second) for inner, middle and outer markers respectively.

It is recommended that the inner marker be from 1000 to 1500 ft, the middle marker at 3500 ± 500 ft and the outer marker 3.9 nautical miles from the threshold. The markers shall be within 100 ft, for the inner marker and 250' for the middle and outer markers, from the extended centerline of the runway.

. Equipment Siting

Localizer equipment shall be located on the extension of the centerline of the runway at the stop end. The glide path antenna should not be less than 400' from the runway centerline.

. Monitoring

An automatic monitoring system shall be provided for the localizer which provides warnings when:

a) Radiation ceases.

b) Navigation and Identification data is removed from the carrier.

c) The facility reverts to lower category performance.

These warnings will be provided when:

a) For Cat I Localizers, the mean course line deviates more than 35' at the ILS reference datum.

b) For Cat II, when course line deviates more than 25'.

c) For Cat III, when mean course shifts more than 20'.

d) A reduction of power to less than 50% for single frequency systems occurs.

e) A reduction of power to less than 80% for two frequency systems occurs.

f) A change of displacement sensitivity of more than 17%.

The glide slope monitoring system shall provide warnings when:

a) Mean glide slope angle shifts more than 0.025 θ .

b) When power drops to less than 50% or 80% as in the case of the Localizer.

c) When accuracy drops below that required for Cat I, II or III performance.

These warnings are utilized only in the control centers at present and automatic transmission of the data should be considered.

5.3.3 ILS Installations. - On a world-wide basis there are 500 ILS installations, of these, half are within the continental United States. A typical installation will have one system of glide-slope, localizer and beacons oriented to the main runway. However, major airports do have several installations oriented to various runways. Most ILS installations are authorized for use within Cat I conditions but not all of them are authorized to the minima for Cat I. Several installations have Cat II authorization. (See Table II-23). Within the near future, a total of 23 Cat II installations will be authorized.

5.3.4 Future Systems. - "The Radio Technical Commission for Aeronautics (RTCA), believing that it is timely to consider a successor system to the ILS, has established Special Committee 117. This committee is composed of expert operational and technical representatives from both government and industry. Its objective is to develop a precision guidance system concept for approach and landing and an associated signal structure. The concept and signal structure should satisfy, to the maximum extent possible, the various operational needs of the several classes of users. The committee is striving to achieve a continuing dialogue between the people who define operational needs, and the scientists and engineers who strive to meet those needs."

The above paragraph is excerpted from an RTCA Paper (Ref. 16). While no formal development decision has been made concerning the so-called "ILS replacement", a considerable amount of constructive and progressive work has already been generated by RTCA SC-117. Of particular importance to this study, at the time of this writing are two subjects. First, a recommendation has been made by SC-117 to concentrate its further efforts on a scanning beam ground based approach and landing system. It is too early in the development cycle to discuss in detail in this report any of the competing proposed system concepts, other than to identify that the scanning beam technique was selected from a series of proposals which included multilateration or hyperbolic concepts as the main alternative category.

For the purposes of this study, the second subject, that of the technical performance requirements set down by SC-117, were considered important enough to be included. In this way, the initial requirements that are being used as design criteria can be viewed in the light of the airborne ILM solution.

TABLE II-23. INSTALLATIONS AUTHORIZED CAT. II MINIMA FOR ILS AS OF 8 DECEMBER 1969

City	Runway	Minima
Atlanta	9R	1600 RVR Day-1200 RVR Night
Chicago, O'Hare	14L	1200 RVR Day-Night
Chicago, O'Hare	14R	1200 RVR Day/Night
Dulles	1R	1600 RVR Day-1200 RVR Night
Denver	35	1600 RVR Day-1200 RVR Night
Detroit	3L	1600 RVR Day/Night
Houston	8	1200 RVR Day/Night
Milwaukee	1	1600 RVR Day/Night
Minneapolis	29L	1200 RVR Day/Night
New Orleans	10	1600 RVR Day-1200 RVR Night
Washington National	36	1600 RVR Day/Night

Note: FAA long range plans call for the installation of Cat. IIIA ILS at 24 locations in the 1970-1080 time period.

. Tentative Technical Requirements - RTCA SC-117

The following Table II-24 contains the minimum performance values for a initially defined series of operational configurations which were considered by SC-117.

TABLE II-24. MINIMUM PERFORMANCE VALUES FOR OPERATIONAL CONFIGURATIONS (Notes: 1/ 8/)

GUIDANCE CHARACTERISTICS	Config. B	Config. D	Config. E	Config. F	Config. G	Config. I	Config. K
2/ Bias:	50' or 0.25°	50' or 0.25°	50' or 0.25°	32' or 0.18°	32' or 0.18°	10' or 0.072°	10' or 0.072°
3/ Noise:	26' or 0.133°	26' or 0.133°	26' or 0.133°	11' or 0.066°	11' or 0.066°	9' or 0.066°	9' or 0.066°
2/ Bias:	N/A	6' or 0.1°	6' or 0.1°	1.2' or 0.1°	1.2' or 0.1°	1.2' or 0.1°	1.2' or 0.1°
3/ Noise:	N/A	7' or 0.117°	7' or 0.117°	1.4' or 0.07°	1.4' or 0.07°	1.4' or 0.07°	1.4' or 0.07°
2/ Bias:	300'	300'	100'	100'	20'	20'	20'
3/ Noise:	6/	6/	6/	6/	6/	6/	6/
Dev. Course Width 4/ AZ	± 350' at Threshold	± 350' at Threshold	± 350' at Threshold	± 350' at Threshold	± 350' at Threshold	Air 5/ Selectable	Air 5/ Selectable
EL	N/A	± .240 x θ	± .240 x θ	± .240 x θ	± .240 x θ	Air 5/ Selectable	Air 5/ Selectable
Data Rate	2 Hz	4 Hz	4 Hz	5 Hz	5 Hz	5 Hz	5 Hz
System Capacity	15 acft	15 acft	15 acft	50 acft	50 acft	50 acft	50 acft
9/ Channelization	40 Channels	40 Channels	40 Channels	40 Channels	40 Channels	40 Channels	40 Channels
COVERAGE	Config. B	Config. D	Config. E	Config. F	Config. G	Config. I	Config. K
(Vertical Guidance) Horz.	N/A	± 20°	± 20°	± 20°	± 20°	± 40°	± 90°
Vert.	N/A	1° - 8°	1° - 20°	1° - 8°	1° - 20°	1° - 20°	1° - 20°
Range	N/A	20 nm	20 nm	20 nm	20 nm	20 nm	20 nm
(Lateral Guidance) Horz.	± 20°	± 20°	± 20°	± 20°	± 20°	± 40°	± 90°
Vert.	1° - 5°	1° - 8°	1° - 20°	1° - 8°	1° - 20°	0° to 20° 7/	0° to 20° 7/
Range	20 nm	20 nm	20 nm	20 nm	20 nm	Stop End To 20 nm	Stop End To 20 nm
DME Horz.	± 20°	± 20°	± 20°	± 20°	± 20°	± 40°	± 90°
Vert.	1° - 5°	1° - 8°	1° - 20°	1° - 8°	1° - 20°	0° to 20° 7/	0° to 20° 7/
Range	20 nm	20 nm	20 nm	20 nm	20 nm	Stop End To 20 nm	Stop End To 20 nm
PATH LOCATION							
Vert.	N/A	Fixed 2° - 6°	2° - 15° Air Select.	Fixed 2° - 6°	2° - 15° Air Select.	2° - 15° Air Select.	2° - 15° Air Select.
AZ	Extended Centerline					Air Select. ± 40°	Air Select. ± 90°

NOTES: 1/ These are net values which include both airborne and ground components of system.

2/ Bias refers to tolerable error of mean (±).

3/ Noise includes spatial, temporal and resolution perturbations.

4/ Accuracy values are specified for the minimum height designated in respective configuration descriptions. Angular values for elevation accuracies use origin at touchdown zone. Azimuth accuracies and course widths are specified with respect to stop end of the runway and use of the following runway lengths as arbitrary references: (1) B, D, and E -- 7,000'; (2) F and G -- 12,000'; (3) I and K -- 14,000'.

5/ Elevation and azimuth course widths are dependent on aircraft type and selected angle θ.

6/ Compatible with a tolerable range rate error; e.g., 10 feet per second. Integration time should be specified.

7/ The angle 0° applies to at least the length of the runway plus 0.5 mile beyond the approach end of the runway.

8/ Additional technical narrative guidance under the following headings is attached hereto:

1. Station Identification.
2. Obstacle Warning.
3. Monitor and Flag Alarms.
4. Missed Approach Guidance.
5. Installation Factors.
6. Co-location with Existing Facilities.
7. Electromagnetic Compatibility (EMC).

9/ If the total system service requires more than one rf frequency, automatic pairing shall be provided.

1. Station Identification. Four sequentially ordered alphabetic characters to identify geographic location, and two numeric characters designating the serviced runway, shall be transmitted as modulations of the guidance signals. In addition, at least four distinct indications of status of the guidance facility shall be provided. These identification and status messages shall be repeated at least every ten seconds, and shall produce aural Morse code or voice outputs from the air-borne equipment. Capability for the automatic recovery and static visual display of the message data is desirable as a supplement to the aural outputs. Capability to transmit "canned messages" which are related to the landing procedure also is desired.

2. Obstacle Warning. An obstacle warning which defines the minimum safe gradient in approach and missed approach areas is desired.

3. Monitors and Flag Alarms. Ground-based monitors shall be provided which automatically detect and respond to significant degradation or loss of any transmitted guidance signal. Monitor tolerances and adjustability shall insure compliance with system accuracy specifications and with any safety criteria peculiar to each installation. Airborne flag alarm signals shall be provided which respond to signal losses from any cause, to unreliably weak signals, and to inconsistencies in signal format tending to result in false data. Separate alarm signals shall be available for azimuth, elevation and distance data. Flag alarm response times shall not exceed one second.

4. Missed Approach Guidance. Lateral guidance shall be continued over the length of the runway and at least 5 nm from departure end into the takeoff/overrun zone. Vertical coverage of the lateral guidance shall extend from the base altitude to at least 2000 feet altitude throughout this region. All other characteristics of missed approach lateral guidance shall duplicate those applicable to approach guidance, except that accuracy shall be ± 160 feet (2σ), over and in the immediate vicinity of the runway. Vertical guidance in the missed approach zone is desirable.

5. Installation Factors. The locations of surface guidance facilities relative to each other and to the landing zone shall be sufficiently flexible to avoid conflicts with existing surface features such as taxiways and structures. Manual adjustments to the airborne equipment in compensation for such variations in installation geometry shall not be permissible.

6. Co-location with Existing Facilities. The instrument landing system provided shall be designed such that its normal performance characteristics fall within prescribed tolerances when co-located with an existing conventional instrument landing system. Co-location shall be interpreted as being physically located so as to serve the same runway with azimuth, elevation and distance guidance, and with no degradation in performance characteristics of the existing system.

7. Electromagnetic Compatibility (EMC). The system and its equipment elements shall neither produce nor be vulnerable to radio interference to such a degree that standard electromagnetic control methods would be ineffective. Misleading indications due to accidental interference shall be prevented. Positive safeguards against hostile jamming are desirable options for military applications.

5.4 VOR/DME as an Approach Aid

Generally speaking, VOR/DME is not used to any great extent as a final approach aid today. This is due, in part, to the fact that the vast majority of airports serving air carrier aircraft are now equipped with some form of Instrument Landing System.

However, if we consider a hypothetical case at an airport which does use VOR/DME as a landing approach aid, we are better able to understand the reluctance of air carriers and airports to rely on this method. Assuming a jet-powered aircraft (see Fig. II-15) on an approach path to an airport runway with a speed of approximately 130 knots, the minimum time lapse allowable between breaking below the 200 ft decision height of Cat I and touchdown is approximately 19 seconds. This means that the start of descent to the runway must occur when the aircraft is approximately over a point 0.69 nautical miles from touchdown.

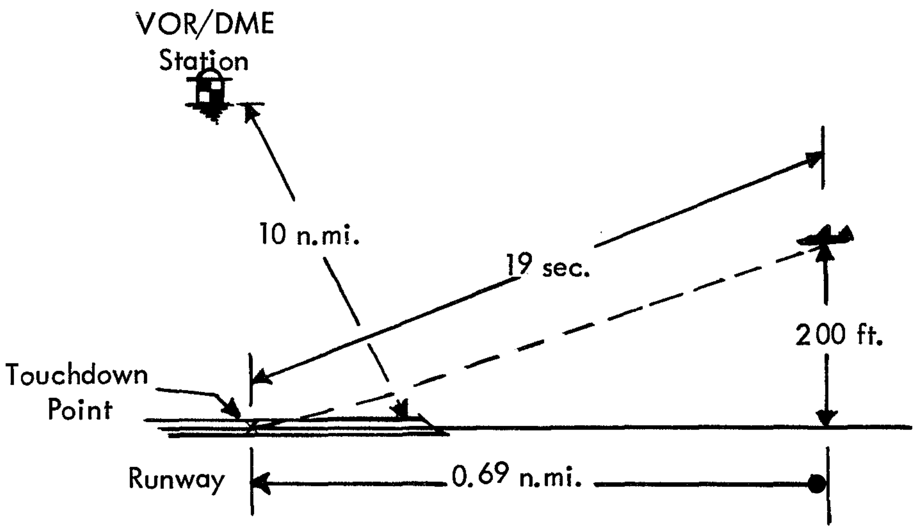


Figure II-15. VOR/DME Landing Approach

Further assuming a VOR/DME station 10 miles from the airport, and using the following figures which represent the generally accepted minimum errors for VOR/DME then the absolute minimum visibility must be the sum of the minimum let down distance and the largest VOR/DME error.

1. The ground based equipment at the station has an inherent error of 1.1° for standard VOR, and 0.5° for precision VOR (PVOR); and a DME error of 0.2 naut. mi. for standard and 0.1 n. mi. for precision equipment.

   Note: Due to the greater magnitude of VOR error, at 10 miles the DME error is insignificant.

2. The airborne equipment has an inherent error of 2° for standard VOR, or 1° if the equipment is extremely well-maintained, and 0.5° for PVOR.

TABLE II-25. VOR/DME APPROACH ERRORS

Case	VOR Ground Equip Error	Aircraft Equipt. Error	Aggregate Error	Maximum Perpendicular Error at 10 N.Mi.	Maximum Total Distance From Touchdown
A	1.1°	2.0°	2.28°	0.38 n. mi.	1.07 n. mi.
B	1.1°	1.0°	1.48°	0.24 n. mi.	0.93 n.mi.
C	0.5°	0.5°	0.7°	0.12 n. mi.	0.81 n.mi.

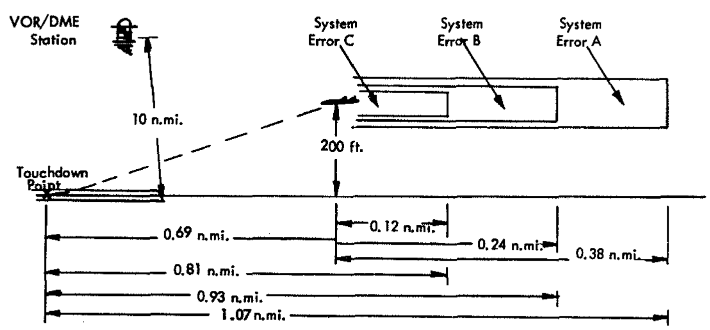


Figure II-16. VOR/DME Approach Errors

The total distances involved for Cases A, B, and C do not take into consideration such factors as flight technical error or pilot induced errors. With these in mind it is readily apparent that none of the VOR/DME candidates can provide a Cat I capability.

Under present FAA regulations, VOR/DME minima are on the average 800 and 1 (i.e., 800 ft above terrain and 1 mile meteorological visibility).

5.5 GCA or PAR

"Ground-controlled approach" (GCA) and "precision approach radar", (PAR) are the respective military and civil names for an X-band, ground-based radar landing system that tracks and guides landing aircraft. Steering corrections are transmitted to the pilot via a standard radio voice link. Consequently, no specialized equipment need be carried by the aircraft.

The system consists of two scanning beams. The vertical plane beam is 1.5° high by 0.6° wide and scans a 20° sector in azimuth, centered on the extended runway center line. The horizontal plane beam is 0.4° high by 3° wide and scans a 7° vertical sector centered on the glide-slope, 2.5° to 3° above the horizontal plane. Each beam makes four scans per second and shows the aircraft's path on two cathode-ray-tube screens, superimposed on a drawing of the ideal glide path. The range accuracy is 200 ft ± 2 percent of range (Ref. 20).

Military GCA systems and operations were authorized to land aircraft in the equivalent of civilian Cat II conditions in 1968. However, GCA/PAR is generally used as a low approach and ILS monitoring system. Overall accuracy and safety is dependent on the alertness and skill of both the pilot and operator.

GCA/PAR has long been recognized to have several weaknesses:

The deficiencies of the GCA included poor closed-loop response, weak signals reflected from the aircraft, obscuration of the reflected signals by weather, and ground "clutter" of the (ground) controller's scope. The cost of having a trained GCA team always available 24 hr. a day, 365 days a year --- also posed a serious deterrent (Ref. 21).

Compiled with these are the modern day problems associated with large jet aircraft (difficult to establish center of aircraft on scope) and heavy traffic flow (GCA/PAR have low system capacity).

5.6 Automatic Landing Systems

Over the past few years several airborne systems have been developed to augment ILS and provide landing guidance in the region from 100 ft altitude downward to the runway.

5.6.1 BLEU Automatic Landing System. - One such system developed by the British Government research agency at the Royal Aircraft Establishment, Blind Landing Experimental Unit was the BLEU system. This system utilizes a combination of ILS, radio altimeter, flare computer and magnetic leader cable. The leader cable system is composed of two cables laid parallel to the runway centerline and extending 5000 feet into the undershoot area and 500-1000 feet past the glide slope antenna. As long as the cables are symetrically installed about the centerline and both supplied with a constant current, then the plane of the centerline is defined by equality of the magnetic fields.

The BLEU system although demonstrably accurate has two economic limitations, the right-of-way requirements in front of the threshold and excessive aircraft receiver weights.

5.6.2 Auto Land. - Another British system is the "Auto Land" developed by SUD-Lear. To some extent a spinoff from BLEU, the Auto Land system came about as a result of improvements in ILS beam stability. The basis of the system is, of course, the more stable ILS beam and the autopilot coupling, but in addition, the system requires a radar altimeter and vertical programming, an open loop glide slope, a flare computer, augmented flight controls and an auto-throttle to provide pitch, speed and descent control.

The Auto Land system has undergone considerable flight testing. Results of 20 landings made at Toulouse (poor ILS glide path) were as follows (Ref. 22).

- between 400 ft and 50 ft all aircraft trajectories were determined to be within $\pm$ 0.1° from centerline of mean descent path defined by glide beam.

- 50% of the landings were inside a 55 meter along-runway zone, and all were within a 128 meter zone (center 608 meters from threshold).

- vertical speed at touchdown was between 0.63 and 2 ft/sec.

5.6.3 Other Systems. - Several automatic landing systems using ILS have been developed in the United States. These are (Ref. 23).

Precision Approach and Landing System Boeing Co. & Bendix Corp. primarily for Boeing 707/720.	(PALS)
Automatic Flight Control System Douglas Aircraft Co. & Sperry Phoenix Co. primarily for DC-8.	(AFCS)

All Weather Landing System (AWLS)
Lockheed-Georgia Co. primarily
for USAF on C141.

5.7 All Weather Landing System Concepts

In the U.K. the current thought is for the pilot to act in a command and monitor role, with the necessity of a pilot takeover hopefully eliminated by reliable automatic systems. In effect then the pilot remains outside of the control loop.

In the U.S. however, the focus is to keep the pilot within the control loop. One concept developed is to use electronic force sensors on the controls and have these inputs added to the automatic control inputs. Therefore, if the pilot wishes to take over, he may also do so by performing his normal maneuvers.

Again, because of economic factors, development has followed along the lines of utilizing improved ILS as the basic input. Although these systems are apparently capable of full automatic landings, commercial aircraft are today only certified to Cat II landings at approved airfields.

5.8 Summary of Approach and Landing Aids

The following limitations exist with today's approach and landing aids. At best these limitations can restrict full utilization of airports in Cat III visibility conditions.

5.8.1 ILS. - ILS, theoretically, can be developed to sufficient accuracy in the localizer and glide slope planes, to be used for Cat III landings. Unfortunately, it is still subject to local distortion, bends, scalloping, etc. Range to touchdown information is presented neither accurately nor adequately to the pilot.

Present ILS systems are limited in the number of aircraft they can handle at a given time and only give a general not optimal approach path to the aircraft. Advanced ILS configurations may appear technically feasible but their economic cost benefit has yet to be determined.

5.8.2 VOR/DME. - Today, VOR/DME is not authorized for use in Cat I conditions. Such developments as PVOR (precision VOR) when used with specialized aircraft equipment are capable of the accuracies required for Cat I and perhaps Cat II landings.

5.8.3 GCA/PAR. - Ground controlled approach presently is not authorized for civilian use below Cat I although it has been demonstrated within the military to be capable of Cat II landings. Accuracy improvements are possible, however, the inherent high costs of equipment and 24 hour GCA teams preclude the utilization of GCA/PAR for Cat III. The restricted utilization rate of GCA/PAR is also a critical factor at large, high density airports.

5.8.4 Automatic Landing Systems. - Various automatic landing systems, although not authorized, have demonstrated Cat III landing capability. The weak link in the automatic landing system chain is the in-bound guidance beam. A system utilizing ILS beam guidance is limited by the vagaries and distortions of ILS at various airports. Although automatic landing systems may be the answer, this single ILS ground to air link is particularly subject to errors and non-standardization of approach. Current ILS systems do not provide for redundancy, or back-up capability, nor do they provide for the steeper descent angles which are characteristic of VSTOL aircraft.

5.9 Conclusion

In conclusion then, it can be seen that a requirement exists for a highly accurate, airborne landing system, which can be used either in a primary or backup role to provide landing information. Such a system would, when coupled with existing systems, give safe, redundant in-bound tracking information; provide standardization of approach at various airports; allow higher utilization of airports; and permit the aircraft to fly its optimal approach path.

6.0 SENSOR PERFORMANCE

6.1 Introduction

This section presents the performance evaluation for various sensors which might be used to meet the broad requirements for the functions of approach and landing aid, roll-out and taxi guidance, and high ground avoidance. The sensors considered here are radar and optical devices which would be suitable for installation in a commercial transport aircraft. Typical equipment parameters and space restrictions related to such an installation are included in hardware considerations.

Radar sensors which operate at X-band (10GHz), Ku band (16GHz), Ka band (35GHz) and V band (70GHz) are considered. These radars are evaluated for their ability to detect runways, with and without enhancement, to detect high ground, and to perform other specific functions. Meteorological attenuation due to rain and fog is a primary factor in the evaluation.

Optical sensors are included for both the visible region, 0.5 to 1.0 microns, and the infra-red region near 10 microns. These are the spectral regions in which extensive development work has been performed recently for low-light-level television and infra-red equipments for military applications. This choice was deliberate so that meaningful performance estimates could be promptly followed by the application of state-of-the-hardware techniques to a proof-of-concept demonstration system.

6.2 Radar, General Background

At V band frequencies it is possible to achieve narrow beamwidth and excellent resolution with a relatively small antenna that will fit in the limited space available in the nose of a typical transport aircraft. Therefore, a first supposition might be that the requirements for an IALM are best met with a radar operating at V band. However, the very high attenuation experienced in rain and fog and the large back-scatter effects produced from precipitation at V-band seriously affect performance. At lower frequencies the effect of fog and rain on performance is not so serious, but the angular resolution is degraded because of the necessarily wider azimuth beamwidth. There is, therefore, an optimum frequency and, in order to determine this, detailed assessments are made of the performance of radars operating on X, Ku, Ka, and V frequency bands. It is assumed that the precise Ka and V-band frequencies are chosen so as to minimize the oxygen plus water vapor absorption. It is further assumed that oxygen absorption will not be a key factor in choosing among the frequency bands once the absorption is minimized. The oxygen absorption characteristic is illustrated in Section 3 of Volume III.

6.2.1 Initial Assumptions About Equipment Characteristics. - So that a meaningful comparison can be made of the performance of radars operating in the various frequency bands, it is necessary to define equipment parameters. A very critical one is the antenna aperture; this should be as wide as possible, especially in the azimuth plane, in order to make the azimuth beamwidth narrow. But to make the antenna suitable for installation in the majority of civil aircraft, the maximum horizontal dimension must be set at something like 1 meter. This is the number which has been assumed for this report. However, in order to assess the performance of systems suitable for installation in the smaller and larger commercial aircraft, sensors with antennas having horizontal dimensions of 0.5 and 1.5 meters are also briefly considered. As regards the maximum vertical dimension of the antenna, it is assumed that this can be as much as 30 cms. Full advantage of this dimension is not taken with the Ka and V-band radars since, for beamwidths wide enough to give adequate coverage in the vertical plane, the apertures can be reduced to 15 cms and 8 cms, respectively.

To keep equipment size and weight down to a reasonable level, a peak transmitter power of 20 kW has been assumed. At V-band, the peak power is 10 kW, since this is the maximum available from existing magnetrons.

Both the IALM and HGA systems require good angular accuracy in the elevation plane and to achieve this capability a monopulse (Ref.24) or interferometer system (Ref.25) has to be used. In this report the calculations are based on the assumption that the monopulse feature would be used, but the conclusions regarding the optimum frequency band would also apply to an interferometer system.

The X-band radar considered in this study is assumed to be horizontally polarized. Extrapolation from available back scattering coefficient data (Ref.26) shows that horizontal as compared with vertical polarization presents a greater relative difference between the returns received from grass and those received from concrete, and thus, is a better choice for runway detection. The Ku, Ka, and V-band radars are assumed to be circularly polarized in order to reduce the effects of back scatter from rain; a rain echo cancellation figure of 15 dB has been assumed (Ref.27).

The receiver noise figures assumed include waveguide losses and are typical of those that would be obtained in the field with present day equipments.

Table II-26 lists the parameters assumed for the various radar equipments. Since, in certain cases, the performance varies considerably with the transmitter pulse width, calculations have been made with pulse widths of 1.0, 0.5 and 0.1 microseconds.

TABLE II-26. PARAMETERS OF RADAR EQUIPMENTS

Parameter	Frequency Band			
	X 10GHz	Ku 16GHz	Ka 35GHz	V 70GHz
Transmitter Power, kW	20	20	20	10
* Azimuth Beamwidth	2.5°	1.5°	0.7°	0.35°
Elevation Beamwidth	7.5°	4.5°	4.0°	4.0°
Polarization	Horizontal	Circular	Circular	Circular
Antenna Gain	2100	5900	14,400	28,800
Noise Figure, dB	10	12	16	25
Pulse Widths, μs	1.0,0.5,0.1	1.0,0.5,0.1	1.0,0.5,0.1	1.0,0.5,0.1

* (1 m aperture)

6.2.2 Initial Assumptions About Environmental Characteristics. - It is, of course, essential for the HGA and IALM radar to work satisfactorily in fog and rain where performance, especially at the higher frequency bands, can be seriously affected. Calculations have, therefore, been made of the effect on performance of 400 ft. and 100 ft visibility fog and of rainfall densities of 1, 4 and 16 mm/hr. Although rainfall densities well in excess of 16 mm/hr can occur in heavy showers and/or in particular geographical regions, it has been concluded that this happens only on a small percentage of occasions and that the showers generally do not extend over a long distance. Consequently, rainfall rates in excess of 16 mm/hr are regarded in this study as representative of only a minor percentage of transport operating experiences.

The figures commonly used for attenuation in fog and rain are the theoretical values (Ref. 8), the derivation of these is discussed in Section 3 , Vol. III. Experimental measurements of attenuation through rainfall give results which are not always equal to the theoretical values (Ref.28). However, these results vary over wide limits and furthermore, are not available for all frequency bands.

The relationship between visibility in fog and water vapor content usually adopted is the empirical one (Ref.29), in which the attenuation is stated to be directly proportional to the water content, i.e. . . . . (*)

$$\bar{M} = 1660/d^{1.43}$$

where d = optical visibility in feet

M = average moisture content in grams/meter^3

This equation is used to give the "theoretical" attenuation in fog of various levels of obscuration. The equation gives a moisture content of 2.3 g/m^3 in fog characterized as 100 ft visibility fog. A moisture content of 0.83 g/m^3 is postulated for 200 ft visibility fog. But Dickson and Hales (Ref.30) give a water content of only 0.412 g/m^3 corresponding to a visibility of 200 ft. Matveev (Ref.31) also states that the maximum liquid water content of thick fog is 0.76 g/m^3. One can deduce, therefore, that the "theoretical" fog attenuation figures are pessimistic and, in practice, that the attenuation could be less than half the calculated value.

Since there are no practical attenuation figures that are universally accepted, we have based our calculations primarily upon the "theoretical" values adopted by radar engineers; these are listed in Table II-27. Although in practice the performance may differ from that predicted, a comparison of the relative performance with the different frequency bands will allow the optimum band to be chosen.

Another weather condition which must be considered is snow. The expression given by Gunn and East (Ref. 8) for the attenuation in snow shows that at X, Ku and Ka frequency bands, the attenuation is well below that of rain of equal water content. This also applies at V-band, except when the precipitation rate is equivalent to 16 mm/hr; in this case the attenuation in snow is shown to be approximately equal to that of the equivalent rainfall. Since the visibility in snow is poor, it is of interest to compare the attenuation in snowfall equivalent to 16 mm/hr with that of the attenuation experienced in 100 ft visibility fog. The attenuation of snow of this density is 0.014, 0.21, 0.51 and 5.8 dB/km (one way) for X, Ku, Ka and V-bands, respectively. A comparison with the figures for 100 ft fog given in Table II-27 shows that as regards attenuation, a system that operates satisfactorily in 100 ft fog should also operate satisfactorily in snowfall with a liquid content equal to 16 mm/hr. It should be noted that these theoretical attenuation values may be twice the typical values observed in practice. Also, fog at 0° has greater attenuation than the values shown here but its probability of occurrence was judged to be small.

(*) More recently Eldridge (Ref.1) has stated that the empirical relationship ($\bar{M} = 950/d^{1.54}$) gives results which agree with measurements, and with this value, the moisture content for 100 ft visibility fog is 0.8 gm/cm^3.

TABLE II-27. RAIN AND FOG ATTENUATION (dB/km, one-way)--THEORETICAL VALUES FOR 18°C.

Frequency Band	Rainfall Rates			Fog Densities	
	1 mm/hr	4 mm/hr	16 mm/hr	100 ft visibility	400 ft visibility
X	0.01	0.05	0.26	0.1	0.02
Ku	0.07	0.25	1.28	0.36	0.08
Ka	0.30	1.07	4.07	1.39	0.27
V	0.80	2.40	7.30	5.12	0.72

As discussed in Section 4, Vol. III, the back scatter from rain also affects performance by producing false signals. The amplitude of the echo is determined by the scattering cross section per unit volume and the theoretical values of this for various rainfall densities (Ref. 8) are listed in Table II-28 below.

Measurements at S-band show that the scattering coefficient is 4 to 10dB below the theoretical value (Ref. 8) and there are indications that this effect is also experienced at higher frequencies. However, in the absence of accepted empirically derived figures, we have used the theoretical values to make a comparison of performance obtained with radars operating at four different frequency bands.

TABLE II-28. RADAR CROSS SECTION (m^2/m^3) OF RAIN AT 18° C

Frequency Band	Rainfall Rates		
	1 mm/hr	4 mm/hr	16mm/hr
X	1.3×10^{-7}	1.0×10^{-6}	9×10^{-6}
Ku	1.3×10^{-6}	1.1×10^{-5}	6×10^{-5}
Ka	1.8×10^{-5}	1.3×10^{-4}	6×10^{-4}
V	2.6×10^{-4}	1.9×10^{-3}	8.7×10^{-3}

This table also applies to attenuation experienced due to back scatter on dry snow which has a liquid content equal to that of rain (Ref. 8).

The hydrometeors having the largest scattering cross sections are water-coated ice spheres, hail, which produce a so called "bright band". This band forms under special atmospheric conditions when the temperature is just above $0^{o}C$, and is only a few hundred feet in vertical extent. It has a scattering cross section of up to 10 dB greater than that of rain of equal water content. However, at maximum range where the effect of this unique return could be most serious, the "bright band" will, in general, occupy only a fraction of the total vertical beamwidth and, consequently, its echo will not be greater than that received from the rain under it. Its special effect, therefore, is disregarded in calculations of attenuation.

6.2.3 Initial Assumptions About Target Signatures. - The performance of an IALM depends upon the signals scattered back from ground at grazing angles as low as 3^{o}. Data appearing in Section 2, Vol. III, shows that very few measurements have been made of the scattering coefficient of various terrains at grazing angles of less than 10^{o}. Extrapolation of existing curves to 3^{o} gives values which are probably reasonably accurate at X and Ku-band frequencies but may be misleading at Ka-band. No results are available for V-band.

The ability of a mapping radar to detect and display an airport runway depends upon the difference between the scattering coefficient of the runway and that of the adjacent ground. The Ohio State University Terrain Handbook (Ref.26) shows that at a 10^{o} grazing angle the scattering coefficient of grass is about 20 dB above that of concrete and 10 dB above that of asphalt. In the absence of any empirical measurements, it is assumed that these figures hold, down to 3^{o} grazing, for the four frequency bands. In reality, the scattering characteristic may rise sharply as the angle is reduced to very small values. This possibility is affected by the type of polarization. It is also realized that at Ka and V-bands the surface roughness of runways is becoming large compared with the wavelength and, consequently, these assumptions may be incorrect. However, the good mapping pictures of airports obtained with Ka-band Airport-Surface Movement Radar Systems show that there is a satisfactory ratio at low grazing angles with this band.

The absolute scattering coefficient of the grass adjacent to the runway will vary from airport to airport depending upon length of grass, dryness of ground, frequency band, etc. For 2-inch grass, extrapolation of the Ohio State University results to 3^{o} incidence angle indicates that the value for X, Ku, and Ka-bands is approximately - 13 dB. Therefore, this figure has been assumed for all frequency bands.

6.2.4 Methodology. - The approach adopted in estimating the radar performance is to define the requirements to meet a given task in terms of a number of signal ratios, for example, terrain signal to noise, terrain signal to rain, etc. Equations giving these ratios are derived in Sections 5, 6 and 7of Vol. III for the various frequency bands and for different weather conditions. The ranges at which all the requirements are met are derived from these data. Although the ratio values adopted for the various requirements are subject to argument, it is considered that they give a realistic indication of the performance that would be obtained in practice.

In addition to calculating performance using the "theoretical" figures for attenuation of rain and fog, an estimate is also made of that obtained with the less pessimistic "typical" figures observed in practice. This will give a more realistic indication of in-service performance, but it should be treated with some caution because the attenuation and back scatter figures used are not universally accepted.

6.3 Radar Detection of Runways

6.3.1 Non-Cooperative Environment. - For a radar carried by an aircraft to have a landing monitor capability, it must be able to measure the aircraft's position and direction relative to the glide path. Glide Slope Monitoring satisfies the conceptual ILM requirement, but in reality the ILM would also predict and display the touchdown point as a desirable added capability. The simplest way of providing the monitoring capability is with a forward looking ground mapping radar which displays a map of the airport having sufficient definition for the pilot to be able to identify the runway and its threshold, together with an indication of aircraft track and distance to go. The advantage of this method is that it does not require any aids, either passive or active, on the ground.

It is also desirable for the radar to have means for measuring the aircraft's position with respect to the glide slope in the elevation plane. As will be shown in Section 6.3.3, this can be achieved, with a radar having monopulse or an interferometer capability in the vertical plane, by pitch stabilizing the boresight so that it is depressed below the horizontal by the amount of the glide path angle, and indicating on the display where the boresight intercepts the ground. The aircraft is on the glide slope when this intercept falls within the desired touchdown area.

A radar is able to detect runways because of the difference between the scattering coefficients of the runway surface and the adjacent ground. However, it should be noted that when the airport is covered with snow, this difference disappears and runways may not be detected. There are numerous airports with concrete or asphalt between the runways and this feature also makes it impossible for the runways to be identified. Because of these limitations, a strong case can be made for a system which does not rely entirely upon signals back scattered from the surface of the airport but rather employs radar reflectors or transponder beacons, suitably placed on the ground, to indicate runway position. These systems are discussed later on in the report.

(A) Visibility of Runway on a Display

Signal Level and Azimuth Beamwidth. - At a range 7 to 10 nm from runway threshold, which is the primary system range design requirement as established in Section 4, the display should indicate the line of the runway, and at ranges of 5 nm and less, the stated objective is to identify both the touchdown point and the intercept of the flight vector with the ground. Information should be available down to a minimum range which depends upon the landing category to be met. It is difficult to lay down precise minimum signal level and azimuth beamwidth conditions that will achieve this, since so much depends upon operator skill and adjustment of the equipment. Recall, too, that capabilities are described with respect to a 1-meter aperture. But in order to compare the performance of radars on different frequency bands, it is necessary to have standard conditions; therefore, for the purpose of this report, it has been assumed that the following requirements are to be met.

Requirements*

a) Azimuth beamwidth narrow enough to allow the pilot to align flight vector to center-line of runway to within 0.40°.

b) A drop in signal amplitude of more than 3 dB as the radar beam sweeps through the runway.

c) Signal from terrain adjacent to runway to be greater than 10 dB above receiver noise.

d) Signal from terrain adjacent to runway to be greater than 10 dB above that from rain at the same range.

In order to establish required runway direction relative to actual aircraft track, the radar must detect and display a reasonable portion of the runway. The amount required depends upon the picture quality but it is likely to be between 1/2 and 1 nm.

o X Band Radar. - In practice it has been found possible when using a display to estimate angular position to within one quarter toone half of the azimuth beamwidth. Since the X-band radar has an azimuth beamwidth of 2.5°, Requirement (a) is not met and it is, therefore, not considered suitable for an unassisted landing monitor for approaches to runways 150 feet in width.

* These requirements are referred to by letters (a) through (d) in the following text and tables.

To obtain acceptable performance with an X band radar without resorting to runway enhancement techniques to improve resolution, the antenna aperture would have to be increased to 1.7m which is too large for an airborne antenna in most current aircraft nose and radome installations. This would give the same detection ranges as those listed in the following paragraph for the Ku band radar with a 1-meter antenna, with the exception that there would be no reduction in range with 16mm/hr rainfall. This is due to the radar cross-section of rain being much less at X band.

o Ku-Band Radar. - Requirement (a) is marginally met with the Ku-band radar having an azimuth beamwidth of 1.5°.

As regards Requirement (b), from Figures III-28 and III-29, Section 5, Volume III, we obtain the following ranges for the detection of 300 ft. wide concrete and asphalt runways. The ranges are halved with 150 ft. wide runways.

TABLE II-29. RANGE (nm)* AT WHICH RUNWAY CAN BE IDENTIFIED ON A DISPLAY OF THE Ku BAND RADAR -- Requirement (b)

Runway Width	Concrete	Asphalt
150 ft.	2.2 (4.1)	2.0 (3.6)
300 ft.	4.4 (8.1)	3.9 (7.2)

It should be noted that as the range to runway is decreased, there is a rapid improvement in the ability of the radar to detect runways. At a range of 3 nm the change in signal as the beam sweeps through a 300 ft concrete runway has increased to 5 dB.

From the calculations made in Section 6, Volume III, the following tables listing the maximum ranges for Requirements (c) and (d), i.e. Terrain Signal/Noise greater than 10dB and Terrain Signal/Rain Echo greater than 10dB, are obtained.

TABLE II-30. RANGE (nm)* AT WHICH TERRAIN SIGNAL/NOISE RATIO HAS FALLEN TO 10 dB -- Requirement (c)

Pulse Length	Rainfall Rates				Fog Densities	
μ sec	0 mm/hr	1 mm/hr	4 mm/hr	16 mm/hr	400 ft	100 ft
1.0	70 (130)	37 (68)	19 (35)	6.5 (12)	32 (60)	15 (28)
0.5	44 (82)	27 (50)	15 (28)	5.9 (11)	24 (45)	12 (22)
0.1	15 (28)	12 (33)	8.1 (15)	3.8 (7)	11 (21)	7.0 (13)

* Ranges are given both in nm and km (kilometers in parentheses)

TABLE II-31. RANGE (nm)* AT WHICH TERRAIN SIGNAL/RAIN ECHO RATIO HAS FALLEN TO 10 dB WITH CIRCULAR POLARIZATION -- Requirement (d)

Rainfall, mm/hr	Range, nm (km)*
1	42 (77)
4	5.3 (9.8)
16	0.8 (1.5)

From Tables II-29, 30 and 31, the following table has been produced which lists the maximum range at which the Requirements (b), (c) and (d) are all satisfied. The Requirement that is limiting the range is given in the form of a lower case letter code immediately following each range entry in the table.

TABLE II-32. RANGE (nm)* AT WHICH THE Ku BAND RADAR DETECTS RUNWAYS

Runway	Pulse Length	Rainfall Rates				Fog Densities	
	μ sec	0 mm/hr	1 mm/hr	4 mm/hr	16 mm/hr	400 ft	100 ft
150 ft Concrete	1.0	2.2 (4.1) b	2.2 (4.1) b	2.2 (4.1) b	0.8 (1.5) d	2.2 (4.0) b	2.2 (4.0) b
	0.5	2.2 (4.1) b	2.2 (4.1) b	2.2 (4.1) b	0.8 (1.5) d	2.2 (4.0) b	2.2 (4.0) b
	0.1	2.2 (4.1) b	2.2 (4.1) b	2.2 (4.1) b	0.8 (1.5) d	2.2 (4.0) b	2.2 (4.0) b
300 ft. Concrete	1.0	4.4 (8.1) b	4.4 (8.1) b	4.4 (8.1) b	0.8 (1.5) d	4.4 (8.1) b	4.4 (8.1) b
	0.5	4.4 (8.1) b	4.4 (8.1) b	4.4 (8.1) b	0.8 (1.5) d	4.4 (8.1) b	4.4 (8.1) b
	0.1	4.4 (8.1) b	4.4 (8.1) b	4.4 (8.1) b	0.8 (1.5) d	4.4 (8.1) b	4.4 (8.1) b
150 ft. Asphalt	1.0	2.0 (3.6) b	2.0 (3.6) b	2.0 (3.6) b	0.8 (1.5) d	2.0 (3.7) b	2.0 (3.7) b
	0.5	2.0 (3.6) b	2.0 (3.6) b	2.0 (3.6) b	0.8 (1.5) d	2.0 (3.7) b	2.0 (3.7) b
	0.1	2.0 (3.6) b	2.0 (3.6) b	2.0 (3.6) b	0.8 (1.5) d	2.0 (3.7) b	2.0 (3.7) b
300 ft. Asphalt	1.0	3.9 (7.2) b	3.9 (7.2) b	3.9 (7.2) b	0.8 (1.5) d	3.9 (3.9) b	3.9 (3.9) b
	0.5	3.9 (7.2) b	3.9 (7.2) b	3.9 (7.2) b	0.8 (1.5) d	3.9 (3.9) b	3.9 (3.9) b
	0.1	3.9 (7.2) b	3.9 (7.2) b	3.9 (7.2) b	0.8 (1.5) d	3.9 (3.9) b	3.9 (3.9) b

* Ranges are given both in nm and km (kilometers in parentheses)
** Limiting Requirements are designated by lower case letters in each column.

This table shows that Requirement (b), change in signal amplitude of 3 dB, is the main limitation (See: Sec. 6.3.1.A); performance with respect to 300 ft. wide runways is marginally acceptable but the range is far too short for operation into 150 ft. runways. Of course, if the azimuth beamwidth could be reduced by increasing the antenna aperture, there would be marked improvement in performance.

An antenna horizontal aperture of 1m is the minimum that can be used with the Ku band radar if the specified azimuth angular accuracy is to be met. Increasing the aperture to 1.5m would reduce the azimuth beam-width to 1° and runway detection range in 100ft visibility fog would increase to over 3nm for 150ft runways and to over 6nm for 300ft runways. These ranges would be maintained in rainfall densities of up to 4mm/hr, but with 16mm/hr rainfall, the backscatter would reduce the detection range to a very low value.

- o Ka-Band Radar. - Requirement (a) is easily met with the Ka band radar since a one-meter aperture yields a 0.7° azimuth beamwidth.

From Section 5, Vol. III, we obtain the following table giving the range at which the runway is detected on the display.

TABLE II-33. RANGE (nm) * AT WHICH RUNWAY IS DETECTED ON A DISPLAY WITH Ka BAND RADAR --- Requirement (b)

Runway Width	Concrete	Asphalt
150 ft	4.8 (8.9)	4.3 (7.9)
300 ft	9.6 (17.8)	8.5 (15.7)

The ranges at which the Terrain Signal/Noise and Terrain Signal/Rain Echo ratios are 10 dB, are given in Tables III-13 & 14 (Vol. III) and are listed below, with the ranges expressed in nautical miles.

TABLE II-34. RANGE (nm) * AT WHICH TERRAIN SIGNAL/NOISE RATIO HAS FALLEN TO 10 dB --- Requirement (c)

Pulse Length (μ sec)	Rainfall Rates				Fog Densities	
	0 mm/hr	1 mm/hr	4 mm/hr	16 mm/hr	400 ft	100 ft
1.0	43 (80)	12 (23)	6.5 (12)	2.4 (4.5)	14 (26)	5.1 (9.5)
0.5	25 (47)	10 (20)	5.2 (9.6)	2.2 (4.0)	11 (20)	4.3 (8.0)
0.1	14 (26)	5.4 (10)	3.2 (6.0)	1.5 (2.7)	5.9(11)	2.7 (5.0)

* Ranges are given both in nm and km (kilometers in parentheses)

TABLE II-35. RANGE (nm) * AT WHICH TERRAIN SIGNAL/RAIN ECHO RATIO HAS FALLEN TO 10 dB WITH CIRCULAR POLARIZATION --- Requirement (d)

Rainfall, mm/hr.	Range, nm.*
1	3.2 (5.9)
4	0.5 (0.93)
16	0.1 (0.19)

The maximum range at which Requirements (b), (c) and (d) are all met are listed in Table II-36.

TABLE II-36. RANGE (nm)* AT WHICH THE Ka BAND RADAR DETECTS RUNWAYS

Runway	Pulse Length µ sec	Rainfall Rates 0 mm/hr	Rainfall Rates 1 mm/hr	Rainfall Rates 4 mm/hr	Rainfall Rates 16 mm/hr	Fog Densities 400 ft	Fog Densities 100 ft
150 ft. Concrete	1.0	4.8 (8.9) b	3.2 (5.9) d	0.5 (0.9) d	0.1 (0.2) d	4.8 (8.9) b	4.8 (8.9) b
	0.5	4.8 (8.9) b	3.2 (5.9) d	0.5 (0.9) d	0.1 (0.2) d	4.8 (8.9) b	4.3 (8.0) c
	0.1	4.8 (8.9) b	3.2 (5.9) d	0.5 (0.9) d	0.1 (0.2) d	4.8 (8.9) b	2.7 (5.0) c
300 ft. Concrete	1.0	9.6 (17.8) b	3.2 (5.9) d	0.5 (0.9) d	0.1 (0.2) d	9.6 (17.7) b	5.1 (9.5) c
	0.5	9.6 (17.8) b	3.2 (5.9) d	0.5 (0.9) d	0.1 (0.2) d	9.6 (17.7) b	4.3 (8.0) c
	0.1	9.6 (17.8) b	3.2 (5.9) d	0.5 (0.9) d	0.1 (0.2) d	5.9 (11) c	2.7 (5.0) c
150 ft. Asphalt	1.0	4.3 (7.9) b	3.2 (5.9) d	0.5 (0.9) d	0.1 (0.2) d	4.3 (7.9) b	4.3 (7.9) b
	0.5	4.3 (7.9) b	3.2 (5.9) d	0.5 (0.9) d	0.1 (0.2) d	4.3 (7.9) b	4.3 (7.9) b
	0.1	4.3 (7.9) b	3.2 (5.9) d	0.5 (0.9) d	0.1 (0.2) d	4.3 (7.9) b	2.7 (5.0) c
300 ft. Asphalt	1.0	8.5 (15.7) b	3.2 (5.9) d	0.5 (0.9) d	0.1 (0.2) d	8.5 (15.7) b	5.1 (9.5) c
	0.5	8.5 (15.7) b	3.2 (5.9) d	0.5 (0.9) d	0.1 (0.2) d	8.5 (15.7) b	4.3 (8.0) c
	0.1	8.5 (15.7) b	3.2 (5.9) d	0.5 (0.9) d	0.1 (0.2) d	5.9 (11) c	2.7 (5.0) c

With an antenna aperture of 0.5m, suitable for installation in the smaller commercial aircraft, the detection ranges would be reduced to those listed on Pages 89, 90 and 91 for the Ku band radar with a 1m antenna, except in rainfall of 4mm/hr and above. With rainfall of this density, the larger cross-section at Ka band would limit the range to below 0.5 nautical miles.

Note: ** Limiting Requirements are designated by lower case code letters in each column.
* Ranges are given both in nm and km (kilometers in parentheses).

An antenna with an aperture of 1.5m, suitable for installation in the larger commercial aircraft, would not give greater detection ranges in rain than those with a 1m antenna. In 100ft visibility fog, there would be a very small increase in range, but in 400ft fog, the range on 100ft runways with a 1μ s transmitter pulse would be greater than 10nm.

o V Band Radar. - The azimuth beamwidth of the V band radar is 0.35°; hence Requirement (a) is easily met.

As regards Requirement (b), no information is available on scattering coefficients at V-band but it is probable that the grass/runway ratio is smaller than is the case at lower frequencies. However, in the absence of empirical evidence, it is assumed to be the same.

From Section 5, Vol. III, the following table is obtained which lists the maximum range at which the runway is detected on the display.

TABLE II-37. RANGE (nm)* AT WHICH RUNWAY IS DETECTED ON A DISPLAY WITH THE V-BAND RADAR ** --- Requirement (b)

Runway Width	Concrete	Asphalt
150 ft.	9.7 (18)	8.6 (16)
300 ft.	19 (35)	17 (31)

From Section 6, Volume III, the following tables are obtained which list the ranges at which the Terrain Signal/Noise and Terrain Signal/Rain Echo ratios are 10 dB.

TABLE II-38. RANGE (nm)* AT WHICH TERRAIN SIGNAL/NOISE RATIO HAS FALLEN TO 10 dB ** --- Requirement (c)

Pulse Length	Rainfall Rates				Fog Densities	
μ sec	0 mm/hr	1 mm/hr	4 mm/hr	16 mm/hr	400 ft	100 ft
1.0	14 (26)	4.5(8.3)	2.5(4.7)	1.2(2.2)	5.0(9.2)	1.5(2.8)
0.5	8.6(16)	3.6(6.6)	2.1(3.9)	1.0(1.9)	4.0(7.4)	1.3(2.4)
0.1	3.0(5.5)	1.9(3.5)	1.3(2.4)	0.7(1.3)	2.2(4.0)	0.9(1.6)

** Limiting Requirements are designated by lower case letters in each column.

* Ranges are given both in nm and km (kilometers in parentheses)

TABLE II-39. RANGE (nm)* AT WHICH TERRAIN SIGNAL/RAIN ECHO RATIO HAS FALLEN TO 10 dB WITH CIRCULAR POLARIZATION --- ** Requirement (d)

Rainfall, mm/hr	Range, nm (km) *
1	0.25 (0.47)
4	0.032 (0.06)
16	0.008 (0.015)

The maximum range at which Requirements (b), (c) and (d) are all met are listed in Table II-40

TABLE II-40. RANGE (nm)* AT WHICH THE V-BAND RADAR DETECTS RUNWAYS **

Runway	Pulse Length	Rainfall Rates				Fog Densities	
	μ sec	0 mm/hr	1 mm/hr	4 mm/hr	16 mm/hr	400 ft	100 ft
150 ft Concrete	1.0	9.6 (18)b	0.25(.47)d	0.032(.06)d	.008(.015)d	4.9(9.2)c	1.5(2.8)c
	0.5	8.6 (16)c	0.25(.47)d	0.032(.06)d	.008(.015)d	3.8(7.4)c	1.2(2.4)c
	0.1	2.9 (5.5)c	0.25(.47)d	0.032(.06)d	.008(.015)d	1.9(4.0)c	0.9(1.6)c
300 ft Concrete	1.0	14.0 (26)c	0.25(.47)d	0.032(.06)d	.008(.015)d	4.9(9.2)c	1.5(2.8)c
	0.5	8.6 (16)c	0.25(.47)d	0.032(.06)d	.008(.015)d	3.8(7.4)c	1.2(2.4)c
	0.1	2.9 (5.5)c	0.25(.47)d	0.032(.06)d	.008(.015)d	1.9(4.0)c	0.9(1.6)c
150 ft Asphalt	1.0	8.5 (16)b	0.25(.47)d	0.032(.06)d	.008(.015)d	4.9(9.2)c	1.5(2.8)c
	0.5	8.5 (16)b	0.25(.47)d	0.032(.06)d	.008(.015)d	3.8(7.4)c	1.2(2.4)c
	0.1	2.9 (5.5)c	0.25(.47)d	0.032(.06)d	.008(.015)d	1.9(4.0)c	0.9(1.6)c
300 ft Asphalt	1.0	14.0 (26)c	0.25(.47)d	0.032(.06)d	.008(.015)d	4.9(9.2)c	1.5(2.8)c
	0.5	8.6 (16)c	0.25(.47)d	0.032(.06)d	.008(.015)d	3.8(7.4)c	1.2(2.4)c
	0.1	2.9 (5.5)c	0.25(.47)d	0.032(.06)d	.008(.015)d	1.9(4.0)c	0.9(1.6)c

The detection range of the V band radar is limited by the attenuation in rain and fog and not by the azimuth beamwidth. In fact, the azimuth beamwidth could be increased to 0.7^{o}, by a reduction in the aperture size to 0.5m, without there being any appreciable change in the detection range in rain and fog.

** Limiting Requirements are designated by lower case letters in each column.

* Ranges are given both in nm and km (kilometers in parentheses)

Increasing the aperture to 1.5m would improve the definition of the ground mapping picture, but the range in rain and fog would not be significantly altered. Table II-40 clearly shows that the performance of the V Band radar is seriously degraded in rain and fog.

o <u>Optimum Frequency Band for Detection of Runways</u>. - Table II-41 shows runway detection performance, under various weather conditions, of radars operating on X, Ku, Ka and V frequency bands, each of which utilizes a 1 meter antenna.

Because of its narrow beamwidth, the V-band radar is seen to have excellent performance in clear weather. But in theory the range in rain and fog will be drastically reduced. It can be argued that reduction of range in rain is not serious since visibility remains reasonably good and, hence, there is no requirement for a landing monitor. The equipment must, however, work satisfactorily in fog but Table II-41 shows that in 100 ft. visibility fog the maximum range from threshold at which a runway is detected is only 1.5 nm with a pulse length of 1.0 μs. The detection range is smaller if "detection" implies that a significant length of runway is being observed. It has already been mentioned that the attenuation figures assumed for fog may be pessimistic. If the water content in 100 ft visibility fog turns out to be half the assumed value, the maximum detection range increases from 1.5 to 2.3 nm.

At Ku-band, the range at which one mile of runway will be perceived is limited by the azimuth beamwidth to between 1 and 3.4 nm from threshold, depending upon the runway composition and its width, in all weather conditions except 16 mm/hr rain.

With the constraints on the antenna aperture and transmitter power, the optimum frequency band for best performance in fog is that at which Requirements (b) and (c) are met at the same range. Examination of the Ka band performance figures for 100 ft. fog shows that the requirement responsible for the limitation in range changes from attenuation to angular discrimination, depending upon the runway width. Hence, for a radar that has to deal with both runway widths, Ka is the optimum frequency band. With a transmitter pulse length of 1.0 μs the range varies from 3 to 4.4 nm depending upon the runway surface and its width. The range capability increases to 7 nm for 300 ft runways assuming 'typical' attenuation in 100 ft. fog.

The maximum range of the Ku band radar is not affected by the transmitter pulse length. But reducing the pulse length of the Ka and V-band radars reduces the maximum range. For a system to work in a 100 ft. visibility fog, the radar minimum range should also be 100 ft and this requires a pulse length of 0.1 μs. Similarly, the pulse length of the radar to cater to a minimum visibility of 400 ft. should not exceed 0.5 μs. Applying these conditions, the maximum range in a 100 ft. fog on a 150 ft. concrete runway is 2.9 nm and 0.9 nm, respectively for Ka and V-bands. The radar with a 400 ft. minimum visibility would have a maximum range, in 400 ft. fog on a 150 ft. concrete runway, of 4.8 nm and 3.8 nm, respectively, for the Ka and V-bands.

TABLE II-41. A SUMMARY OF DETECTION RANGES FOR UNENHANCED RUNWAYS

Runway Width and Material	Pulse Width µs	Rainfall Rates												Fog Densities					
		0 mm/hr			1 mm/hr			4 mm/hr			16 mm/hr			400 ft			100 ft		
		Ku	Ka	V	Ku	Ka	V	Ku	Ka	V	Ku	Ka	V	Ku	Ka	V	Ku	Ka	V
150' Concrete	1.0	2.2	4.8	9.6	2.2	3.2	0.25	2.2	0.5	0.032	0.8	0.1	0.008	2.2	4.8	4.9	2.2	4.8	1.5
	0.5	↓	↓	8.6	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	3.8	↓	4.3	1.2
	0.1	↓	↓	2.9	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	1.9	↓	2.7	0.9
300' Concrete	1.0	4.4	9.6	14	4.4	↓	↓	4.4	↓	↓	↓	↓	↓	4.4	9.6	4.9	4.4	5.1	1.5
	0.5	↓	↓	8.6	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	9.6	3.8	↓	4.3	1.2
	0.1	↓	↓	2.9	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	5.9	1.9	↓	2.7	0.9
150' Asphalt	1.0	2.0	4.3	8.5	2.0	↓	↓	2.0	↓	↓	↓	↓	↓	2.0	4.3	4.9	2.0	4.3	1.5
	0.5	↓	↓	8.5	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	3.8	↓	4.3	1.2
	0.1	↓	↓	2.9	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	1.9	↓	2.7	0.9
300' Asphalt	1.0	3.9	8.5	14	3.9	↓	↓	3.9	↓	↓	↓	↓	↓	3.9	8.5	4.9	3.9	5.1	1.5
	0.5	↓	↓	8.6	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	8.5	3.8	↓	4.3	1.2
	0.1	↓	↓	2.9	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	5.9	1.9	↓	2.7	0.9

FREQUENCY BAND

The effect that the size of the horizontal aperture of the antenna has on the detection range of runways is shown in Table II-42. This lists the ranges obtained in 400 ft. visibility fog with apertures of 0.5m, 1.0m and 1.5m, for transmitter pulse lengths of 1.0 μs and 0.5 μs.

TABLE II-42. VARIATION OF RUNWAY DETECTION RANGE WITH ANTENNA APERTURE

Antenna Aperture (m)	Runway Width (ft)	Runway Detection Range in 400 ft Fog					
		Ku Band		Ka Band		V Band	
		1.0μs	0.5μs	1.0μs	0.5μs	1.0μs	0.5μs
0.5	300 ft	0 0	0 0	4.4 (8.2)	4.4 (8.2)	4.5 (8.3)	3.5 (6.5)
	150 ft	0 0	0 0	2.2 (4.1)	2.2 (4.1)	4.5 (8.3)	3.5 (6.5)
1.0	300 ft	4.4 (8.1)	4.4 (8.1)	9.6 (17.7)	9.6 (17.7)	4.9 (9.2)	3.8 (7.4)
	150 ft	2.2 (4.0)	2.2 (4.0)	4.8 (8.9)	4.8 (8.9)	4.9 (9.2)	3.8 (7.4)
1.5	300 ft	6.0 (11.1)	6.0 (11.1)	15.0 (27.8)	11.0 (20.4)	5.2 (9.6)	4.0 (7.4)
	150 ft	3.0 (5.6)	3.0 (5.6)	10.0 (18.5)	10.0 (18.5)	5.2 (9.6)	4.0 (7.4)

The performance of the V-band radar is limited by the attenuation in the rain and fog and, as a result, the variation of detection range with aperture size is quite small. With both the Ku and Ka band radars the detection range increases with an increase in the size of the antenna aperture. If good performance in rain is not essential, the optimum frequency band for a radar with a 0.5m antenna is V band. But when space is available for a 1.5m antenna Ka is the optimum frequency band.

Table II-41 demonstrates that none of the frequencies considered provides for the 7 to 10 mile range desired. It is concluded, therefore, that direct observation of the unenhanced runway is not a promising concept, and that some form of runway enhancement is desirable.

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* Ranges are given both in nm and km (kilometers in parentheses).

(B) Interference

o Causes of Interference. - For the radar to perform satisfactorily as a landing monitor, the display should not be obscured with interfering signals from other radars. A limited number of spurious returns will not be troublesome since the interference signals reveal themselves by moving about the display; however a continuous presentation of false signals or frequent presentation of a large number of interfering signals could make it very difficult to detect the runway.

The strongest form of interference occurs when the beams of two aircraft are pointed directly at each other. Table III-32, Volume III, summarizes an analysis for the ranges at which this kind of interference can occur. It shows that, in theory, at Ku band most aircraft within optical range could contribute to the creation of an interference pattern. The table also shows that, even in 100 ft visibility fog, interference can be generated over a range of 50 nm.

Signals transmitted by one aircraft and reflected from the ground into the radar receiver of a second aircraft can produce interference under certain conditions. Section 7 (Volume III) shows that the ratio of interference signal to desired signal has a maximum value when the range to the ground along the antenna boresight of the aircraft causing the interference is at its minimum value. The maximum value occurs just before the aircraft flares out for touchdown. Table III-33 of Section 7, Volume III, shows that with X and Ku bands operating in 100 ft visibility fog, aircraft out to 10 nm from touchdown could be subject to interference. Interference occurs only when the antenna beams intercept the same patch of ground and the interfering carrier frequency is within the receiver pass band.

With an azimuth beamwidth of β° and a sector scan of Φ°, the probability of the beams intercepting the same patch of ground is 1 in $(\Phi/\beta)^2$. Thus, with Ku-band radars having azimuth beamwidths of 1.5° and sector scans of 60°, the probability is one in 1600. The aircraft capable of producing interference are all those within a 10 nm radius of touchdown having a scan pattern which intersects that of the landing aircraft. The number of aircraft meeting these conditions is probably less than 10 and, consequently, the total probability of interference with the Ku-band radar is 1 in 160. It would be lower still with the Ka-band radar because of its narrower beamwidth.

The ranges over which side-lobe-to-side-lobe transmission of interference can occur is shown in Table III-31, Volume III. In the case of side-lobe transmission, the interference is independent of the directions in which the antennas are pointing. This type of interference can occur over substantial ranges. For example, with an 0.5 μs Ku band radar, aircraft similarly equipped within a radius of 97 nm could cause interference in clear weather. Since there could be up to 100 aircraft within this range of a busy airport, the potential interference could be serious. But it is interesting to note that under conditions when a landing monitor is really needed, i.e., 100 ft visibility fog, the range is very much reduced.

In 100 ft visibility fog, the interference is significant over a range of approximately 1 nm at V band, 5 nm at Ka band, 20 nm at Ku band, and 60 nm at X band.

o Methods for Overcoming Interference. - As regards the direct side-lobe to side-lobe interference, no alleviation is obtained from the low probability of the two antennas pointing at each other. The simplest way of reducing interference is to space the transmitter frequencies over a wide band. For example, if it were possible to utilize 50 separate channels, when there are 100 aircraft within interference range, an average of only two cause interference. In poor visibility, the number of radar equipped aircraft likely to be within interference range is assumed to be very much less than 100, and hence, the probability of interference becomes very small.

With main beam to side-lobe direct interference, any radar within optical range can, regardless of weather conditions, cause interference. Assuming there are 160 aircraft within this range; then, on average, antenna beam scanning reduces the number of radars producing interference signals at any one time to $160 \times \beta/\Phi$, where β is the azimuth beamwidth and Φ the sector scan angle. This number is 4 with a Ku-band radar. If the transmitter frequencies were spaced over a wide band, this type of interference would not be troublesome.

6.3.2 Passively-Cooperative Environment. - For identification of a runway with a mapping radar there must be a difference between the scattering coefficients of the runway and the adjacent ground. This is the case with airports having concrete runways surrounded by grass. However, when the airport is covered with snow, or when the ground between runways is paved with concrete or asphalt, there may be considerably less difference between the returns from the two areas; thus, the runway may be more difficult to see.

One method of overcoming this problem is to identify the runway with passive reflectors. Three ways of using these for IALM purposes are set out below:

1. A display showing reflectors and intercept point of flight vector. The pilot monitors the approach by noting the position of the flight vector intercept with respect to the touchdown reflector. A slight complication with this method can be experienced since the touchdown reflector has to be placed to one side of the runway thereby requiring use of an offset technique.

2. The radar is locked-on in azimuth and elevation planes to the touchdown reflector. From the angular information obtained the position of the aircraft relative to the glide path can be computed.

3. A track while scan radar is employed which tracks the touchdown reflector. This can provide, in addition to position relative to glide path, a high ground detection capability.

In this section we are mainly concerned with determining the optimum frequency band for the detection of reflectors. For this it is assumed that the following requirements must be met.

a) A number of reflectors might be placed so as to produce a pattern on the cockpit display which is immediately identifiable at a range of say 10 nm and indicates runway alignment and its threshold. A concept of this kind strongly suggests automated pattern recognition - an added degree of complexity.

b) The azimuth beamwidth of the radar must be small enough to prevent any large object or building on the airport being in the same pulse packet as the reflector.

c) For the required azimuth angular accuracy of 0.4°, the azimuth beamwidth should not exceed 2.0°. Alternatively, monopulse resolution enhancement may be employed in the horizontal plane and in this case the beamwidth need only be less than 10°.

d) The signal from a reflector should be 10 dB above noise.

e) The signal from a reflector should be 10 dB above the signal from terrain at the same range.

f) The signal from a reflector should be 10 dB above signal from rain at the same range.

Requirement (a) can be met with a variety of patterns. One suggestion is shown in Figure II-17, but the optimum pattern for a given airport will depend upon disposition of its buildings, aircraft parking areas, adjacent metropolitan features, etc. With a sufficient number of reflectors, it would, in theory, be possible to produce a coded pattern giving the identity of the airport. However, past experience (Ref.32) shows that confusion with returns from airport buildings makes runway identification difficult at a range of 10 nm.

Regarding Requirement (b), the X band radar with an azimuth beam width of 2.5° has a pulse packet width of 2,650 ft. at a range of 10 nm and, consequently, difficulty may be found in finding places for reflectors more than this distance from buildings. But with the higher frequency bands, this factor will be less of a problem because the width of the pulse packet will be correspondingly smaller.

To meet Requirement (c) with the X band radar, monopulse resolution improvement will have to be used in the azimuth plane. This will not be necessary on the other bands.

Requirements (d), (e) and (f) should be met with a reflector placed 1 nm beyond the threshold so that the line of the runway can be established. These requirements depend on equipment parameters and propagation conditions and will be considered separately for each frequency band.

The Ku, Ka, and V Band radars are postulated to be circularly polarized and the radar cross-section of a typical corner reflector will be below that obtained with linear polarization. However, this can be remedied by using the technique proposed by Latmiral and Sposito (Ref.33). These sources describe a method for improving the response of a corner reflector to a circularly polarized transmission by adding a wire grid to the reflector.

The individual elements of this combined analysis are contained in Section 6 of Volume III. In the following paragraphs, the results are reiterated and combined.

o X-Band Radar. - From Section 6 of Volume III, we obtain the following tables giving performance with a reflector having an echoing area of 1000 meters^2. This is produced with a corner reflector having a side dimension of 68 cms.

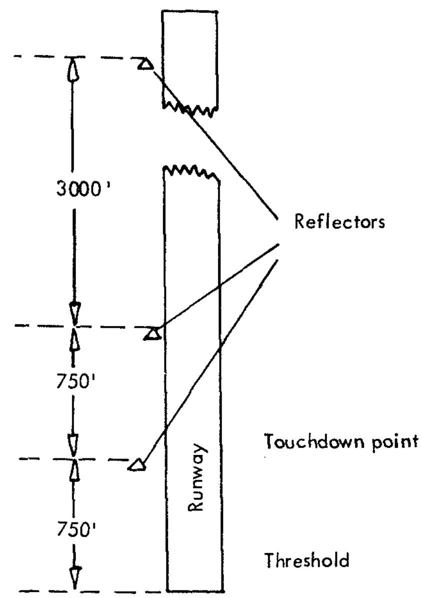


Figure II-17. Disposition of Reflectors

TABLE II-43. RANGE (nm)* AT WHICH THE REFLECTOR SIGNAL/NOISE RATIO HAS FALLEN TO 10 dB. ** --- Requirement (d)

Pulse Length µ sec	Rainfall Rates				Fog Densities	
	0 mm/hr	1 mm/hr	4 mm/hr	16 mm/hr	400 ft	100 ft
1.0	54 (100)	49 (90)	37 (68)	18 (34)	44 (82)	28 (52)
0.5	45 (84)	40 (74)	33 (61)	17 (32)	38 (70)	25 (47)
0.1	30 (56)	28 (51)	24 (44)	14 (26)	25 (47)	19 (36)

** Limiting Requirements are designated by lower case letters in each column.

* Ranges are given both in nm and km (kilometers in parentheses)

TABLE II-44. RANGE (nm)* AT WHICH THE REFLECTOR SIGNAL/TERRAIN SIGNAL RATIO HAS FALLEN TO 10 dB. ** --- Requirement (e)

Pulse Length (μs)	Range, nm (km) *
1.0	3.1 (5.7)
0.5	6.0 (11.0)
0.1	31.0 (57.0)

TABLE II-45. RANGE (nm)* AT WHICH THE REFLECTOR SIGNAL/RAIN ECHO RATIO HAS FALLEN TO 10 dB WITH LINEAR POLARIZATION --- ** Requirement (f)

Pulse Length μ sec.	Rainfall Rates		
	1 mm/hr	4 mm/hr	16 mm/hr
1.0	16 (30)	5.9 (11)	1.8 (3.4)
0.5	23 (43)	8.1 (15)	2.6 (4.8)
0.1	51 (95)	18 (34)	5.9 (11)

The three tables are combined to give the maximum range at which Requirements (d), (e) and (f) are all met. The Ranges are listed in Table II-46 together with the limiting requirement.

TABLE II-46. MAXIMUM RANGE (nm)* OF THE X-BAND RADAR ON A 1000 METER^2 REFLECTOR --- ** Limiting Requirement (see footnote)

Pulse Length μ sec	Rainfall Rates				Fog Densities	
	0 mm/hr	1 mm/hr	4 mm/hr	16 mm/hr	400 ft	100 ft
1.0	3.1(5.7)e	3.1(5.7)e	3.1(5.7)e	1.8(3.4)f	3.1(5.7)e	3.1(5.7)e
0.5	5.9(11)e	5.9(11)e	5.9(11)e	2.6(4.8)f	5.9(11)e	5.9(11)e
0.1	30 (56)d	28 (51)d	18.0(34)f	5.9(11)f	25 (47)d	19 (36)d

** Limiting Requirements are designated by lower case letters in each column.

* Ranges are given both in nm and km (kilometers in parentheses)

o Ku Band Radar. - Since a corner reflector with a side dimension of 68 cms is somewhat large, a smaller one, still giving an echoing area of 1000 meter^2, is considered for the Ku band radar. Such a reflector would have a side dimension of 54 cms. From Section 6, Vol. III, the ranges for Requirements (d), (e) and (f) are listed below.

TABLE II-47. RANGE (nm)* AT WHICH REFLECTOR SIGNAL/NOISE RATIO HAS FALLEN TO 10 dB. --- ** Requirement (d)

Pulse Length	Rainfall Rates				Fog Densities	
μ sec	0 mm/hr	1 mm/hr	4 mm/hr	16 mm/hr	400 ft	100 ft
1.0	65 (120)	38 (70)	22 (41)	7.6 (14)	34 (63)	18 (33)
0.5	54 (100)	34 (63)	21 (38)	7.0 (13)	31 (58)	17 (31)
0.1	36 (67)	27 (50)	17 (31)	6.5 (12)	24 (45)	14 (26)

TABLE II-48. RANGE (nm)* AT WHICH REFLECTOR SIGNAL/TERRAIN SIGNAL RATIO HAS FALLEN TO 10 dB. --- ** Requirement (e)

Pulse Length μ sec	Range, nm (km) *
1.0	5.0 (9.3)
0.5	10 (19)
0.1	50 (93)

** Limiting Requirements are designated by lower case letters in each column.
* Ranges are given both in nm and km (kilometers in parentheses)

TABLE II-49. RANGE (nm)* AT WHICH REFLECTOR SIGNAL/RAIN ECHO HAS FALLEN TO 10 dB WITH CIRCULAR POLARIZATION
--- ** Requirement (f)

Pulse Length μs	Rainfall Rates		
	1 mm/hr	4 mm/hr	16 mm/hr
1.0	46 (85)	16 (30)	6.5 (12)
0.5	65 (120)	23 (42)	9.2 (17)
0.1	143 (265)	51 (94)	20 (37)

From Tables II-47, 48 and 49, the maximum ranges which meet all the Requirements (d), (e) and (f), are obtained and these are listed in the Table II-50.

TABLE II-50. MAXIMUM RANGE (nm)* OF THE Ku BAND RADAR ON A 1000 METER^2 REFLECTOR. --- ** Limiting Requirement (see footnote)

Pulse Length μ sec	Rainfall Rates				Fog Densities	
	0 mm/hr	1 mm/hr	4 mm/hr	16 mm/hr	400 ft	100 ft
1.0	5.0(9.3)e	5.0(9.3)e	5.0(9.3)e	5.0(9.3)e	5.0(9.3)e	5.0(9.3)e
0.5	10 (19)e	10 (19)e	10 (19)e	7.0(13)d	10 (19)e	10 (19)e
0.1	36 (67)d	27 (50)d	17 (31)d	6.5(12)d	24 (45)d	14 (26)d

o Ka Band Radar. - At Ka band frequency, a corner reflector with an echoing area of 1000 meter^2 has a side dimension of 36 cm; the ranges at which the signal reflected from it meets Requirements (d), (e) and (f) are listed in the following tables. These tables have been derived from Section 6, Vol. III.

** Limiting Requirements are designated by lower case letters in each column.

* Ranges are given both in nm and km (kilometers in parentheses)

TABLE II-51. RANGE (nm)* AT WHICH REFLECTOR SIGNAL/NOISE RATIO HAS FALLEN TO 10 dB ** --- Requirement (d)

Pulse Length µ sec	Rainfall Rates				Fog Densities	
	0 mm/hr	1 mm/hr	4 mm/hr	16 mm/hr	400 ft	100 ft
1.0	54 (100)	17 (32)	8.1 (15)	3.2 (6)	19 (36)	7.0 (13)
0.5	45 (84)	16 (30)	7.6 (14)	3.1 (5.7)	17 (32)	6.5 (12)
0.1	30 (56)	12 (23)	6.5 (12)	2.8 (5.1)	14 (26)	5.4 (10)

TABLE II-52. RANGE (nm)* AT WHICH THE REFLECTOR SIGNAL/TERRAIN SIGNAL HAS FALLEN TO 10 dB ** --- Requirement (f)

Pulse Length µ sec	Range, nm (km) *
1.0	11 (20)
0.5	22 (40)
0.1	108 (200)

TABLE II-53. RANGE (nm)* AT WHICH THE REFLECTOR SIGNAL/RAIN ECHO HAS FALLEN TO 10 dB WITH CIRCULAR POLARIZATION ** --Requirement (f)

Pulse Length	Rainfall Rates		
µs	1 mm/hr	4 mm/hr	16 mm/hr
1.0	19 (35)	7.6 (14)	3.3 (6.1)
0.5	26 (49)	10 (19)	4.6 (8.6)
0.1	59 (110)	23 (43)	10 (19)

* Ranges are given both in nm and km (kilometers in parentheses)

The maximum range at which Requirements (d), (e) and (f) are all met is listed in the following table.

TABLE II-54. MAXIMUM RANGE (nm) * OF THE Ka BAND RADAR ON A 1000 METER^2 REFLECTOR ** --- Limiting Requirement (see footnote)

Pulse Length	Rainfall Rates				Fog Densities	
μ sec	0 mm/hr	1 mm/hr	4 mm/hr	16 mm/hr	400 ft	100 ft
1.0	11 (20) e	11 (20) e	7.6 (14) f	3.2 (6) d	11 (20) e	7.0 (13) d
0.5	22 (40) e	16 (30) d	7.6 (14) d	3.1 (5.7) d	17 (32) d	6.5 (12) d
0.1	30 (56) d	12 (23) d	6.5 (12) d	2.8 (5.1) d	14 (26) d	5.4 (10) d

o V Band Radar. - The performance of the V band radar on a 1000 meter^2 reflector is listed in the following tables. The corner reflector with this echoing area has a 26 cms side.

TABLE II-55. RANGE (nm)* AT WHICH THE REFLECTOR SIGNAL/NOISE HAS FALLEN TO 10 dB ** --- Requirement (d)

Pulse Length	Rainfall Rates				Fog Densities	
μ sec.	0 mm/hr	1 mm/hr	4 mm/hr	16 mm/hr	400 ft	100 ft
1.0	27 (50)	7.6 (14)	4.0 (7.4)	1.8 (3.4)	8.1 (15)	2.3 (4.3)
0.5	23 (43)	7.0 (13)	3.8 (7.0)	1.7 (3.2)	7.6 (14)	2.2 (4.1)
0.1	15 (28)	5.4 (10)	3.2 (5.9)	1.5 (2.8)	5.4 (10)	1.9 (3.5)

* Ranges are given both in nm and km (kilometers in parentheses)

** Limiting Requirements are designated by lower case letters in each column.

TABLE II-56. RANGE (nm)* AT WHICH THE REFLECTOR SIGNAL/TERRAIN SIGNAL HAS FALLEN TO 10 dB ** --- Requirement (e)

Pulse Length (μ sec)	Range, nm (km) *
1.0	22 (40)
0.5	43 (80)
0.1	216 (400)

TABLE II-57. RANGE (nm)* AT WHICH THE REFLECTOR SIGNAL/RAIN ECHO HAS FALLEN TO 10 dB WITH CIRCULAR POLARIZATION ** --- Requirement (f)

Pulse Length μs	Rainfall Rates		
	1 mm/hr	4 mm/hr	16 mm/hr
1.0	7.6 (14)	2.6 (4.9)	1.4 (2.5)
0.5	10 (19)	3.6 (6.7)	1.8 (3.4)
0.1	24 (44)	8.1 (15)	4.2 (7.8)

From Tables II-55, 56 and 57, the following table is obtained which lists the maximum range that at which Requirements (d), (e) and (f) are all met.

* Ranges are given both in nm and km (kilometers in parentheses)

TABLE II-58. MAXIMUM RANGE (nm)* OF THE V-BAND RADAR ON A 1000 METER^2 REFLECTOR ** --- Limiting Requirement (see footnote)

Pulse Length µ sec.	Rainfall Rates				Fog Densities	
	0 mm/hr	1 mm/hr	4 mm/hr	16 mm/hr	400 ft	100 ft
1.0	22 (40)e	7.6 (14)f	2.6 (4.9) f	1.4 (2.5) f	8.1 (15) d	2.3 (4.3) d
0.5	23 (43)d	7.0 (13)d	3.6 (6.7) f	1.7 (3.2) d	7.6 (14) d	2.2 (4.1) d
0.1	15 (28)d	5.4 (10)d	3.2 (5.9)d	1.5 (2.8) d	5.4 (10) d	1.9 (3.5) d

* Ranges are given both in nm and km (kilometers in parentheses)
** Limiting Requirements are designated by lower case letters in each column.

(B) Interference. - With runway reflectors, the background interference from other aircraft is not so pronounced as it is with with unenhanced runways. This is because the interference signal has to be greater than the reflector signal instead of the terrain signal, and the system is designed so that the reflector signal is always more than 10 dB above the terrain signal.

Section 6.3.1.B shows that with unenhanced runways interference signals will appear on the PPI but the amount should not be too troublesome. Hence, with runway reflectors interference should not be a "problem".

Optimum Frequency Band for the Detection of Runway With Passive Reflector Enhancement. - Table II-59 lists the ranges at which a 1000 m^2 reflector is detected in 100-ft visibility fog, with radars operating on different frequency bands employing antennas with horizontal apertures of 0.5 m, 1.0 m and 1.5 m. Ranges are given for transmitter pulse lengths of 1.0, 0.5 and 0.1 µsec.

This Table shows that the detection range falls with a decrease in the size of the horizontal aperture of the antenna but, even with a 0.5 m antenna (aperture), adequate ranges can be obtained with the X- and Ku-band radars.

In summary, it has been shown that the best performance with a reflector having the smallest mechanical dimensions is obtained with the Ku band radar. A Ku band radar having a 0.1 µsec pulse and a nominal 1 m antenna requires a corner reflector with a side dimension of 37. 5 cms in order to achieve a detection range of 10 nm in 100 ft visibility fog. Installation conditions might either dictate a smaller antenna or allow a larger antenna. Using the same reflector, reducing the antenna size from 1 m to 0.5 m reduces the range from 10 nm to 7 nm On the other hand, increasing the antenna size from 1 m to 1.5 m increases the detection range from 10 nm to 12 nm.

The following subparagraphs, including Tables II-60, 61 and 62 contain a discussion showing how these results were obtained.

The detection range of reflectors having a radar cross-section of 1000 m^2 is shown in Table II-60 . Which is the optimum frequency is not immediately obvious from the Table, since the choice depends upon a determination as to which operational feature is considered most important.

V-band would probably be ruled out because of its inherently poor performance in rain and in 100 ft. visibility fog. It has, however, excellent performance in clear weather and offers quite reasonable performance in 400 ft. visibility fog.

The X-band radar with a narrow transmitter pulse gives excellent performance in most weather conditions, including rainfall rates of up to 16 mm/hr. However, if there is a requirement for the display to be supplemented with a radar map of the runway, the wide beamwidth at X band precludes this frequency.

Both the Ku and Ka-band radars provide good performance in all weather conditions except very heavy rainfall; the ranges offered at Ku band are somewhat greater than at Ka band because of the lower attenuation experienced in rain and fog.

TABLE II-59. DETECTION RANGE (nm)* IN 100-ft FOG OF 1000 m^2 REFLECTOR WITH ANTENNAS OF VARIOUS HORIZONTAL SIZES

Frequency Band	Pulse Length (μs)	Antenna Horizontal Aperture (m)		
		0.5 m	1.0 m	1.5 m
X	1.0	1.5 (2.8)	3.1 (5.7)	4.7 (8.7)
	0.5	3.0 (5.6)	5.9 (11)	9.0 (16.7)
	0.1	15.0 (27.8)	19 (36)	22.0 (40.8)
Ku	1.0	2.5 (4.6)	5.0 (9.3)	7.5 (13.9)
	0.5	5.0 (9.3)	10 (19)	15.0 (27.8)
	0.1	10.0 (18.5)	14 (26)	17.0 (31.5)
Ka	1.0	4.9 (9.1)	7.0 (13)	9.1 (16.9)
	0.5	4.5 (8.3)	6.5 (12)	8.2 (15.2)
	0.1	3.8 (7.0)	5.4 (10)	6.7 (12.4)
V	1.0	1.6 (3.0)	2.3 (4.3)	2.9 (5.4)
	0.5	1.5 (2.8)	2.2 (4.1)	2.7 (5.0)
	0.1	1.3 (2.4)	1.9 (3.5)	2.4 (4.4)

* Ranges are given both in nm and km (kilometers in parentheses)

Table II-60 shows that a reflector cross-section of 1000 m^2 is unnecessarily large, especially at the lower frequencies, because for the most part the range capability exceeds the required 10 nm. A corner reflector only displays a correct cross section over a particular range of incidence angles . .. that is when the reflecting surfaces are at the correct angle to one another within a close tolerance. The larger the cross section, the closer is the required tolerance. It will be difficult to achieve this with 1000 $meter^2$ reflectors; hence, it is very desirable to reduce the reflector size.

The minimum reflector cross section for a given range is obtained when the pulse length is such that the Reflector Signal/Noise and Reflector Signal/Terrain Signal are both equal to 10 dB at the stated range. Values for the cross section and pulse length that meet this requirement have been presented in Section 6 of Volume III, and from these data Table II-61 has been derived for 100-ft visibility fog, the most stringent of the meteorological design criteria.

TABLE II-60. RANGE (nm) AT WHICH A 1000 m^2 REFLECTOR IS DETECTED

(a) Under Nominal Rainfall Rates

Pulse Width μs	Rainfall Rates 0 mm/hr X	Ku	Ka	V	1 mm/hr X	Ku	Ka	V	4 mm/hr X	Ku	Ka	V	16 mm/hr X	Ku	Ka	V
1.0	3.1	5	11	22	3.1	5	11	7.6	3.1	5	7.6	2.6	1.8	5	3.2	1.4
0.5	5.9	10	22	23	5.9	10	16	7.0	5.9	10	7.6	3.6	2.6	7	3.1	1.7
0.1	30	36	30	15	28	27	12	5.4	18	17	6.5	3.2	5.9	6.5	2.8	1.5

FREQUENCY BAND

(b) Under the two Selected Fog Density Conditions

Pulse Width μs	Fog Densities 400 ft X	Ku	Ka	V	100 ft X	Ku	Ka	V
1.0	3.1	5.0	11	8.1	3.1	5.0	7.0	2.3
0.5	5.9	10	17	7.6	5.9	10	6.5	2.2
0.1	25	24	14	5.4	19	14	5.4	1.9

FREQUENCY BAND

TABLE II-61. OPTIMUM CORNER REFLECTOR SIZE AND TRANSMITTER PULSE LENGTH FOR VARIOUS DETECTION RANGES IN 100 ft FOG

Frequency Band	Maximum Detection Range, nm * →	10	5	2
X	Reflector Cross Section, m^2	130	19	1.6
	Reflector Side Dimension, cm	51	25	13.5
	Pulse Length, μs	0.04	0.01	0.002
Ku	Reflector Cross Section, m^2	220	17	1.0
	Reflector Side Dimension, cm	37.5	20	1.2
	Pulse Length, μs	0.10	0.015	0.002
Ka	Reflector Cross Section, m^2	2500	220	2.6
	Reflector Side Dimension, cm	46	25.5	8.3
	Pulse Length, μs	2.5	0.35	0.013
V	Reflector Cross Section, m^2	2×10^{12}	2.7×10^6	220
	Reflector Side Dimension, cm	—	—	17.7
	Pulse Length, μs	4×10^9	9.3×10^3	2.2

The 'theoretical' attenuation for fog has been assumed in this table; if this value is halved -- to give an indication of probable performance in practice -- the values for Ka and V bands change to those listed in Table II-62. The performance at X and Ku bands is only slightly affected.

Tables II-61 and II-62 show that for a maximum range requirement of 10 nm, either X or Ku band radars should be used. If the attenuation in fog is less than the theoretical value, it would be possible to use a radar operating on Ka band. With V band, the maximum practical detection range in 100-ft visibility fog is only about 3 nm, and this is achieved only when the attenuation is half the theoretical value.

TABLE II-62. OPTIMUM CORNER REFLECTOR SIZE AND TRANSMITTER PULSE LENGTH FOR VARIOUS DETECTION RANGES IN 100 ft FOG -- HALF THEORETICAL ATTENUATION

Frequency Band	Maximum Detection Range, nm * →	10	5	2
Ka	Reflector Cross Section, m^2	1000	46	1.4
	Reflector Side Dimension, cm	37	17.2	7.2
	Pulse Length, μs	1.0	0.07	0.007
V	Reflector Cross Section, m^2	very	very	21
	Reflector Side Dimension, cm	large	large	10.2
	Pulse Length, μs	values	values	0.2

In most cases the transmitter pulse length best suited for minimum sized reflectors is less than 0.1 μs. Such a transmitter would occupy a wide frequency spectrum which would increase the potential amount of interference. It is, therefore, desirable to increase the pulse length to at least 0.1 μs in order to keep the interference down to a reasonable level. However, it is also desirable to keep the pulse length at 0.1 μs to allow a minimum range of 100 ft. When the pulse length is increased from its optimum value there must be a corresponding increase in the reflector cross section in order to maintain the reflector Signal/Terrain Signal at 10 dB at maximum range. The resulting reflector size is given in Table II-63.

Table II-63 shows that the frequency band which requires the smallest reflector kit is Ku band; to meet a range requirement of 10 nm, reflector size should be 220 meters^2. With this reflector, the rainfall rate will have to exceed 16 mm/hr before rain-front echoes become a nuisance.

TABLE II-63. REFLECTOR SIZE FOR VARIOUS DETECTION RANGES IN 100 ft FOG. FIGURES IN PARENTHESES GIVE TYPICAL PERFORMANCE ASSUMING HALF THEORETICAL ATTENUATION

Frequency Band	Maximum Detection Range, nm →	10	5	2
X	Reflector Cross Section, m^2	325	170	70
	Reflector Side Dimension, cm	51	43	35
	Pulse Length, μs	0.1	0.1	0.1
Ku	Reflector Cross Section, m^2	220	114	42
	Reflector Side Dimension, cm	37.5	31.6	24.6
	Pulse Length, μs	0.1	0.1	0.1
Ka	Reflector Cross Section, m^2	2500 (1000)	220 (65)	18.8 (21)
	Reflector Side Dimension, cm	46 (37)	25.5 (18.6)	13.7 (14.7)
	Pulse Length, μs	2.5 (1.0)	0.35 (0.1)	0.1 (0.1)
V	Reflector Cross Section, m^2	very	very	(21)
	Reflector Side Dimension, cm	large	large	(10.2)
	Pulse Length, μs	values	values	(0.2)

o Pattern Recognition. - Modern airports with large clusters of buildings can produce a complex radar map which can cause the pilot difficulty in identifying the reflector pattern at a 10 nm range. It is conceivable that a system could, be developed which would automatically identify a given pattern of radar returns; however, this kind of capability suggests a degree of system complexity which is undesirable. A much simpler solution involves the use of two or more reflectors, spaced given distances apart in a direction parallel to the runway, to give a signal comprising a number of pulses separated by known intervals. By processing the video output of the radar with circuits using delay lines, it is possible to eliminate all signals unless they have this precise coding. By installing along the runway a number of these space coded reflectors it should, in theory, be possible to show the runway without extraneous signals. In practice, however, the cancellation will not be perfect and experimental work should be carried out to establish the improvement that can be gained with this approach.

6.3.3 Actively-Cooperative Environment. -

o Beacon Transponders. - The disadvantage of a landing monitor which has to operate without any radar enhancement on the ground is that at long ranges, and particularly when the ground is covered with snow, it may be difficult if not impossible to detect the runway. Passive reflectors along the runway could provide a simple solution to the problem and, with the techniques suggested above could significantly reduce the number of the potentially confusing returns from airport buildings.

Alternatively, beacons could be used in place of reflectors to identify the runway. These could be coded to give positive identification and thus would aid the pilot in identifying airport, runway complex and in the presence of parallel runways, the correct one. They would enable the pilot to be absolutely sure that he is monitoring approach to the correct point on the runway of intended landing.

It could be argued that the beacon system would not be so reliable as one using passive reflectors. But with modern solid state techniques, together with employment of redundant configurations, it should be possible to satisfy the most stringent requirements in this respect.

In order to minimize unnecessary triggering of the beacons, they would be fitted with directive antennas so that only aircraft flying the approach path would operate them.

o Possible Beacon Systems. - A beacon may reply either on the same frequency as the transmitter or on a different frequency. When the beacon's frequency differs from that of the radar, the display in the aircraft can be designed to display only the beacon's response. The energy returned from terrain, runways and airport buildings is at the radar frequency and, therefore, can be rejected. Runway identification is significantly simpler once the entire background of radar information is removed from the display. A further advantage of this method is the fact that the beacon has only to produce a signal which is substantially above the receiver noise, rather than a signal which is substantially above the terrain return. This means that a lower level of beacon power is required.

As with corner reflectors, adequate azimuth angular accuracy can be obtained without monopulse resolution enhancement, except at X band.

Section 6, Vol. III presents the results of calculations of the power required to produce a Beacon Signal/Noise Ratio of 10dB at a range of 10 nm. The power required when in the presence of 100 ft. visibility fog or 16 mm/hr rain is listed in the following table. The beacon antenna is assumed to have azimuth and elevation beamwidths of 10^{o}.

TABLE II-64. BEACON POWER REQUIRED

Frequency Band	Pulse Length (μs)	Beacon Power Requirements (mW)	
		100 ft Visibility Fog	16 mm/hr Rain
X	1.0	0.044	0.09
	0.5	0.088	0.18
	0.1	0.44	0.90
Ku	1.0	0.19	8.1
	0.5	0.38	16.2
	0.1	1.90	81
Ka	1.0	84	6.6×10^6
	0.5	168	13.2×10^6
	0.1	840	6.6×10^7
V	1.0	5×10^{10}	1.2×10^{13}
	0.5	1×10^{11}	2.4×10^{13}
	0.1	5×10^{11}	1.2×10^{14}

This table shows that a V band beacon requires a very large transmitter power, thus, would not be practical. The Ka band system would require reasonable power for operation in 100 ft. visibility fog but would be excessive for operation in 16 mm/hr rainfall. Both Ku and X band systems are seen to operate satisfactorily with transmitter power that can be achieved with solid state sources (Ref. 34), even when there is severe attenuation in the 16 mm/hr rain. It should be noted that no echoes are received from rain with a beacon system.

Reducing the pulse length of the airborne system improves accuracy in range and since the beacon power required with a 0.1 μs pulse system is easily achieved, it is recommended that this value be specified in design of an IALM which is to incorporate a beacon.

To show the line of the runway as well as the touchdown point, at least two beacons are required. By arranging for the beacons to give a coded reply consisting of a number of pulses at specific spacing, both the threshold and identity of the runway can be established.

o Interference. - Since the beacon will respond to any input signal above a given strength and at the right frequency, the presence of a large number of aircraft near an airport could cause confusion as to the correct location of the threshold. In addition to the wanted signal, there could be a multiplicity of extraneous replies appearing on the cockpit display. On a visual display, these extraneous replies would appear to be random in nature and would not be mistaken for false replies. With suitable precautions they can be reduced to an acceptable level.

The beacon antenna should be directed so that only aircraft within a specified bearing of the approach path could trigger the beacon. In the azimuth direction, the beamwidth should be wide enough so that an aircraft positioned 10nm from the runway, with a typical navigation error, is still within it. For example, if this error were 1nm in a cross-track direction, the beamwidth would have to be 12^o. In the elevation direction, the beamwidth should be wide enough to cater to all possible approach angles in the order of 1^o to 10^o.

Interference will occur only when two aircraft transmitting antennas point simultaneously at a beacon. As shown in Section 6.3.1.B, the probability of this happening is 1 in 1600 with the Ku-band radar. Thus, if there are 50 aircraft in the beacon beam, the probability of interference would be 1 in 32. This level of interference is probably acceptable. But if flight trials show that this is not the case, interference suppression techniques would have to be used in radar receiver.

As the aircraft approaches the beacon, the amplitude of the signal received from the side lobes of the radar's antenna enentually becomes strong enough to trigger the beacon. For example, with a side lobe level of -30dB, a beacon which is just triggered by the main beam at a range of 10nm is triggered by the side lobes at a range of 1900 ft. When this occurs, the extra beacon pulses transmitted will increase the interference level. Side lobe triggering can be prevented by arranging for the beacon assumed to be located at the side of runway at the touchdown point, to have an azimuth polar diagram shaped, so that at short ranges, the radar side lobe signal received by the beacon is reduced below triggering level.

Referring to Figure II-18, the signal received by the beacon is proportional to

$$\frac{f(\theta)}{R^2} = \frac{f(\theta)\sin^2\theta}{d^2}$$

where $f(\theta)$ = antenna gain in direction θ, R = range and d = beam offset.

Hence, if $f(\theta)$ is made proportional to $\text{cosec}^2\theta$, the signal received by the beacon is kept constant as the range decreases. Although it is impracticable to make the polar diagram follow this for values of θ up to 90^o, it is possible to reduce the amount of side lobe triggering to an insignificant level.

o Optimum Frequency Band for Beacon System. - With both Ka and V frequency bands the beacon transmitter power required is very large and it is well outside the range of present day solid state techniques. The disadvantage of X band is that monopulse would have to be provided in the azimuth plane in order to achieve adequate accuracy. Hence, it is concluded that the optimum frequency band is Ku.

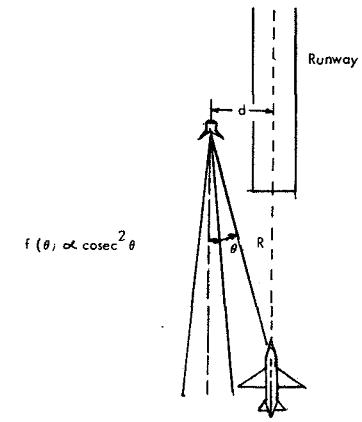


Figure II-18. Beacon Antenna Polar Diagram for Reducing Side-Lobe Triggering

6.4 Detection and Identification of High Ground Hazards to Flight - The Terrain Avoidance Problem

6.4.1 Introduction. - Errors in navigation have resulted in numerous aircraft flying into high ground both enroute and during the approach phase. Accidents of this type can be prevented by fitting the aircraft with a radar which detects high ground in and near the flight path of the vehicle and which warns the pilot that he should maneuver the aircraft to prevent a collision. In order not to subject the aircraft and its passengers to undue stress, the high ground should be detected in sufficient time for only a gentle avoidance maneuver to be necessary and, as shown in Section 4 of this Volume, this is of the order of 5 nm. The information presented to the pilot should enable him to decide whether to climb or to turn in order to prevent a collision.

An essential feature of any high ground avoidance radar is that false alarms should be reduced to a very low level. These may arise from receiver noise, interference from other radars and from rain echoes. An equipment that gave an unnecessary warning once or twice per flight would not be acceptable.

In its simplest form the radar determines range to ground along a path fixed in azimuth and depressed 1° to 2° below the flight vector. The systems would produce a warning when the range is less than 5 nm. The disadvantage of such a system is that it could be dangerous for the pilot to turn since there is no information about the terrain on either side of the flight vector. Consequently, it is proposed that the radar scans in azimuth and obtains information on the height of the terrain in a sector of ± 30° about headings. This would be shown on a display and, in addition, it can be arranged for the presence of ground within certain range and clearance height limits to give both an aural and a visual warning signal.

In military terrain avoidance systems, it is usual to show on a PPI, ground which appears above an assumed horizontal plane defined at a predetermined distance below the aircraft... as set by a range-gating type device. Area of ground coverage is limited to a range extending from approximately 1/2 mi. to 10 nmi (or more) in front of the aircraft. This requires a wide elevation beamwidth. However, for civil applications, the radar may have to provide, in addition, a landing monitor facility which would require that the elevation beamwidth be relatively small if the radar is to give satsifactory performance in this mode. Since civil aircraft require a warning system rather than one which allows continuous terrain avoidance to be carried out, the narrower beamwidth would be adequate.

Normally in a monopulse system, terrain above a plane containing the antenna boresight line is displayed. But with off-boresight processing (Ref. 24), it is possible to display terrain that extends above a horizontal plane that can be positioned a preset distance below the aircraft. The extent of this clearance plane is determined by the elevation beamwidth. Figure II-19(a) shows the minimum detection ranges of the radars having the elevation beamwidths given in Table II-26 for clearance heights of 1000 ft. and 2000 ft. Any ground above the clearance plane would be shown on a display and, in addition, any high ground along the flight path of the aircraft would operate a warning signal. Although the clearance plane does not extend to a minimum range of 1/2 nm, it would appear to be impossible for a civil aircraft to maneuver in such a manner that high ground, not first detected in the range of 2 to 5nm, could hazard the aircraft. The clearance height finally chosen would depend upon experience gained during flight testing, but will probably be between 1000 and 2000 ft.

During the landing phase, it can be argued that when the runway threshold is seen on the display and is properly intercepted by the radar boresight axis, it is impossible for any high ground to be in the path of the aircraft.

It is, therefore, not essential to provide an extensive ground avoidance capability. However, as discussed in Section 4 of this Volume, high ground along the approach path that is likely to hazard the aircraft should be detected and a warning given to the pilot. The technique used enroute for detecting ground above a fixed horizontal clearance plane cannot be used when the aircraft is on the approach path since the touchdown point will eventually appear above it. Consequently, the clearance plane must be shaped as shown, for example, in Figure II-20 and this must be continually changed as the range decreases in order to prevent unnecessary high ground warnings.

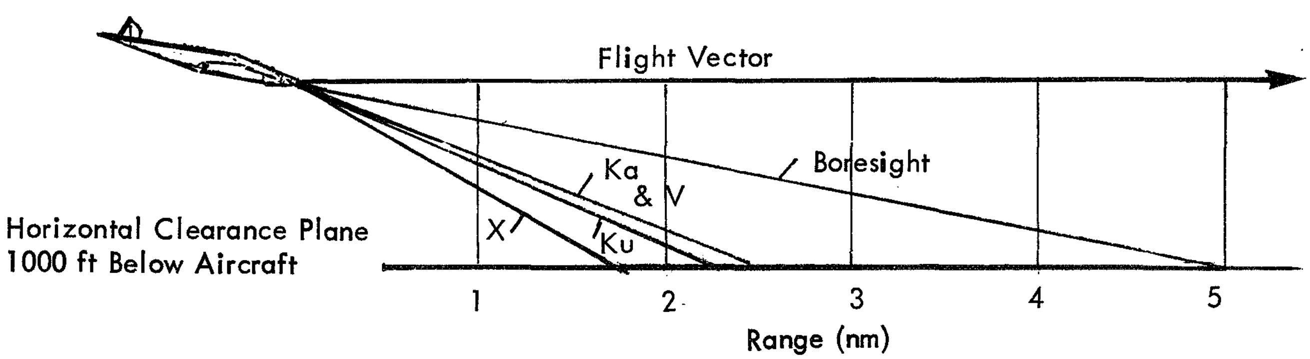


Figure II-19(a) Extent of Clearance Plane

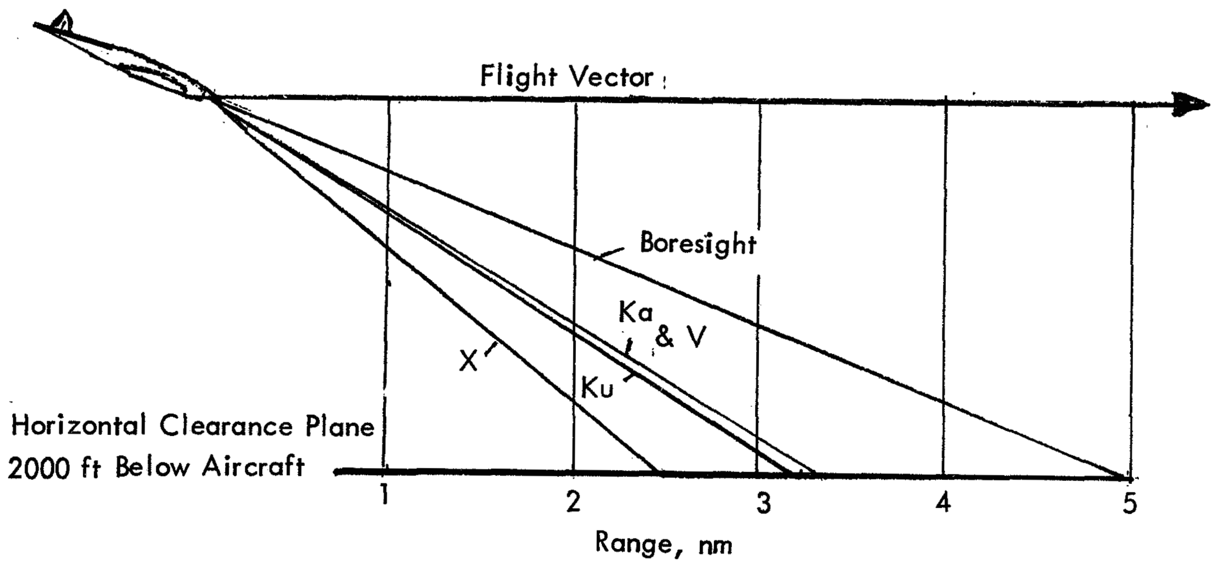


Figure II-19 (b). Extent of Clearance Plane

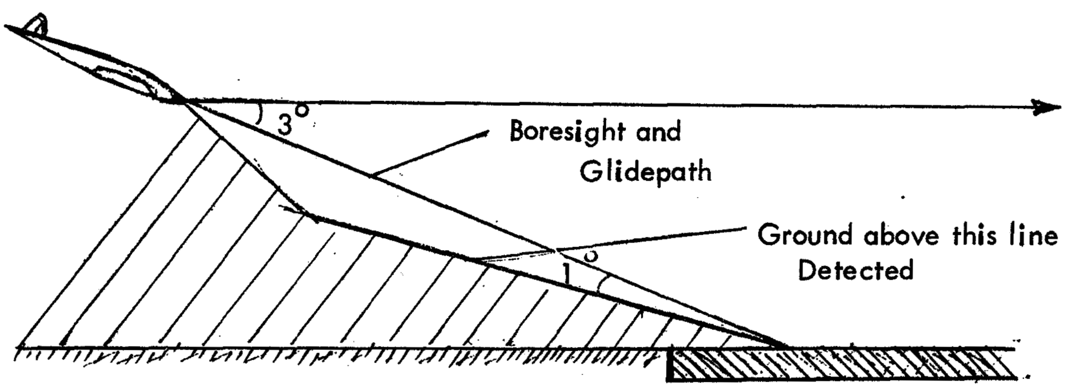


Figure II-20. High Ground Detection in Landing Phase

6.4.2 Accuracy Requirements.- For high ground avoidance, the critical radar parameter is the boresight accuracy in the elevation plane. It is this parameter which determines the minimum clearance height that can be selected. This clearance height must be larger than the height error due to uncertainty in the boresight position. With a monopulse system, the boresight angular error is, typically, elevation beamwidth divided by 20 (Ref.25). For example, with the Ku band radar, it is $4.5/20 = 0.23°$. This is well below the $0.6°$ given in Section 4.5.2 of this Volume for the overall elevation angle error.

The boresight depression angle depends upon the clearance height and warning range required. For example, if these are 100 ft. and 5 nm, respectively the angle is $2°$. The boresight should be depressed $2°$ from the flight vector. This requires knowledge of aircraft angle of attack. This quantity can be obtained from an Airstream Detection Device. Alternatively, the boresight could be depressed from the horizontal by the selected angle in deference to the argument that during straight and level enroute flying the flight vector is always horizontal. During the descent phase the angle would be increased so as to maintain the the selected angle below the flight path.

6.4.3. Signal Level Requirements. - The equipment should be set up so that any signal at less than the maximum detection range, which has a sum component above a given threshold and a difference component above a given angle with respect to the boresight, is recognized as high ground and is shown on a display. A critical design feature is the threshold level. If it is too low, false signals are produced from noise and from rain fronts. Though uniform area of rainfall will not produce an above-boresight signal with a monopulse radar, a rain front with a suitable slope could produce a signal denoting high ground. On the other hand, if the threshold level is set too high, high ground may not be detected. Therefore, the threshold setting is selected as a careful compromise and, as shown below, varies with range in order to obtain the best performance.

Referring to Figure II-21, the threshold level is arbitrarily set 20dB above receiver noise level to prevent random noise spikes from appearing as signals. In order to prevent rain echoes producing false signals the threshold level is raised as the range decreases. But to ensure that high ground is always detected the threshold level at which a signal will be displayed is set 6dB below the calculated signal level for terrain with presence of 16 mm/hr rainfall between the aircraft and the high ground. This caters to the maximum path attenuation and allows for 6dB fall-off in radar performance. A rain echo has to be above this level to produce a false signal. In summary the equipment should meet the following:

Requirements:

(a) Returns from terrain within 10nm of the aircraft must produce a signal which is more than 20dB above the receiver noise level even in the presence of rainfall rates of 16mm/hr.

(b) Triggering threshold level should be set at 6dB below the expected signal level of the return from terrain.

(c) The sum signal from a rain-front must not exceed threshold level.

It should be noted that Requirements (a) and (b) must be met to detect a hazardous situation. Requirement (c) should be met to prevent false warnings.

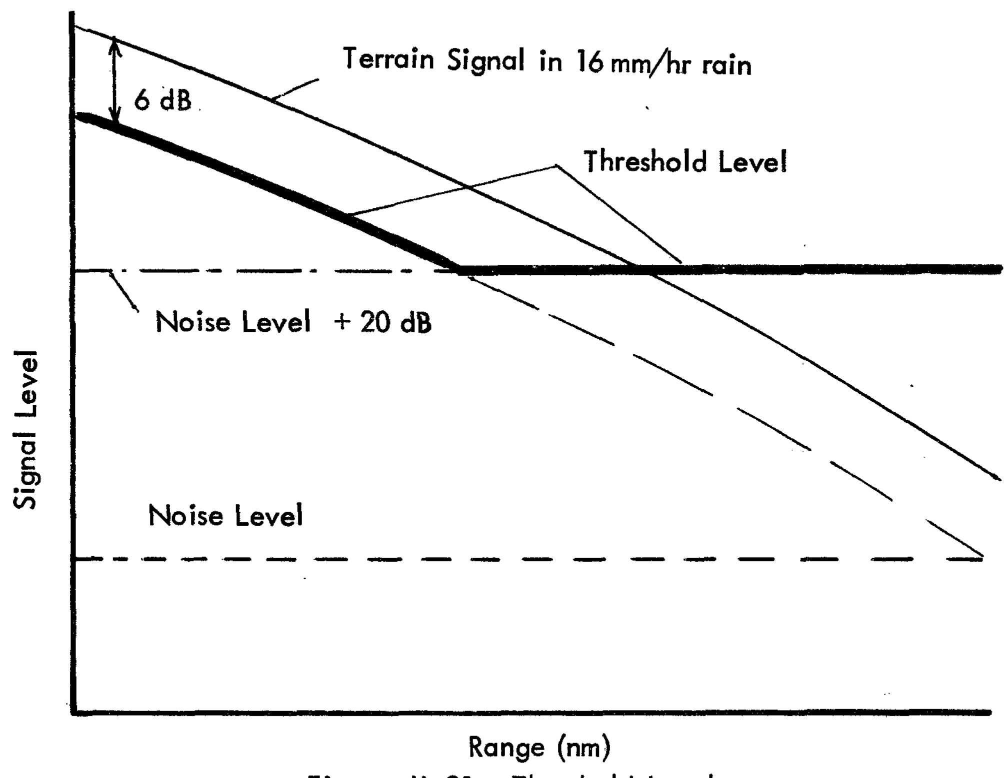


Figure II-21. Threshold Level

o X-Band Radar. - The ranges at which Requirement (a) is met in various weather conditions are listed in Table II-65. These have been derived from Table III-14 of Volume III

TABLE II-65. RANGE (nm)* AT WHICH TERRAIN SIGNAL/NOISE IS 20 dB WITH THE X-BAND RADAR (RANGE IN km IN PARENTHESES)

Pulse Length	Rainfall Rates				Fog Densities	
μ sec.	0 mm/hr	1 mm/hr	4 mm/hr	16 mm/hr	400 ft	100 ft
1.0	30.0 (55.0)	28.0 (52.0)	22.0 (41.0)	12.0 (22.0)	26.0 (48.0)	18.0 (33.0)
0.5	19.0 (35.0)	18.0 (33.0)	15.0 (28.0)	8.6 (16.0)	17.0 (31.0)	13.0 (24.0)
0.1	6.5 (12.0)	6.5 (12.0)	5.9 (11.0)	4.3 (8.0)	5.9 (11.0)	5.4 (10.0)

* Ranges are given both in nm and km (kilometers in parentheses)

The threshold level is derived from Table III-28 of Volume III by subtracting 6dB from the terrain signal when the rainfall density is 16 mm/hr, provided this does not fall below a level corresponding to receiver noise plus 20dB. The values obtained are given in the following table for pulse lengths of 1.0, 0.5 and 0.1 μs.

TABLE II-66. THRESHOLD LEVEL (-dBW) FOR X-BAND RADAR

Range * nm (km)	Pulse Length		
	1.0 μs	0.5 μs	0.1 μs
0.54 (1)	68.22	71.22	78.22
1.08 (2)	77.74	80.74	87.74
2.16 (4)	87.78	90.78	97.78
5.40 (10)	102.90	105.90	104.00
10.8 (20)	114.00	111.00	104.00

* Ranges are given both in nm and km (kilometers in parentheses)

From Equation (32) of Section 6, Volume III, the following table has been obtained which lists the rain-front signals at various ranges. The attenuation between the aircraft and the rain-front is assumed to be zero.

TABLE II-67. RAIN-FRONT SIGNALS (-dBW) AT X BAND

Range nm (km)	Pulse Length								
	1 mm/hr rain-front			4 mm/hr rain-front			16 mm/hr rain-front		
	1.0 μs	0.5 μs	0.1 μs	1.0 μs	0.5 μs	0.1 μs	1.0 μs	0.5 μs	0.1 μs
0.54 (1)	83.7	86.7	93.7	74.7	77.7	84.7	64.7	67.7	74.7
1.08 (2)	89.7	92.7	99.7	80.7	83.7	90.7	70.7	73.7	80.7
2.16 (4)	95.7	98.7	105.7	86.7	89.7	96.7	76.7	79.7	86.7
5.40 (10)	103.7	106.7	113.7	94.7	97.7	104.7	84.7	87.7	94.7
10.8 (20)	109.7	112.7	119.7	100.7	103.7	110.7	90.7	93.7	100.7

The threshold level is indicated by the thick line in this table. At ranges below the line the rain echoes are above the threshold and therefore will appear on the radar display.

The relation of the rain echo signal to the threshold level is also shown in Figure II-22 for a pulse length of 1.0 μs. This shows that a 1 mm/hr rain echo is above the threshold at 6.5 nm and at 1.5 nm from 4 mm/hr rain. With 16 mm/hr rain the echo is above the threshold at all ranges.

It is known from in-service experience with X band terrain following radars that the rain echoes have much less effect on performance than that which is predicted above. This is almost certainly due to the following three causes. First, with high ground the angle of grazing is, in general, much greater than the 3° assumed to cover the landing approach phase - an angle of 30° might be more typical value the result of which would be an increase in the estimated terrain signal of 10dB. Second, the radar cross section of rain is likely to be 10dB below the theoretical value. Thirdly, the water content of clouds

TABLE II-68. TYPICAL HGA PERFORMANCE OF THE X-BAND RADAR WITH A (1.0 μs) PULSE LENGTH

Range of high ground detection through 1 g/m^3 cloud, or fog	* 38 (70.4)
Range of high ground detection through 16 mm/hr rain	16 (29.6)
Range at which a 16 mm/hr rain echo exceeds threshold level	8 (14.8)

* Ranges are given both in nm and km (kilometers in parentheses)

covering the high ground is not likely to exceed 1 gram/meter^3, which is about that assumed for fog of 100 ft visibility -- this halves the attenuation since this is directly proportional to water content.

With these 'typical' values, the performance obtained is given in Table II-68. These have been derived by making the appropriate substitutions in the equations given in Section 6, Volume III.

No assessment has been made of the 'typical' performance for pulse lengths of 0.5 and 0.1 μs since Table II-65 shows that it would be inferior to that obtained with 1μs.

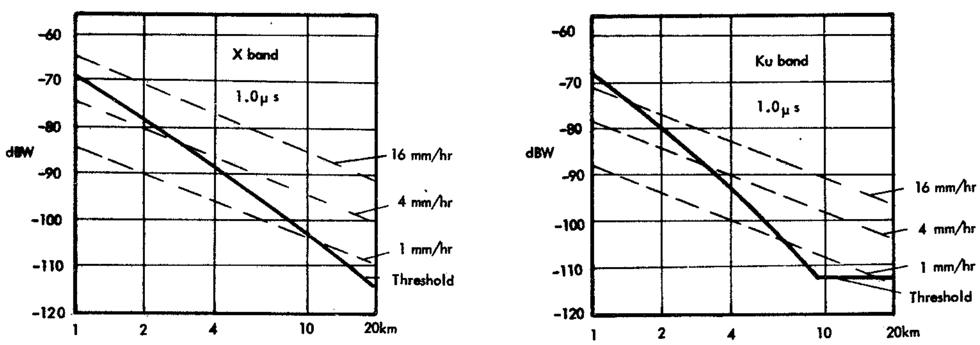


Figure II-22. Amplitude of Rain Echoes -- X and Ku Bands

o Ku Band Radar. - The performance of the Ku-band radar, derived in a manner similar to that of the X-band radar, is summarized in the following tables.

TABLE II-69. RANGE (nm)* AT WHICH TERRAIN SIGNAL/NOISE IS GREATER THAN 20 dB WITH Ku BAND

Pulse Length μ sec	Rainfall Rates				Fog Densities	
	0 mm/hr	1 mm/hr	4 mm/hr	16 mm/hr	400 ft	100 ft
1.0	32 (60)	22 (41)	13 (24)	5.1(9.5)	20.5(38)	11 (20)
0.5	19 (35)	15 (27)	9.2(17)	3.9(7.2)	14 (25)	7.6(14)
0.1	6.5(12)	5.9(11)	4.5(8.4)	2.4(4.5)	5.4(10)	3.8(7.1)

* Ranges are given both in nm and km (kilometers in parentheses)

With a 1.0 μs equipment the range is greater than 10nm, except when rainfall of 16 mm/hr extends between the aircraft and the terrain; in that case the range falls to 5.1 nm.

From Equations (22) and (28) of Section 6, Volume III, the following table has been derived listing the threshold level which meets Requirement (b) for transmitter pulse lengths of 1.0, 0.5 and 0.1 μs.

TABLE II-70. THRESHOLD LEVEL (-dBW) AT Ku BAND

Range km (nm) *	Pulse Length 1.0 μs	0.5 μs	0.1 μs
1 (0.54)	67.26	70.26	77.26
2 (1.08)	78.82	81.82	88.82
4 (2.16)	93.94	96.94	102
10 (5.39)	112	109	102
20 (10.78)	112	109	102

The amplitude of the rain-front signal derived from Equation (33) of Section 6, Vol. III is listed below for various pulse lengths. Circular polarization is assumed.

TABLE II-71. RAIN-FRONT SIGNALS (-dBW) AT Ku BAND

Range km (nm) *	Rainfall Rates: 1 mm/hr rain-front			4 mm/hr rain-front			16 mm/hr rain-front		
	1.0 μs	0.5 μs	0.1 μs	1.0 μs	0.5 μs	0.1 μs	1.0 μs	0.5 μs	0.1 μs
1 (0.54)	87.6	90.6	97.6	78.6	81.6	88.6	70.6	73.6	80.6
2 (1.08)	93.6	96.6	103.6	84.6	87.6	94.6	76.6	79.6	86.6
4 (2.16)	99.6	102.6	109.6	90.6	93.6	100.6	82.6	85.6	92.6
10 (5.39)	107.6	110.6	117.6	98.6	111.6	108.6	90.6	93.6	100.6
20 (10.78)	113.6	116.6	123.6	104.6	107.6	114.6	96.6	99.6	106.6

At ranges below the thick line the rain echo is above the threshold level. A more exact indication of the range beyond which the echo exceeds the threshold is obtained from Figure II-22 for a pulse length of 1.0μs. This shows that ranges are as follows:

1 mm/hr - 3.8 nm

4 mm/hr - 1.6 nm

16 mm/hr - 0.8 nm

When the range calculations are based on 'typical' conditions, the following performance is obtained.

TABLE II-72. TYPICAL HGA PERFORMANCE OF THE Ku BAND RADAR WITH A (1.0 μs) PULSE LENGTH

Range of high ground detection through 1 g/m^3 cloud, or fog	22.0 nm	(40.8) km
Range of high ground detection through 16 mm/hr rain	5.4 nm	(10.0) km
Range at which a 16 mm/hr rain echo exceeds threshold	4.9 nm	(9.1) km

o Ka-band Radar. - The ranges at which Requirement (a) is met are listed in Table II-73 These are obtained from Table III-14 of Section 6, Volume III.

TABLE II-73. RANGE (nm)* AT WHICH TERRAIN SIGNAL/NOISE IS GREATER THAN 20 dB AT Ka BAND

Pulse Length	Rainfall Rates				Fog Densities	
μ sec	0 mm/hr	1 mm/hr	4 mm/hr	16 mm/hr	400 ft	100 ft
1.0	19 (36)	9.7(18)	4.8(8.8)	1.9(3.5)	8.6(16)	4.0(7.4)
0.5	12 (23)	7.0(13)	3.8(7.1)	1.7(3.1)	6.5(12)	3.2(6.0)
0.1	4.3(7.9)	3.2(6.0)	2.2(4.1)	1.1(2.1)	3.1(5.8)	1.9(3.6)

The effect of rain and fog on the detection range of high ground is quite serious at Ka-band. Table II-73 shows that with a 1.0 μs pulse, the ranges in 4 mm/hr and 16 mm/hr are 4.8 and 1.9 nm, respectively, and it is only 4.0 nm in 100 ft. visibility fog. The ranges are even lower with shorter pulse lengths.

The threshold level that meets Requirement (b) is obtained from Equations (23) and (29) of Section 6, Vol. III and is given in the following table for various ranges and pulse lengths.

* Ranges are given both in nm and km (kilometers in parentheses)

TABLE II-74. THRESHOLD LEVEL (-dBW) AT Ka BAND

Range km (nm) *	Pulse Length 1.0 μs	0.5 μs	0.1 μs
1 (0.54)	75.34	78.34	85.34
2 (1.08)	92.48	95.48	98
4 (2.16)	108	105	98
10 (5.39)	108	105	98
20 (10.78)	108	105	98

The amplitude of the rain front signal is given by Equation (34) of Section 6, Vol. III and from this we derive the following values for various ranges and pulse lengths with circular polarization.

TABLE II-75. RAIN-FRONT SIGNALS (-dBW) AT Ka BAND

Range km (nm) *	Rainfall Rates: 1 mm/hr rain-front			4 mm/hr rain-front			16 mm/hr rain-front		
	1.0 μs	0.5 μs	0.1 μs	1.0 μs	0.5 μs	0.1 μs	1.0 μs	0.5 μs	0.1 μs
1 (0.54)	79	82	89	71	74	87	64	62	74
2 (1.08)	85	88	95	77	80	87	70	73	80
4 (2.16)	91	94	101	83	86	93	76	79	86
10 (5.39)	99	102	109	91	94	101	84	87	94
20 (10.78)	105	108	115	97	100	107	90	93	100

At ranges below the heavy line the rain-front signal is above the threshold level and, hence, produces a false warning. Figure II-23 shows that with a pulse length of 1.0 μs, 1 mm/hr rain echoes are greater than the threshold at ranges greater than 0.9 nm. With rainfall densities of 4 mm/hr and greater, the rain echo exceeds the threshold from ranges of less than 0.5 nm.

When 'typical' conditions are assumed the improvement in performance is illustrated in the following table.

TABLE II-76. TYPICAL HGA PERFORMANCE OF THE Ka BAND RADAR WITH A (1.0 μs) PULSE LENGTH

Range of high ground detection through 1 g/m^3 cloud, or fog	8.0 nm	(14.8) km
Range of high ground detection through 16 mm/hr rain	2.4 nm	(4.4) km
Range at which a 1 mm/hr rain echo exceeds the threshold	1.0 nm	(1.9) km
Range at which a 4 mm/hr rain echo exceeds the threshold	1.3 nm	(2.4) km

o V-Band Radar. -From Table III-14 of Section 6, Volume III, the ranges at which Requirement (a) is met are listed below for various weather conditions.

TABLE II-77. RANGE (nm)* AT WHICH TERRAIN SIGNAL/NOISE IS GREATER THAN 20 dB WITH V-BAND

Pulse Length	Rainfall Rates				Fog Densities	
μ sec	0 mm/hr	1 mm/hr	4 mm/hr	16 mm/hr	400 ft	100 ft
1.0	5.9(11)	3.0(5.5)	1.8(3.4)	0.9(1.7)	3.2(6.0)	1.1(2.1)
0.5	3.9(7.3)	2.3(4.3)	1.5(2.8)	0.8(1.4)	2.5(4.7)	1.0(1.8)
0.1	1.4(2.5)	1.1(2.0)	0.8(1.5)	0.4(0.8)	1.2(2.2)	0.5(1.0)

This table shows that the range, even in 400 ft. fog, is unacceptably low.

* Ranges are given both in nm and km (kilometers in parentheses)

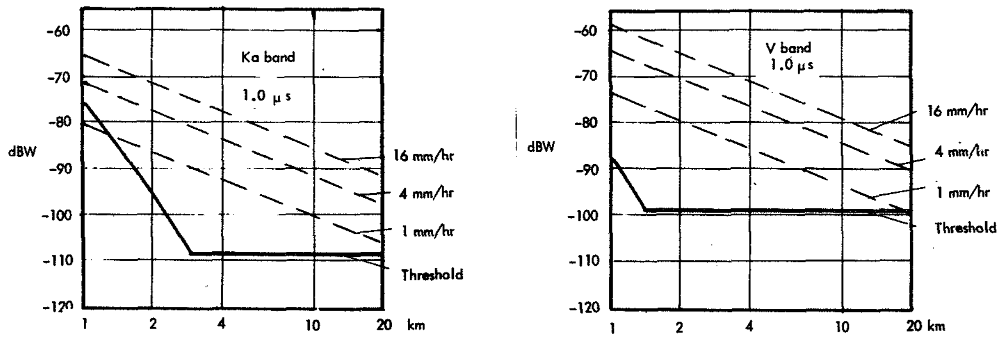


Figure II-23. Amplitude of Rain Echoes -- Ka and V Bands

The threshold level that meets Requirement (b) is obtained from Equations (24) and (30) of Section 6, Volume III and these are listed in the following table.

TABLE II-78. THRESHOLD LEVEL (-dBW) AT V-BAND

Range km (nm) *	Pulse Length		
	1.0 us	0.5 us	0.1 us
1 (0.54)	87.7	90.7	88
2 (1.08)	99	96	88
4 (2.16)	99	96	88
10 (5.39)	99	96	88
20 (10.78)	99	96	88

Equation (35) of Section 6, Volume III gives the amplitude of the rain-front echo. By substitution we obtain the following table listing the echo amplitude at various ranges, for various rainfall densities and for various pulse lengths.

TABLE II-79. RAIN-FRONT SIGNAL (-dBW) AT V-BAND

Range km (nm) *		Rainfall Rates								
		1 mm/hr rain-front			4 mm/hr rain-front			16 mm/hr rain-front		
		1.0 μs	0.5 μs	0.1 μs	1.0 μs	0.5 μs	0.1 μs	1.0 μs	0.5 μs	0.1 μs
1	(0.54)	73.8	76.8	83.8	64.8	67.8	74.8	58.8	61.8	68.8
2	(1.08)	79.8	82.8	89.8	70.8	73.8	80.8	64.8	67.8	74.8
4	(2.16)	85.8	88.8	95.8	76.8	79.8	86.8	70.8	73.8	80.8
10	(5.39)	93.8	96.8	103.8	84.8	87.8	94.8	78.8	81.8	88.8
20	(10.78)	99.8	102.8	109.8	90.8	93.8	100.8	84.8	87.8	94.8

At ranges above the thick line the rain echo is above the threshold level and false signals occur. This is also illustrated in Figure II-23 which shows that the echo from rainfall of densities of 1 mm/hr and greater is well above the threshold level over the range of 0.5 to 10 nm.

With 'typical' figures the performance is given in the following table.

TABLE II-80. TYPICAL HGA PERFORMANCE WITH THE V-BAND RADAR WITH A (1.0 μs) PULSE LENGTH

Range of high ground detection through 1 g/m^3 cloud, or fog	2.5 nm	(4.6) km
Range of high ground detection through 16 mm/hr rain	1.2 nm	(2.2) km
Range over which a 16 mm/hr rain echo exceeds the threshold	0.5 to 5.4 nm	(0.9) to (10.0) km
Range over which a 4 mm/hr rain echo exceeds the threshold	0.5 to 2.7 nm	(0.9) to (5.0) km
Range over which a 1 mm/hr rain echo exceeds the threshold	0.7 to 1.1 nm	(1.3) to (2.0) km

Optimum Frequency Band. - The calculations show that the best performance is obtained with a long pulse length regardless of frequency band. Consequently, it is assumed that a 1.0 μs pulse length will be used; the related performance to be expected is shown in Tables II-81, 82, and 83.

TABLE II-81. RANGE (nm) AT WHICH HIGH GROUND IS DETECTED -- (1 μs) PULSE LENGTH

		Frequency Band			
		X	Ku	Ka	V
Rain	4 mm/hr	22	13	4.8	1.8
	16 mm/hr	12	5.1	1.9	0.9
Fog, 100' Theoretical Parameters		18	11	4.0	1.1
Heavy Fog (1g/m^3) 'typical' parameters		38	22	8	2.5

TABLE II-82. RANGE (nm) AT WHICH RAIN ECHO IS ABOVE THRESHOLD LEVEL -- (1 μs) PULSE LENGTH. (Rain Echo Exceeds Threshold for Ranges Greater than the Values Shown)

		Frequency Band			
		X	Ku	Ka	V
Rain	1 mm/hr	6.5	3.8	0.9	0^+
	4 mm/hr	1.5	1.6	0.5	0^+
	16 mm/hr	0^+	0.8	0^+	0^+

TABLE II-83. RANGE (nm) AT WHICH RAIN ECHO IS ABOVE THRESHOLD LEVEL -- (1 μs) PULSE LENGTH, TYPICAL PARAMETER

		Frequency Band			
		X	Ku	Ka	V
Rain	1 mm/hr	—	—	Greater than 1.0	Between 0.7 and 1.1
	4 mm/hr	—	—	Greater than 1.3	Between 0.5 and 2.7
	16 mm/hr	Greater than 8	Greater than 4.9	—	Between 0.5 and 5.4

Table II-81 shows that the range at which high ground is detected falls off rapidly with an increase in frequency. At V-Band it is unacceptably low, even assuming 'typical' conditions. The Ka-band radar's range is marginal for an HGA system - it is between 4 and 8 nm in conditions of poor visibility. Both the X and Ku-band radars have adequate range capability.

Although the detection range with the Ka-band radar may be adequate, Tables II-82 & II-83 show that the echoes from rainfall rates of 4 mm/hr and greater can seriously affect performance by producing false warnings. The X and Ku-band radars are not affected as greatly in this respect and have comparable performance. This is due to the use of circular polarization of Ku-band off-setting the increase with frequency of the radar cross section of rain.

It can be concluded that there is little to choose between X and Ku-bands, either is suitable for an HGA radar having a performance meeting the needs of civil aircraft.

The performance of a radar in the high ground avoidance mode is not appreciably affected by changes in the antenna's horizontal aperture. A narrow antenna beam is not required for precise angular resolution in the horizontal plane and the main effect of a change in antenna size is on antenna gain which changes the detection range. For example, reducing the horizontal aperture from 1m to 0.5m would reduce the detection range by 20% and this would be acceptable both with the X and Ku-band radars. Increasing the aperture to 1.5m would increase the detection range by 15%.

o Turning Flight. - In order to continue to display ground above a horizontal clearance plane when the aircraft is banked during a turn, the antenna should be roll stabilized or, alternatively, artificially roll stabilized by suitably varying pitch angle with azimuth angle. The latter is attractive since it avoids the complexity of a roll stabilization axis.

It is also desirable during turning flight to lead the antenna into the turn by an amount which depends upon the radius of the turn in order for the ground on either side of the curved flight path to be examined. This is illustrated in Figure II-24. When the antenna scans about the fore and aft axis of the aircraft, the section AB of the flight path is examined for high ground, but when the antenna is led into the turn, the section examined is increased to AC.

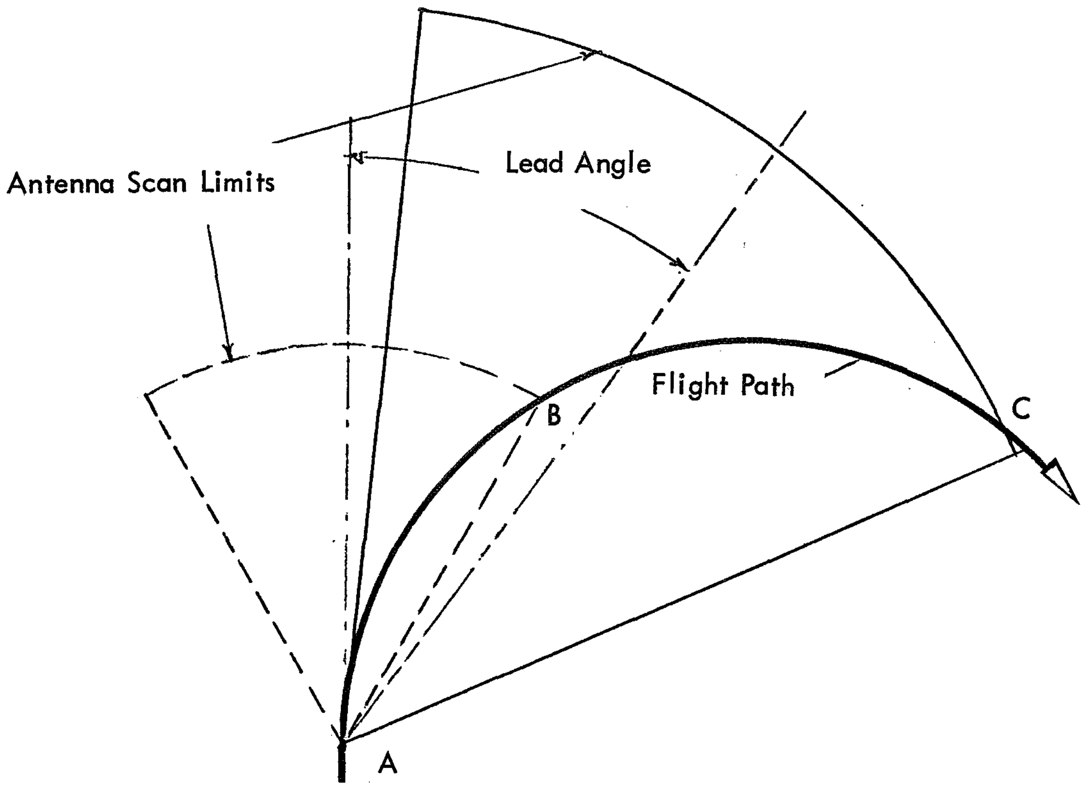


Figure II-24. Antenna Lead Angle During Turning Flight

o Interference. - An interference signal from another radar on the same frequency can produce a false alarm when its amplitude is above the threshold and when it occurs in the 0 to 5 nm range period. Whether an interference signal would indeed produce a false alarm or would be rejected depends upon the precise form of signal processing and display (visual or aural) that is used.

TABLE II-84. AIRCRAFT SEPARATION AT WHICH SIDE-LOBE TO SIDE-LOBE INTERFERENCE OCCURS

Frequency Band	Separation
X	25 nm (46) km
Ku	39 nm (72) km
Ka	13 nm (24) km
V	3 nm (5.6) km

The most likely cause of interference is occasioned by side-lobe to side-lobe transmission. The amplitude of this interference is given by Equations (21 to 24), Section 6, Vol.III, and the range at which this is equal to the 5 nm threshold level is given in Table II-84. These are the ranges for clear weather; in fog and rain they will be lower. Both enroute and on the approach there can be a number of aircraft within interference range, especially with the X and Ku band radars.

When the antenna beam of one aircraft is pointing at a second aircraft, the amplitude of the interference signal is considerably increased and interference can occur when aircraft are within optical range. The probability of interference occuring with the X-band radar is, for example,

1 in 24,	due to antenna beamwidth, 2.5^{o}, and scan angle, 60^{o}.
1 in 10,	if magnetrons frequencies are spread over 10 channels.
1 in 20,	with a detection range of 5 nm and a pulse repetition frequency of 1000Hz.

This gives an overall probability of a false warning due to interference from another aircraft within optical range of 1 in 4800, at X-band.

When both beams are pointing at each other the interference still occurs when the aircraft are within optical range but the probability is reduced to 1 in 115200 at X band.

Table III-33, Section 7, Vol. III shows that on the approach path, signals reflected from the ground from one aircraft to another can cause interference. This is significant only when both beams illuminate the same patch of ground and the probability of this is low.

Although the probability of interference from another aircraft is low, along busy air routes and near airports, the number of aircraft within interference range could be large and, hence, it will be necessary to use interference rejection circuits to prevent false warnings. These operate by supressing the first received pulse unless, after a number of transmitter pulses, a given percentage has been received at the same range. In this way, interference signals which move in range from pulse to pulse because of non-synchronized pulse repetition frequencies are eliminated.

6.5 Specific Functions

In this section, several specific functions of the overall hazard warning and avoidance system are briefly discussed. Among these functions are the monitoring of the landing approach with respect to the desired glide path, the detection of obstacles on the runway and the assistance of roll out and taxi.

6.5.1 Glide Slope Monitoring in the Elevation Plane. - The simplest way to monitor vertical position on the glide path is to compare computed required height with measured height. Required height may be found by multiplying Slant Range to Threshold, as seen by the radar, with the sine function on the intended glide slope, i.e., sin 3°. Measured height could be derived by reference to a radar altimeter (over level terrain) or pressure altimeter corrected for pressure altitude variation and height of runway above sea level. However, these two methods rely upon the usual aircraft systems and do not furnish a truly independent measure of altitude.

A method which is more in keeping with the desire for independent measurement would be to obtain angular information in the elevation plane from the radar. For the required accuracy of 0.37° (See Section 4), a monopulse or interferometer technique must be used. With such a system, it is possible to show on a display, the position where the boresight intercepts the ground with an angular accuracy of about one twentieth the elevation beamwidth (Ref.35). This gives for the radars considered in this report, a boresight error of 0.38° at X-band, 0.23° at Ku-band and 0.20° at Ka and V-bands.

When the antenna is pitch-stabilized so that the boresight is depressed from the horizontal by an angle which is equal to the glide path angle, the aircraft is on the glide path when the boresight intercepts the desired touchdown point. In order to identify the touchdown point on the display a marking is placed at the appropriate distance from the runway threshold.

In the case of the enhanced runway, numerous reflector (beacon) patterns are possible and the need will exist to develop a display system which allows display of the monitor information to the pilot in a form which is quickly understood. Foremost, at the concept stage, is a set of points or lines which synchronize with the returns from the reflectors when the landing is proceeding satisfactorily. If one reflector is adjacent to the desired touchdown point, the radar monitor can track that reflector for vertical guidance.

With a system in which the radar is locked on to the reflector at the touchdown point, the necessary angular information is obtained from the angular position of the antenna. It should be noted that this system requires monopulse capability in the azimuth plane as well as in the elevation plane so that the reflector or transponder can be tracked.

6.5.2 Detection and Recognition of Obstacles on Runway. - Introduction. - An obstacle on the runway large enough to hazard a landing aircraft is likely to have a radar cross section of 1 $meter^2$. Such an obstacle could be detected by a radar when the signal from the object is well above the signal from the ground adjacent to the runway at the same range. If we assume that this margin is 10 dB then the requirements to be met are as follows:

Requirements:

(a) Signal from terrain adjacent to runway to be greater than 10dB above receiver noise.

** (b) Signal from target of 1 $meter^2$ or greater, to be greater than 10dB above signal from terrain adjacent to runway.

(c) Signal from terrain adjacent to runway to be 10dB above that from rain front at same range.

• Detection Range. - Tables III-13 and III-14, Section 6, Vol. III give the ranges at which Requirements (a) and (c) are met. The range at which Requirement (b) is met is obtained by substitution into Equations (65) to (68) of Section 6, Volume III.

A cursory examination shows that Requirement (b) is the limiting requirement for all frequency bands; the ranges at which this requirement is met as a function of frequency are listed in Table II-85. *

Note: ** This is the limiting requirement for detection of a 1 m^2 obstacle on the runway.

* This table clearly shows that a radar of the types considered will not detect an obstacle of 1 $meter^2$ cross-section on the runway at a range which is great enough for the pilot to take avoiding action or to abort the landing. However, when proceeding along the taxiway, a 0.1 μs pulse length should provide a detection range which would be adequate for the detection of an obstacle such as another aircraft or small highway vehicle.

TABLE II-85. RANGE (ft) AT WHICH SIGNAL FROM TARGET OF 1 m^2 CROSS SECTION IS 10 dB ABOVE SIGNAL FROM TERRAIN AT SAME RANGE

Frequency Band	Pulse Width	Range in feet at which $S_c/S_t = 10$ *
X	1.0	18 (5.7)
	0.5	37 (11.4)
	0.1	187 (57)
Ku	1.0	30 (9.3)
	0.5	61 (18.6)
	0.1	305 (93.0)
Ka	1.0	65 (20.0)
	0.5	131 (40.0)
	0.1	656 (200.0)
V	1.0	131 (40.0)
	0.5	262 (80.0)
	0.1	1312 (400.0)

* Range is given both in feet and meters (meters within parentheses)

6.5.3 Performance of Landing Monitor During Taxi Phase. - An aircraft equipment that provides a radar map of an airport with sufficient definition for it to be used as an IALM should be able to provide an aircraft on the ground with mapping information to enable it to proceed along the taxiway to the terminal under conditions of poor visibility. The range the radar requires on the ground is very much less than that which is required in the air. It will depend upon the taxi speed and the complexities of the taxi track but 500 to 1000 ft. would probably be adequate. It is, of course, important for the minimum range to be as low as possible and for this a narrow pulse length must be used. With a pulse length of 0.1 μ s, it should be possible to make the minimum range capability less than 100 ft.

The X-band radar with a 2.5° azimuth beamwidth, has a pulse packet width of 40 ft. at a range of 1000 ft.; thus, the definition this provides is not adequate. However, the azimuth resolution obtained with the Ku, Ka and V-band radars should be good enough.

Because the maximum range is only 1000 ft., the performance is not seriously affected by fog. At V band, for example, the two way attenuation in 100 ft. visibility fog is only about 3 dB at a range of 1000 ft.

The pilot's task might be made somewhat easier if corner reflectors were deployed to identify the taxiway and, as suggested earlier, it is possible to use space coded groups to remove extraneous signals and to identify a particular taxiway. The size of the corner reflector required to give a signal 10 dB above that from the surrounding terrain, at a range of 1000 ft., is given by Equations (81) to (84) of Section 6. Table II-86 lists corner reflector size requirements for different frequency bands, all operating at a pulse length of 0.1 μs.

TABLE II-86. CORNER REFLECTOR SIZE FOR 10 dB REFLECTOR SIGNAL TO TERRAIN SIGNAL AT 1000 ft. PULSE LENGTH (0.1 μs)

Frequency Band	Echoing Area, m^2	Reflector side Dimension, cm
X	5.4	18.4
Ku	3.2	12.8
Ka	1.5	7.1
V	0.8	4.3

This table shows that the reflector size required is very much smaller than that needed to identify a runway for a landing system and, hence, should not confuse a pilot landing an aircraft.

As regards other aircraft or vehicles on the taxiway, Section 6.5.2 shows that a radar with a pulse length of 0.1 μs detects an obstacle with a radar cross section of 1 $meter^2$ at a range of approximately 150 ft. at X band, 280 ft. at Ku band, 600 ft. at Ka band, and 1200 ft. at V band. This capability should give adequate warning of the proximity of other aircraft or airport vehicles on the taxiway.

6.5.4 Physiological and Other Consequences of Using the Radar in the Taxiway and Ramp Areas. - When aircraft are on the ground and the nose radar is switched on, ground personnel can be subjected to microwave radiation. The mean power density of the radiation near the antenna is given in the following table. A duty cycle of 0.001 has been assumed.

TABLE II-87. MEAN RADIATION POWER DENSITY

Frequency Band	Peak Power kW	Mean Power mW	Antenna Aperture cm^2	Power Density mW/cm^2
X	20×10^3	20×10^3	3×10^3	6.7
Ku	20×10^3	20×10^3	3×10^3	6.7
Ka	20×10^3	20×10^3	1.5×10^3	13
V	10×10^3	10×10^3	8×10^2	12

These power densities which extend to the Rayleigh distance from the antenna ($a^2/2\lambda$) are listed in the following table.

TABLE II-88. RAYLEIGH DISTANCE FROM ANTENNA

Frequency Band	Rayleigh Distance feet *
X	56 (17)
Ku	89 (27)
Ka	198 (60)
V	463 (140)

* Ranges are given both in feet and meters (meters in parentheses)

The Maximum Safe Exposure Level (MSEL) officially specified by the US Armed Services is $10 mW/cm^2$ (Ref. 36). Thus it is seen that the radiation from the X and Ku-band radars is below the danger level. But the Ka and V-band radars have radiation levels slightly above the maximum permitted value out to ranges of 60 and 140 meters, respectively, from the antenna. If one postulates an efficiency for the Ka and V band antennas of something approaching 50%, radiation is reduced to a level which is below the maximum specified figure. It would only become a problem if the MSEL were lowered further (Ref. 36).

Another ramification of the emission of microwave radiation in the terminal area is the possibility of damaging other radar equipments fitted to other aircraft on the ground. For example, an unprotected X-band radar which was inadvertently pointed at a second transmitting, 20kW X-band radar, could receive sufficient energy to burn out its mixer crystals. For this event to occur the equipment receiving the radiated energy would have to be in a switched-off mode and not protected by passive T/R Limiters and/or mechanical shutter. Since it is now standard practice to fit airborne radar with these protective devices, the radiation hazard on other radars is assumed not to be a problem.

The effects of the radar radiation on both personnel and other equipments can also be reduced by operating the radar in a low power mode during taxi operations. The needs during taxi are for relatively short range operations and a low power mode could be both convenient and useful.

6.6 Recommended Frequency Band for Combined ILM and HGA Radar

6.6.1 Introduction. - So far in this report ILM and HGA systems have been considered separately and it is shown that best performance of each is obtained on different frequency bands. However, both these systems need large forward looking antennas installed in the nose of the aircraft and, because of the limited space available, this presents serious installation problems. There is also the cost consideration. It is unlikely that an airline would pay for two radars, in addition to the weather radar. A possible solution would be to use a common antenna aperture for the two frequency bands. This would minimize the installation problem, but would be expensive.

There is, therefore, a strong case for meeting both the ILM and HGA requirements with one radar. Naturally, with a common equipment there will be some degradation in performance in the two modes. This is considered below.

Although the maximum ranges in the HGA and ILM modes are the main criteria for deciding which is the optimum frequency band, there are other features which may affect the choice. These other features are listed below together with an indication of how these change with frequency. The band which gives the best performance is indicated with a circle; an X indicates that performance is very unsatisfactory. This table is used when it is difficult to obtain a clear choice of optimum frequency band just from the range performance.*

TABLE II-89. OPTIMUM FREQUENCY BAND FOR VARIOUS CONDITIONS (Other than ILM or HGA)

FREQUENCY BAND	X	Ku	Ka	V
Interference				o
Obstacle Detection in HGA		o		
Radar Complexity		o	o	o
Taxiway Guidance:				
Without Reflectors	x			o
With Reflectors	o	o	o	o
Obstacle Detection	o			
Radiation Hazard	o	o		

*Ranges in this section are given both in nautical miles (nm) and kilometers (km). Kilometers are in parentheses.

6.6.2 Runways Without Enhancement. - For an equipment that has to operate against runways not enhanced with reflectors or beacons, the only frequency bands that can be considered are Ka and V. With X and Ku bands the detection range of 150 ft runways is less than 1 nm because of beamwidth limitation and this is obviously inadequate.

It has been shown that a radar designed to have a minimum range of 100 ft has a very poor detection range especially with V band. It is, therefore, of interest to examine, in addition, the performance when the minimum range required is 800 ft. This is obtained with a 1 μs transmitter pulse length. The "theoretical" performance obtained with this radar is listed in Table II-90. Also listed is "typical performance" expected in practice. The following assumptions have been made in deriving the "typical performance."

(1) Water content in fog is half theoretical value.

(2) Rain cross section is 10dB below theoretical figure.

(3) Angle of grazing with high ground is 30° in HGA mode.

TABLE II-90. PERFORMANCE OF THE Ka AND V-BAND RADARS IN HGA AND ILM MODES (PULSE LENGTH 1.0 μs)

MODE	PERFORMANCE			
	"THEORETICAL"		"TYPICAL"	
	Ka	V	Ka	V
HGA				
Range in 100 ft fog, nm	4.0 (7.4)	1.1 (2.0	8.0 (14.8)	2.5 (4.6)
Range in 16 mm/hr rain, nm	1.9 (3.5)	0.9 (1.7	2.4 (4.4)	1.2 (2.2)
False returns from 4 mm/hr rain	Yes	Yes	No	Yes
ILM				
Range in 800 ft fog, nm	4.8 (8.9)	9.6 (17.8	4.8 (8.9)	9.6 (17.8)
Range in 100 ft fog, nm	4.8 (8.9)	1.5 (2.8	4.8 (8.9)	3.2 (5.9)
Range in 16 mm/hr rain, nm	0.1 (0.18)	0.008(0.01	1.0 (1.9)	0.08 (0.15)

This table shows that the V band radar has good ILM performance in visibility conditions down to 800 ft., but the detection ranges in the HGA mode, where it is essential to operate in 100 ft. visibility fog, are low.

For taxiway guidance the transmitter pulse length must be reduced to 0.1μs. It is relatively simple to design a radar so that the pulse length can be switched from 1.0 to 0.1μs, but considerable complexity is involved in changing the receiver bandwidth from 1 to 10MHz, so as to maintain this at its optimum value. It is suggested, therefore, that the receiver bandwidth is kept constant at 10MHz. The effect this has on the performance is shown in the following table.

TABLE II-91. PERFORMANCE OF THE Ka AND V-BAND RADARS WITH A TAXIWAY GUIDANCE CAPABILITY

MODE	PERFORMANCE			
	"THEORETICAL"		"TYPICAL"	
	Ka	V	Ka	V
HGA 1.0μs				
Range in 100 ft fog, nm.	2.9 (5.3)	0.9 (1.6)	6.0 (11.1)	1.3 (3.3)
Range in 16 mm/hr rain, nm.	1.4 (2.6)	0.6 (1.1)	1.9 (3.5)	0.9 (3.5)
False returns from 4 mm/hr rain .	Yes	Yes	No	Yes
IALM 150 ft Concrete Runway				
1.0 s Transmitter Pulse				
Detection Range in 800 ft fog, nm	4.8 (8.9)	9.6 (17.8)	4.8 (8.9)	9.6 (17.8)
Detection Range in 400 ft fog, nm	4.8 (8.9)	3.2 (5.9)	4.8 (8.9)	4.9 (9.1)
Detection Range in 100 ft fog, nm	4.8 (8.9)	1.4 (2.6)	4.8 (8.9)	1.9 (3.5)
Detection Range in 16 mm/hr rain, nm	0.1 (0.18)	0.008(0.015)	1.0 (1.8)	0.08 (0.15)
0.1μs Transmitter Pulse				
Detection Range in 400 ft fog, nm	3.2 (5.9)	1.1 (2.0)	4.8 (8.9)	1.9 (3.5)
Detection Range in 100 ft fog, nm	2.9 (5.4)	0.9 (1.7)	4.3 (8.0)	1.2 (0.15)
Detection Range in 16 mm/hr rain, nm	0.1 (0.18)	0.008(0.015)	1.0 (1.9)	0.08 (0.15)

This table shows that the detection range of the V band radar in the HGA mode is too short, even assuming "typical" conditions. Hence for an equipment that has to provide both HGA and IALM modes the only suitable band is Ka. The change in the detection ranges in the IALM mode with transmitter pulse length is not significant under "typical" conditions and, therefore, it is proposed that the same pulse length of 0.1μs is used for the approach and landing phase and for the taxi phase.

Reducing the horizontal aperture of the antenna to 0.5m to accommodate a smaller aircraft would reduce the HGA ranges by 20% and, because of the increase in the azimuth beamwidth, the runway detection range of the Ku band radar in the IALM mode would be reduced to 2.2nm.

Increasing the horizontal aperture to 1.5m if installation space allowed, would increase the range in fog in the HGA mode by 15%, but this would still not make the performance of the V band radar adequate. The range of the Ka band radar in the IALM mode on 150 ft runways would also increase by approximately 15% in fog. The performance in rain would not be affected by this change in aperture size. Therefore, a 1.5m aperture does not appear to hold a significant advantage over a 1.0m aperture.

6.6.3 Runways With Enhancement. -

Runways With Corner Reflectors. - The range of the V band radar in a 100 ft. visibility fog and in 16mm/hr rain is unacceptably low in both the ILM and HGA modes. With Ka band the performance is marginal in both modes; but good detection ranges are obtained at X and Ku bands. The Ku band is the better choice of these two since it requires the smaller corner reflector. Furthermore, Table II-89 shows that Ku is the better of the two.

The optimum pulse length for the HGA mode is 1.0μs and for the ILM mode it is 0.1μs. The transmitter should, therefore, be designed so that the pulse length can be switched to either of these two values. As discussed in Section 6.6.2, it is impracticable to make a corresponding change to the receiver bandwidth in order to maintain it at its optimum value and it is, therefore, suggested that it should be made 10MHz wide. The performance of such an equipment is given in the following table.

This equipment also gives good taxiway guidance when switched to a pulse length of 0.1μs.

TABLE II-92. PERFORMANCE OF THE Ku BAND RADAR IN HGA AND ILM MODES
(Runway Enhanced with Reflectors)

MODE	"THEORETICAL" * PERFORMANCE	"TYPICAL" * PERFORMANCE
HGA (1.0 μ s)		
Range in 100 ft fog	7 (13.0)	14 (25.9)
Range in 16 mm/hr rain	3.8 (7.0)	5.0 (9.3)
False Returns from 16 mm/hr rain fronts	Yes	No
ILM (0.1 μ s) 22m^2 Reflector		
Range in 100 ft fog, nm	10 (18.5)	10 (18.5)
Range in 16 mm/hr rain, nm	5.4 (10.0)	5.4 (10.0)

*"Theoretical" and "Typical" are consistent with the definition set down in the previous Section, Runways Without Enhancement.

Runways with Beacon Transponders. - Page 59 of Volume III shows that the beacon transmitter power required increases rapidly with frequency. That required for V-band is impracticably large, but for the other bands the power required can now be achieved with solid state sources.

As regards HGA performance, X and Ku bands give satisfactory performance, but Table II-93 shows that when other performance factors are taken into consideration, Ku is the better choice.

The pulse length for HGA should be 1.0μs, but for the ILM mode, 0.1μs is probably the best value and this can also be used for taxiway guidance. As described in the previous topic, the receiver bandwidth should be 10 MHz in order to allow for the 0.1μs pulse and, in order to reduce complexity, this is also used when the pulse length is 1.0μs. The performance obtained with this system is listed in Table II-94.

TABLE II-93. PERFORMANCE OF THE Ku BAND RADAR IN HGA AND ILM MODES (Runway Beacons)

MODE	"THEORETICAL" PERFORMANCE	"TYPICAL" PERFORMANCE
HGA (1.0 μs)		
Range in 100 ft fog	7.0 (12.9)	14 (25.9)
Range in 16 mm/hr rain	3.8 (7.0)	5.0 (9.3)
False Returns from 16 mm/hr rainfronts	Yes	No
ILM (0.1 μs) 81mWBeacon		
Range in 100 ft fog	24 (44.4)	40 (74.0)
Range in 16 mm/hr rain	10 (18.5)	10 (18.5)

With a beacon power of 81mW, ILM operates satisfactorily in 16mm/hr rain as well as in 100 ft. visibility fog and, since it is a beacon system, there are no rain echoes to confuse the pilot.

The performance would be altered if either a larger or smaller installation space were considered. Reducing the antenna horizontal aperture from 1m to 0.5m would reduce the HGA ranges by 20% and the IALM ranges by 30%. On the other hand, increasing the aperture to 1.5m would increase the HGA ranges by 15% and the IALM ranges by 23%.

6.6.4 Alternative Solution. -

- Introduction

An alternative solution that is worthy of consideration is a single equipment that has weather radar, HGA, ILM and taxiway guidance capabilities. This is attractive since it overcomes the problem of finding space in the nose of an aircraft for a multiple antenna installation and because it reduces the complexity and cost of the equipment required.

To meet weather radar requirements it is most likely that X band would have to be used and such a system is considered below. But for certain applications, Ku or C band is a possibility and there is no reason why this solution should not be adopted on these bands.

Because of its wide azimuth beamwidth and ILM system that operates on X band is not satisfactory without some form of runway enhancement. Although beam sharpening improves the angular resolution with point targets and with beacons, it does not improve runway definition as seen on a radar map of the airport. Consequently, this system requires reflectors or beacons to identify the runway and taxiway.

- Antenna Requirements

The main antenna requirements are as follows:

(1) Weather Radar

Pencil beam, typically 3° wide.

Azimuth scan ± 90°.

Pitch stabilized with respect to the horizontal.

(2) HGA

Pencil beam in azimuth.

Beam sharpening required in elevation plane to give angular accuracy of 0.3°

Azimuth scan, greater than ± 30°.

Boresight pitch stabilized with respect to horizontal or flight vector.

(3) ILM

Beam sharpening required in elevation plane for angular accuracy of 0.3°.

Beam sharpening required in azimuth plane for angular accuracy of 0.4°.

Azimuth scan, greater than ± 30°.

Elevation boresight pitch stabilized with respect to the horizontal.

(4) Taxiway Guidance

Beam sharpening required in azimuth plane for angular accuracy of better than 1.5°.

Azimuth scan, greater than ± 30°.

An antenna that has beam sharpening in both azimuth and elevation planes is capable of meeting all the above requirements and this can be provided either by monopulse or interferometer techniques. Both these are well known and have been extensively used in military systems.

- Transmitter/Receiver Requirements

The transmitter pulse length of a weather radar is usually several microseconds long and the receiver bandwidth correspondingly narrow in order to obtain adequate range. There is no reason why the same pulse length should not be used for HGA but, as discussed earlier, for ILM and taxiway guidance the pulse length should be much shorter, for example 0.1μs, with a 10MHz receiver bandwidth. This is achieved quite easily by designing the transmitter so that the pulse length can be switched, for example from 5μs to 0.1μs. With the short pulse length, a wide band sum receiver is required, in addition to the two wide band receivers associated with the monopulse difference, or interferometer channels.

- Performance

Since only one equipment has to be installed in the nose of the aircraft, there is no reason to limit its transmitter power to 20kW in order to cut down its size and it could be increased to about 70kW, which is typical of weather radar equipments fitted to civil aircraft. In this case its weather radar performance would be similar to that of a typical 70kW weather radar.

In the HGA and ILM modes its performance is slightly changed from that of the X band equipments considered earlier in the report because of difference in the parameters. When these are substituted in the appropriate equations of Vol. III, Section 6, we find that the performance is as listed in Table II-94. This is for a monopulse system with an antenna diameter of 3 feet, and parameters as listed. The parameters not listed are the same as those in Table III-11 of Volume III.

This table shows that satisfactory performance is obtained with an X band equipment in the HGA and ILM modes, provided beam sharpening techniques are used. If it is concluded that runway enhancement has to be used to provide acceptable performance in the ILM mode, i.e., a range of at least 5 nm on all types of runways, under all weather conditions, then an X band equipment is the best choice. As well as acting as an ILM

TABLE II-94. PERFORMANCE OF THE X BAND MULTI-MODE RADAR IN HGA AND ILM MODES

MODE	PARAMETERS		PERFORMANCE	"THEORETICAL"	"TYPICAL"
HGA	Transmitter Power	70kW	Range in 100 ft fog	21 (39) *	37 (68) *
	Pulse Length	5μs	Range in 16 mm/hr rain	13 (24)	19 (35)
	Receiver bandwidth	10MHz	False echoes in 0 to 10nm range		
	Antenna gain	33dB	From 4 mm/hr rain	Yes	No
			From 16 mm/hr rain	Yes	No
ILM	Transmitter Power	70kW	Corner Reflector		
	Pulse Length	0.1μs	Size for 10 nm Range		
	Receiver bandwidth	10MHz	In 16 mm/hr rain	3500m^2	350m^2
	Antenna gain	33dB	Beacon Power for 10 nm range in 16 mm/hr rain	1.2mW	1.2mW

it can provide HGA and weather radar information. Although the equipment is more complex than a weather radar, its cost would be much less than that of a weather radar plus a separate ILM-HGA radar. In addition the installation problems are considerably reduced.

In the smaller commercial aircraft where there would be space only to install an antenna with a horizontal aperture of 0.5m, the ranges of the radar in the HGA mode would be reduced by 20% and the corresponding figure in the IALM mode would be 30%. The range in the IALM mode could be maintained at 10nm in 16mm/hr rain by increasing the beacon power to 2.4mW. It is seen, therefore, as far as the HGA and IALM modes are concerned, satisfactory performance can be obtained with a small antenna having a horizontal aperture of 0.5m; in practice, the performance requirements of the weather radars will dictate the antenna size.

Large aircraft could be fitted with an antenna having a horizontal aperture of 1.5m and this would increase the ranges in the HGA and IALM modes by 15% and 23%, respectively.

* Ranges are given both in nm and km (kilometers in parentheses)

6.7 Optical Sensors

6.7.1 Introduction. - The performance of optical sensors depends upon the design parameters such as aperture size and detector sensitivity, but the main factor that limits the detection range is the attenuation and scattering rather than absorption. Attenuation reduces the amplitude of the wanted signal whereas scattering from other light sources increases the background illumination level.

Possible wavebands for optical sensors range from the visible band to the far infra-red, but in this report we shall restrict our consideration to two bands. These are the 0.5 to 1 micron band and the far infra-red wavelength of 10 microns. The reason for this is that there has been, over the past few years, extensive development of equipments on these bands for military applications.

6.7.2 Optical Sensor Systems for Runway Detection. -

Sensor Requirements. - The performance requirements of optical sensors are not necessarily the same as those for an approach and landing role. There are two main differences. First, military targets are not cooperative and sources of illumination that would help in their detection are usually absent. Airports, on the other hand, can always be assumed to have approach and runway lights. Second, operation in fog is desirable in the military case, but it is absolutely essential for an IALM. In general terms, an optical IALM sensor must operate in fog and have detection ranges on the approach and runway lights, greater than those obtained visually and unaided by the pilot.

Fog affects performance by attenuation and scattering. Attenuation reduces the intensity of the lights being viewed and this is overcome by improving the sensor sensitivity. Scattering from lights and, during the day from the sun, raises the background illumination level and reduces the contrast ratio. This reduces the range at which lights can be seen by an amount which is independent of the sensor sensitivity.

There are numerous conditions of poor visibility when one considers all the possible variations in the height and density of clouds and fogs. Analysis of all possible conditions would be a monumental task and, therefore, the investigation is limited to a few typical cases.

Active systems as well as passive systems have been developed which provide self-illumination of the target to improve night operation. But with approach lighting, this is unnecessary and, therefore, such systems are not considered.

Effect of Scattering on Sensor Range. - Consider the case, illustrated in Figure II-25 of an aircraft descending through a layer of fog having an attenuation coefficient α. The sensor is required to detect light L_1 in the presence of scatter from light L_2. During the day, detection must take place in the presence of scatter from solar radiation as well as from light L_2.

The irradiance at the sensor S from the light L_1 is given by the equation

$$H_1 = \frac{P}{(R + D)^2} \quad \text{Exp} \, [-\alpha \, (R+D)]$$

where P is the radiant intensity of the light and α is the attenuation coefficient.

As regards the background illumination, we shall assume that it is produced by scattering from the region shown shaded in Figure II-25 and, in order to simplify the calculations, it is further assumed that the forward scattering and attenuation coefficients are equal. By integration we obtain the following equation for the total scattered power density at the sensor

$$H_s = \frac{P \alpha A}{4 \pi} \cdot \frac{(5R - D)}{RD} \cdot \frac{\text{Exp} \, [-\alpha R]}{(R + D)^2}$$

where A is the aperture area of the light L_1.

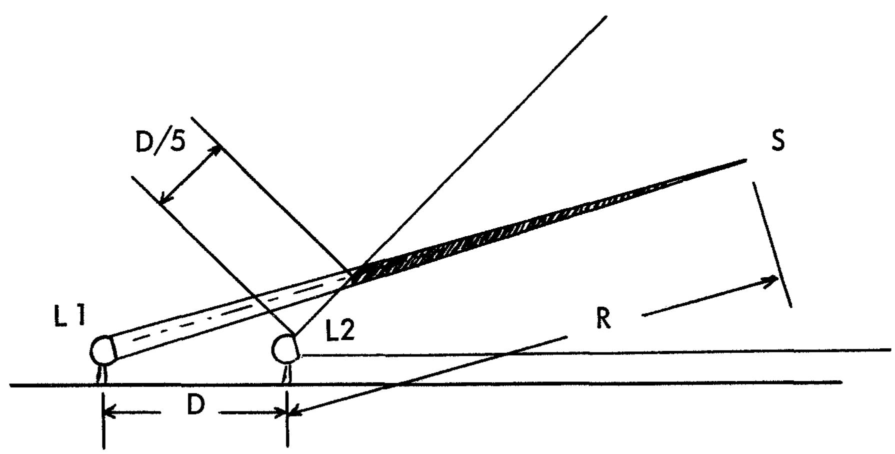


Figure II-25. Scattering in Fog.

For light L_1 to be seen, H_1 must be greater than H_s. If this ratio is taken as 2:1 then the condition for visibility is :

$$\frac{P}{(R+D)^2} \cdot \text{Exp}\,[-\alpha\,(R+D)] > 2\,\frac{P\,\alpha A}{4\,\pi} \cdot \frac{(5R-D)}{RD} \cdot \frac{\text{Exp}\,[-\alpha R]}{(R+D)^2}$$

i.e.,

$$\text{Exp}\,[-\alpha\,D] > \frac{\alpha A}{2\,\pi} \cdot \frac{(5R-D)}{RD}$$

when $A = 1\ ft^2$ and D is small compared with 5R, this simplifies to:

$$\text{Exp}\,[-\alpha\,D] \quad \frac{2.5}{\pi} \cdot \frac{\alpha}{D}$$

This condition is plotted in Figure II-26. It shows that as the attenuation coefficient increases there is a rapid fall in the distance at which the light ahead of the one producing the glare can be seen.

Flight trials have shown that for a landing to be carried out in poor visibility, a segment of the approach lighting at least 300 ft long must be seen by the pilot (Ref.37). Figure II-26 shows that this is only possible when the attenuation is less than $3 \times 10^{-2} ft^{-1}$. This corresponds to a meteorological visibility of about 300 ft with a 0.5 μ sensor and to 100 ft with a 10 μ sensor. These limiting visibility conditions are irrespective of the lighting intensity and the sensitivity of the sensor.

During the day glare from the sun can seriously reduce the range at which the approach lights can be seen. The main factors that affect the range are the strength of the solar radiation along the viewing path and the density of the fog or cloud.

Considering the case shown in Figure II-27, we obtain by integration the following equation for the total scattered irradiance at the sensor S in the solid angle subtended by the light L.

$$H_s = \frac{140}{40\,\pi} \cdot \frac{A}{R^2} \cdot \text{Exp}\,[-\alpha X] \left\{1 - \text{Exp}\,[-\alpha R]\right\}$$

where: Solar radiation = $140 W ft^{-2}$
- A = Aperture area of light
- α = Attenuation coefficient
- $\alpha/10$ = Scattering coefficient at 90°
- X = Distance optical path is below top of fog or cloud
- R = Range to light

With a light of radiant intensity $P\ Wsr^{-1}$ the irradiance at the sensor is:

$$H_1 = \frac{P}{R^2} \cdot \text{Exp}\,[-\alpha R]$$

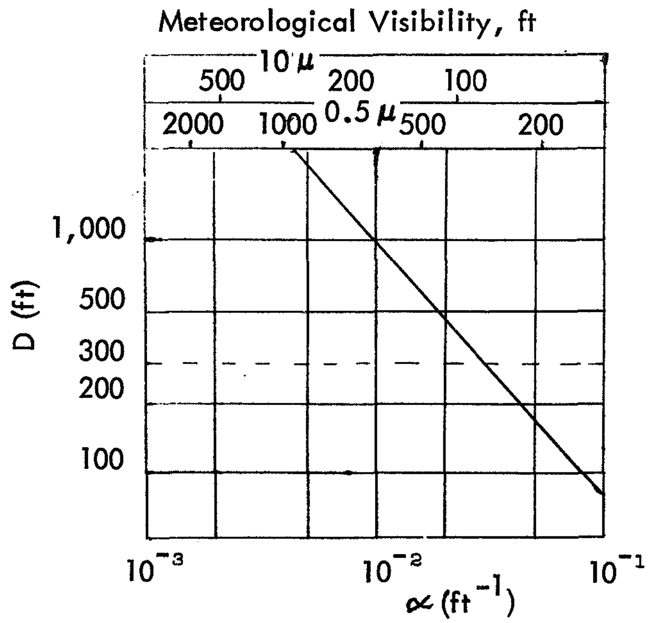


Figure II-26. Effect of Scatter on Sensor Range

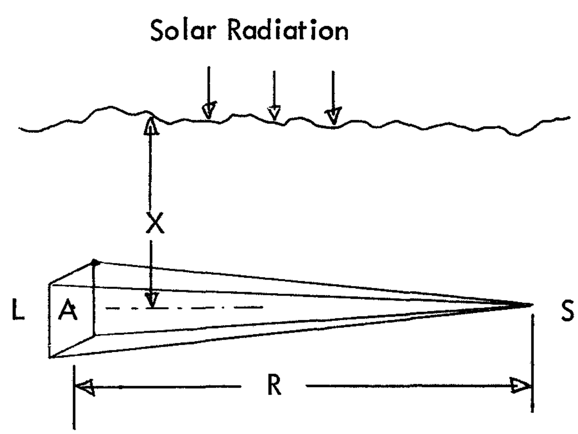


Figure II-27. Scattering from Solar Radiation

Assuming that H_1 must be more than twice H_s for the light to be seen then, neglecting the difference in the spectral distribution of the sun and approach light, the condition for visibility is:

$$\text{Exp}\,[-\alpha R] > 2\ \frac{140}{40} \cdot \frac{A}{P} \cdot \text{Exp}\,[-\alpha X] \left\{1\text{-Exp}\,[-\alpha R]\right\}$$

Substituting the typical values:

$P = 15\ \text{Wsr}^{-1}$ (10,000 candelas)

Note: (the candela and the "candle" are equivalent units)

$A = 1\ \text{ft}^2$

gives the following:

$$\text{Exp}\,[-\alpha R] > \frac{\text{Exp}\,[-\alpha X] \left\{1\text{-Exp}\,[-\alpha R]\right\}}{6.75}$$

This relationship is plotted on Figure II-28.

The important conclusion to be drawn about sun glare is that to be absolutely sure of it not affecting visibility, the distance below the top of the cloud or fog must be greater than the range of the light to be detected. It is also interesting to note that when the attenuation coefficient falls below a critical value, detection of a light at a given range is no longer affected by sun glare. For example, a light can be seen at a range of 1000 ft with a 0.5 μ sensor in fog or cloud with a meteorological visibility of 2000 ft irrespective of the height of the cloud or fog layer.

o Sensor Performance. - With a low light level TV system having a sensitivity of 10^{-8} lumens/ft^2, and assuming that the spectral distribution of the approach light matches the spectral response of the sensor, the range at which the light of P candelas is detected is given by the equation:

$$\frac{P}{R^2}\ \text{Exp}\,[-\alpha R] = 10^{-8}$$

Figure II-29 plots the detection range against attenuation coefficient for a nighttime approach light of 1000 candelas and a daytime light of 1000 candelas.

From Figures II-26, 28, and 29, the following table has been derived which lists the limiting meteorological visibilities for sensor ranges of 500 ft and 1000 ft. Also listed in parenthesis is the factor that is causing the limitation.

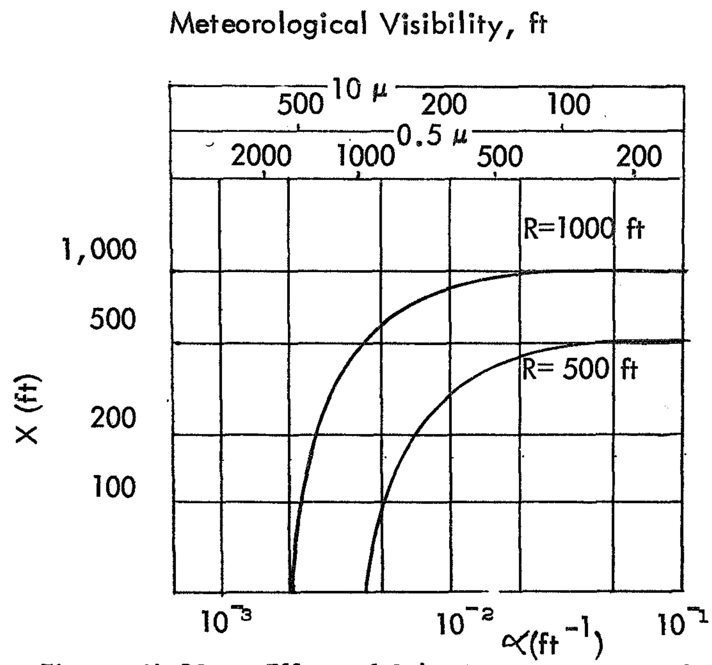


Figure II-28. Effect of Solar Radiation on Performance

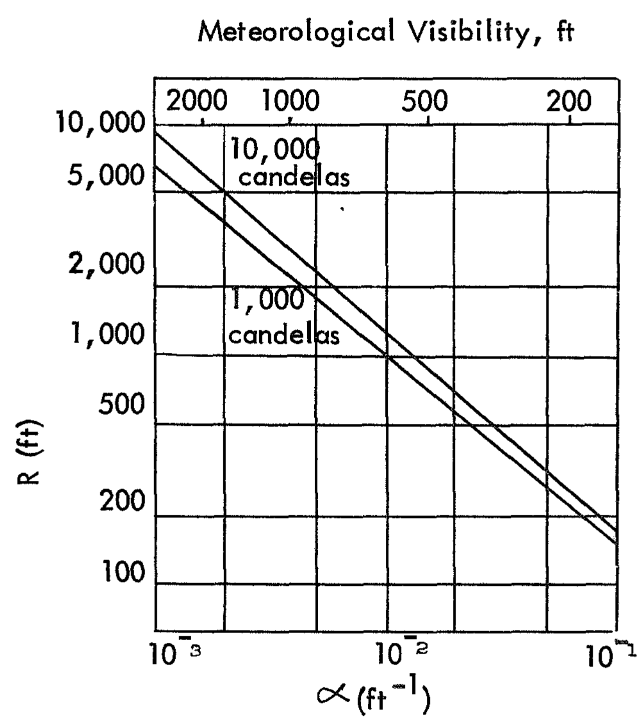


Figure II-29. LLLTV Sensor Performance

TABLE II-95. Performance of LLLTV Sensor

Range Required ft	Limiting Meteorological Visibility, ft	
	Day	Night
500	1000 (solar glare)	390 (sensitivity)
1000	1700 (solar glare)	600 (sensitivity

This table shows that the sensor range is not all that different from the meteorological visibility and when one takes into account the improvement in visual range when runway and approach lighting is used, it is obvious that little or no benefit is obtained by the use of this sensor.

Figure II-30 plots the detection range of a 10 micron sensor against attenuation coefficient. It has been assumed that the power radiated by an approach light in a frequency band corresponding to the spectral response of the detector is such that the intensity of illumination at the detector at a distance R is given by:

$$\frac{1}{10R^2} \text{ Exp } [-\alpha R] \text{ w/ft}^2 \quad \text{at night}$$

and $$\frac{1}{R^2} \text{ Exp } [-\alpha R] \text{ w/ft}^2 \quad \text{during the day}$$

It is further assumed that the sensor has a cooled detector, followed by an amplifier with a 10^5Hz bandwidth, giving an effective detectivity of 5×10^8 w^{-1}, and an aperture of 4×10^{-2} ft^2.

From Figures II-26, 28 and 30, the following table is obtained which lists the limiting meteorological visibilities for sensor ranges of 500ft and 1000ft. The factor that limits the performance is given in parenthesis.

TABLE II-96. PERFORMANCE OF INFRA-RED SENSOR

Range Required	Limiting Meteorological Visibility, ft	
ft	Day	Night
500	300 (solar glare)	300 (sensitivity)
1000	500 (solar glare)	800 (sensitivity)

This table shows that in most cases the infrared sensor has slightly greater detection ranges than the 0.5 micron sensor, but the increase over that obtained visually by the pilot is marginal.

This cursory analysis of the performance of optical sensors in the detection of runways with approach lights has shown, in the cases considered, it is not all that different from that obtained visually by the pilot. A more detailed examination may reveal that the optimum wavelength is between 0.5 and 10 microns but significant improvement is unlikely. Since these sensors are large and expensive, it is concluded that the marginal increase in the detection ranges does not justify their adoption as a landing aid.

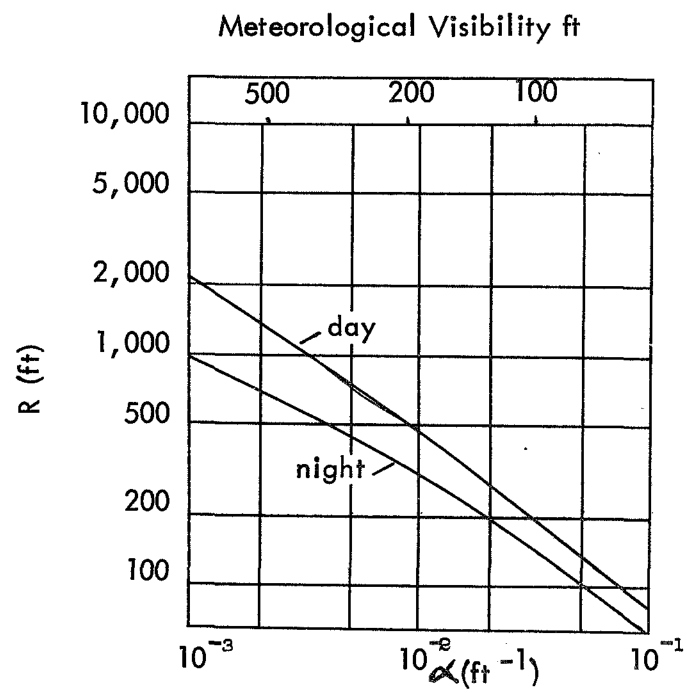


Figure II-30. Range of Infrared Sensor.

6.8 Summary

In summarizing sensor performance, the following items stand out:

1. The radar range performance on unenhanced runways falls short of the desired performance. Ka band gives the best performance of the radars studied. Its range is on the order of 3 to 5 nm in clear weather and light rain but the range capability deteriorates rapidly in heavy rain.

2. When passive reflectors are used to enhance the runway, X band and Ku band are the best choices, with Ka band having slightly less range capability. Ranges of from 7 to 10 nm can be achieved at both X band and Ku band. However, the resolution at X band is not adequate to produce a radar map of the runway.

3. When beacons are used to enhance the runways, Ku band is desired over X band because of its better resolution. The beacon power required at either Ka band or V band is too large.

4. For the high ground avoidance function, a long pulse length (1.0 μ sec or longer) is desired. Both X band and Ku band give adequate performance. Ka band range is marginal and the V band range is poor.

5. For roll out and taxi assistance in Category III conditions, resolution requirements tend to favor the choice of the higher frequency bands.

6. Two alternatives are presented as summary suggestions:

   a) A combined ILM and HGA radar system with the following features...

      o Ku band frequency

      o 1 m antenna aperture in azimuth

      o runways enhanced by reflectors

      o 1.0 and 0.1 μ s pulse widths available

   b) A combined ILM, HGA, weather, and taxiway guidance radar with the following features...

      o X-band frequency (possibly Ku band)

      o 1 m antenna aperture in azimuth

      o runways enhanced by reflectors or beacons

      o 5.0 and 0.1 μ s pulse widths available

7. A cursory investigation of optical sensors indicated they do not offer much improvement over existing visual capability.

7.0 SYSTEM CONFIGURATIONS

7.1 Introduction

Previous sections of this report have dealt with the economic and operational aspects of the aircraft hazard warning and avoidance problem. Technical data regarding the performance of available sensors under varying conditions of reduced visibility has been developed in the context of the functions to be performed and the level of performance to be provided. It now remains to postulate, from an operational integrated system viewpoint, one or more viable system concepts in which the major system elements, the interface between elements, and the overall functional performance capability are identified.

Systems that have IALM, ROTA and HGA capabilities in general will comprise a primary sensor (or a combination of sensors) which determines the position and presentation of a runway, its centerline and the required touch-down point; and high ground with respect to the aircraft velocity vector, a processor which converts, modifies, or operates upon information derived by the sensor(s) and a display which is fed from the processor. In addition, inputs from other sensors in the aircraft are usually required by the processor in order for it to effectively provide the display with the desired information. The choice of primary system sensor depends in major part upon the maximum range requirements, target signature characteristics and the maximum fog density or precipitation rate that may be encountered. For most system applications the reduced range capability of optical systems, both passive and active, makes them unsuitable.

An IALM system, particularly one which relies upon some measure of runway signature enhancement, can be made compatible with ROTA system requirements. Such a system could also provide HGA capability, although range performance of Ka and V band radars during enroute operations in precipitation-bearing clouds may be marginal. Where a lower frequency band is adopted, adequate HGA performance can be provided except in the most intense storms.

Three system configurations have been postulated ranging in complexity, size and performance as a function of candidate user, i.e., commuter, regional or trunk carrier, the kinds of aircraft operated by the respective carriers and the airfield environment into which they operate.

The assumption is made that most commuter airlines operate regularly into airfields which do not now have Cat II qualified ILS installations and may well not have such a capability for many years. Furthermore, an agressive airline management will continually strive to open up additional service into communities not now provided with scheduled service. Since the aircraft operated by these carriers is restricted in size by regulations, the proposed IALM and HGA equipment must be restricted in size and probably the complexity as well. The antenna length will probably be 0.5 meter or less. Thus, the first level system is suggested to be one which provides the pilot with the ability to approach and land at any airfield only when the visibility conditions are not worse than 200 ft and 1/2 mile, i.e., Cat I. The economic analysis of Section 3 has already indicated the large benefit in reduced operating losses that could accrue to airline operators from the capability to operate at reduced minima. Table II-17 has shown the distribution of airports in a typical route structure to which this capability could be applied. High ground warning would be provided. ROTA capability would be marginal for a system designed for Cat I operation only. Simple, low-cost runway signature enhancement such as passive corner reflectors is assumed. A design objective should be to take advantage of the existing weather radar bay.

These criteria suggest a system which displays the runway, centerline and threshold and some vertical guidance information.

It is anticipated that regional carriers and some trunks will continue to operate twin and tri-jet equipment into airfields which either are not ILS equipped or if ILS equipped, not Cat II qualified for sometime to come. However, the design objective should be to meet Cat II performance criteria, i.e., 100 ft and 3/16 mile. The IALM system postulated for this category aircraft assumes that antenna size must be restricted to 1 meter or less. The system should perform all of the functions provided for in the previously described system concept and in addition, must provide more precise vertical guidance information.

The trunk carriers generally operate into airfields which are already equipped with ILS, some qualified to Cat II, several more planned for Cat II qualification in the next few years and with a gradual upgrading to Cat III underway for selected airfields. As a consequence, it would appear that the motivation exists for a system which not only provides the High Ground Avoidance capability and approach monitor capability discussed above, but also supplies command information relative to the approach path of sufficient accuracy to determine whether or not the on-board Cat III guidance system is performing properly.

The trunks are gradually requiring aircraft which, in terms of size, cost and potential productivity, will allow for equipment of significantly greater performance and levels of automation. These new aircraft could possibly accomodate antennas of greater length and/or the use of a shared antenna for multiple frequencies, i.e., X band for HGA and weather avoidance and initial orientation during approach and V band or Ka band for the IALM and ROTA tasks. Such a combination would assure the ability to cope with 100 ft visibility fog and/or rainfall rates up to 16 mm/hr while guaranteeing the availability of very high resolution during the last one mile to touchdown, the roll-out phase and finally during taxi.

A fundamental requirement of all three system configurations is that the airfield/ runway complex be immediately identifiable by the pilot and that little or no additional workload be imposed on the pilot in the operation of these systems.

In summary then it is seen that at least three candidate system configurations can be identified.

(1) A hazard avoidance radar monitor system providing warning of severe weather (typical weather radar), the proximity of high ground and the location of runway center-line and threshold.

(2) A system which provides all of the features listed in (1) above and in addition, supplies flight director or flight path command information with sufficient accuracy to permit Cat II approach minima to be utilized.

(3) The most complex system will provide all of the features of (1) and (2) above and in addition be of such accuracy that it may be used to monitor an approach under Cat III criteria. Further it shall provide information necessary to roll-out, turn-off and taxi-in conditions of zero visibility.

It should be pointed out that these system configurations have deliberately been chosen to be general in nature. No unique or proprietary features of particular manufacturers' hardware have been included.

7.2 Configuration I - System with Pictorial Situation Display

The system block diagram for the simple radar approach monitor system is shown in Figure II-31.

To produce a situation display, the sensor works as a pitch & roll stabilized ground mapping radar. In the IALM mode, the display would show the runway, together with the track cursor and intercept of the velocity vector. The boresight is pitch stabilized so as to be depressed from the horizontal by the approach path angle. When the aircraft is correctly positioned on the approach path, the boresight intercept and the track cursor should intersect at the touchdown point. Warning of high ground near the flight path is obtained by off-boresight processing of the return radar signals so that any high ground within a predetermined sector produces a warning signal. During enroute flying the display shows a clearance plane display of high ground above a predetermined distance below the flight path. The main characteristics of this system are as follows:

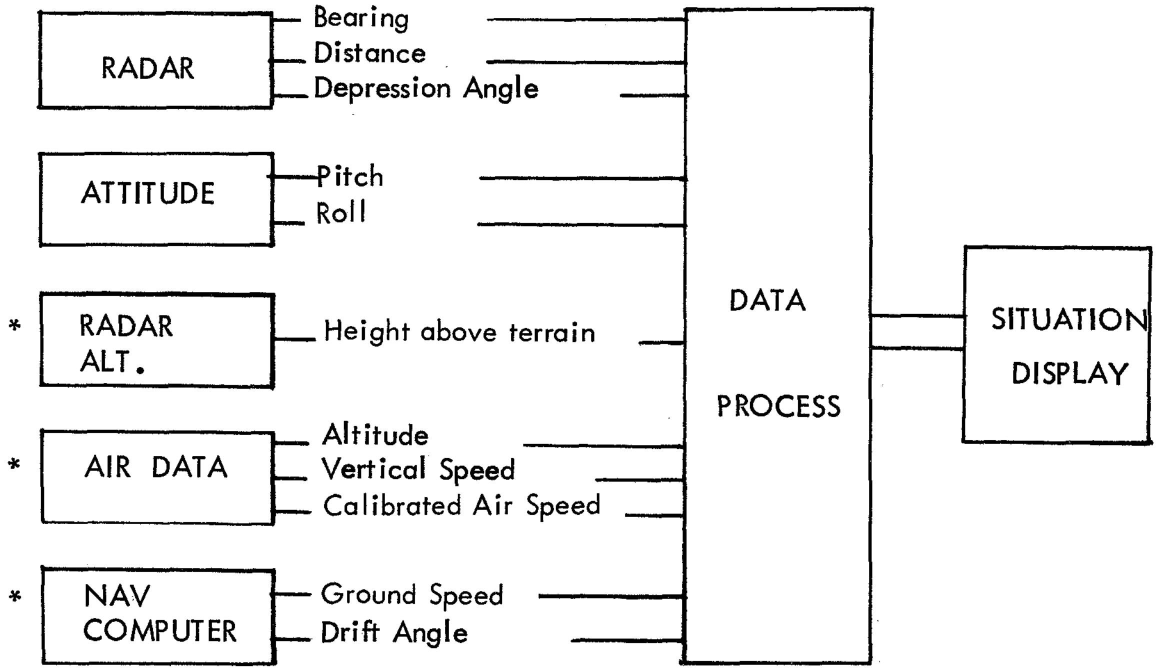


Figure II-31. Candidate System Configuration No. 1

- Antenna: Monopulse/Interferometer in elevation.
  Monopulse/Interferometer in azimuth (if X band sensor).
  Pitch stabilized.
  Roll stabilized.
  Azimuth scan.

- Receiver: Off-boresight processing capability.

- Input Required: Pitch angle.
  Drift angle.
  Ground speed.
  Selected descent angle.
  Selected approach path angle.

Note:

* Optional inputs, according to system mechanization

. Outputs - Enroute and During Descent	Warning of high ground near flight path. Profile and plan views of clearance plane display of high ground.
. On approach	Warning of high ground near flight path. Velocity stabilized display of runway with flight vector intercept superimposed. Aircraft track indicated by cursor.
. Taxiway	Situation display showing taxiway.

The approach capability can be achieved without runway enhancement for most domestic operations, however, improved performance could be achieved if runway enhnacement were introduced.

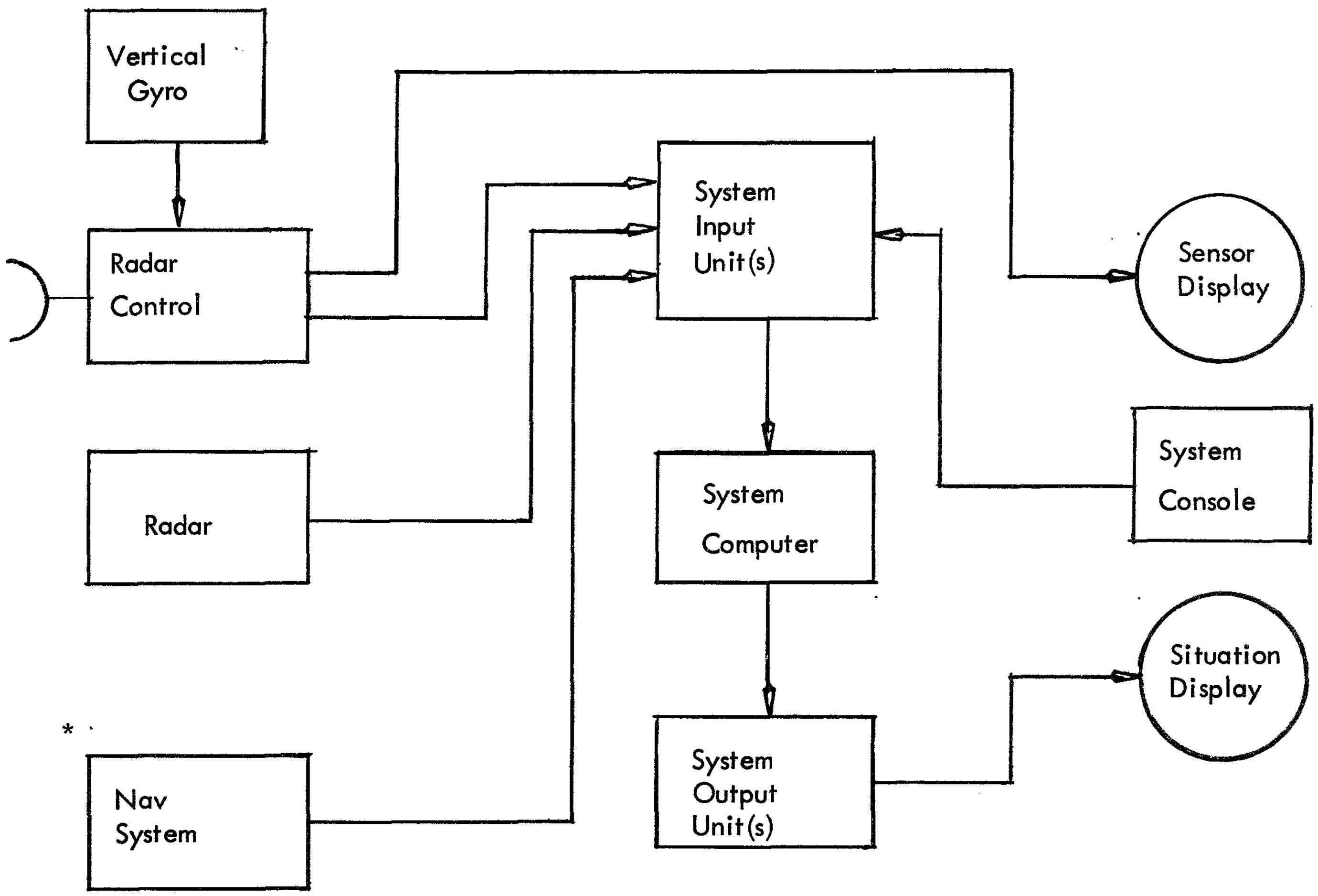
It will be observed that the system requires a minimum of new airborne equipment and radar upgrading, hence, it could be relatively inexpensive.

7.3 Configuration II - System with Director Type Display

The system block diagram for Configuration II is shown in Figure II-32.

For a system with a director type display the radar must determine the aircraft's position relative to a discrete point on the ground. This can only be achieved if the particular point is enhanced by a reflector or beacon so as to produce a readily distinguishable signal. Between 10nm and 5nm from touchdown, the radar in a track-while-scan mode is locked on to the enhanced point, which is defined as being proximate to the touchdown point. The range and angular position of this point relative to the aircraft's axes are obtained by the radar and fed, together with pitch, roll and heading of the aircraft, and runway heading, to a computer which derives the horizontal and vertical distances from the selected glide slope and localizer approach path. The main characteristics of this system are listed below:

. Antenna	Monopulse/Interferometer in elevation. Monopulse/Interferometer in azimuth. Pitch stabilization. Roll stabilization.
. Receiver	Off-boresight processing capability. Track while scan capability.



*Optional input according to system mechanization.

Figure II-32. Candidate System Configuration No. II.

. Computer	Computes distance in two planes from correct approach path.
. Inputs Required	Pitch angle. Roll angle. Drift angle. Aircraft heading. Selected descent angle. Selected runway heading.
. Outputs - Enroute and during descent	Warning of high ground near flight path. Clearance plane display of high ground.
. On approach	Warning of high ground near flight path. Display of runway. Vertical distance from correct approach path. Horizontal distance from correct approach path. Range to touchdown. Predicted touchdown point.
. Taxiway	Display showing enhanced taxiway.

The enroute and descent high ground warning functions are identical to those of Configuration No. 1. The system computer and display are configured to provide aircrew assistance in acquiring the runway on radar.

The radar and system computer requirements are increased in this system over Configuration No. 1.

The advantages of the system (System No. II) are these:

- Pilot manipulation requirements are reduced over Configuration 1.
- Additional interpretation of data display is not necessary.
- Pilot assistance functions can be performed to optimize runway and terrain data acquisition.

The disadvantages are these:

. Increased complexity, hence increased cost.

. Possible decreased overall system reliability, also relatable to increased complexity.

7.4 Configuration III - System with IALM, ROTA, HGA and Weather Radar Capabilities

A maximum capability version of a fully automatic multi-sensor system concept is shown in Figure II-33. The performance capability of this type of system mechanization is as follows:

. Possibility of two additional position sensors.

. A multi-sensor display and processing system.

. Generation of situation and flight director data for approach monitoring.

. Automatic terrain warning and generation of guidance data to assure hazard avoidance.

. Sensor data selection.

The advantages of this approach are:

. Operator manipulation is substantially reduced.

. Cross checking of two independent sources of guidance data can be achieved.

. Flight Director operating techniques can be utilized.

. Missed approach-guidance can be provided.

With runway and taxiway enhancement, an X band sensor can very easily meet the performance requirements of IALM and ROTA. It also provides adequate performance in the HGA mode. As pointed out in Section 6.6 there is no reason why the same X band sensor should not also meet enroute weather radar requirements. In this way, with a single equipment that is not much more expensive than a weather radar, it is possible to provide, in addition to the weather radar capability, IALM, ROTA and HGA capabilities.

It is to be observed that each of the two more complex system approaches can be configured so that the simple radar approach monitor capability of the first system is available in any event. The approach to be used is dependent on relative development and mechanization costs and the overall system objectives.

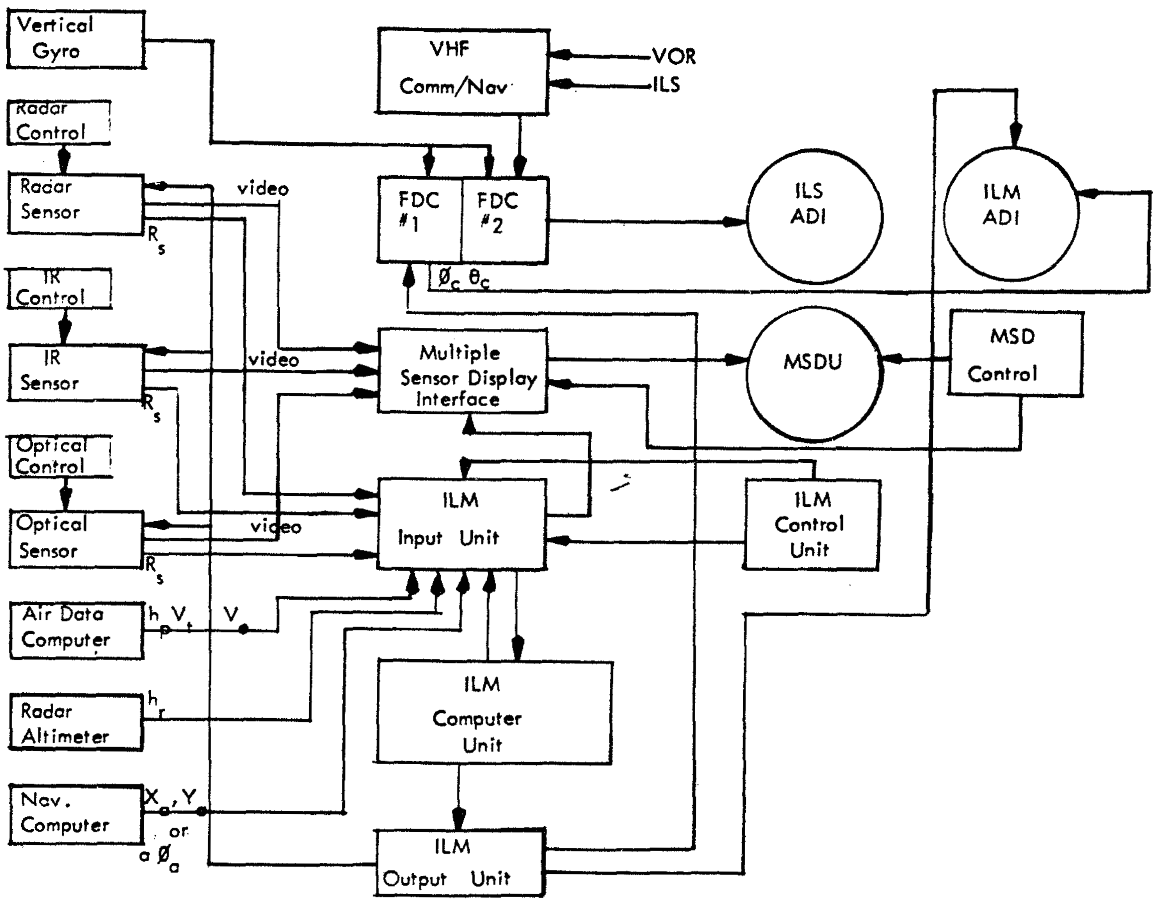


Figure II-33. Candidate System No. 3

8.0 CONCLUSIONS

8.1 Introduction

Each of the preceding sections of this report has dealt with a particular aspect of the hazard warning and avoidance problem. In most cases, each section has had included in it a summary of the major conclusions drawn from the material in that section. It is the purpose of these paragraphs here to draw together all of these related conclusions into one summary section. The conclusions contained herein are factual and summary in nature. Wherever possible reference will be made to the major section of this report which contains the detailed substantiating data which support the stated conclusions.

8.2 Meteorological Effects (Section 2.2)

Optical visibility is most severely restricted by dense fog, which can create situations of essentially zero visibility at ground level. Heavy rain does not necessarily degrade visibility unless accompanied by fog or low clouds. The rainfall rate of 16 mm/hr was taken as the nominal maximum value for this study. Much heavier rains do occur but with small probability of occurrence and short durations. The visibility range in 16 mm/hr rainfall is approximately 5600 feet. A reasonable attenuation of falling snow is somewhat less than that of 4 mm/hr of rain. Smog is similar to fog with a visibility of 2400 feet.

Due to the probability of occurrence of combined rain and fog in the Southern and Southeastern U.S. in the winter months, as one example, it was concluded that the hazard warning and avoidance system must have adequate runway detection performance and high ground avoidance performance under the condition that both fog and heavy (16 mm/hr) rainfall exist simultaneously.

8.3 Accident Statistics (Section 2.3)

Of the 820 accidents which occurred to certificated air carriers during the period of 1958 to 1967, 110 could be classified as those in which the existence of an airborne hazard warning and avoidance system could have significantly contributed to the avoidance of these accidents. These 110 accidents accounted for 37% of all of the fatalities suffered in the 820 accidents. 63% of these "applicable" accidents occurred during the final approach (24% - 10 miles to 1 1/2 miles from runway threshold) and landing (39% - 1 1/2 miles to runway threshold) phases of the flight. The final approach accidents typically occurred in poor visibility. 25 of the 43 landing phase accidents occurred in "daytime" conditions, implying that the pilot could see the runway.

There is a need for either high-ground or runway orientation at distances up to 10 miles from runway threshold. Few accidents occur beyond 10 miles. It appears that visual acquisition of the runway is, of itself, not adequate for safe operation. A combination of instantly recognizable runway identification and orientation coupled with command guidance information similar to ILS but generated completely independently of ILS is required for proper landing operations.

8.4 Economic Benefits (Section 3 and Appendix A)

Poor visibility has an adverse economic effect on flight operations by creating delays in landing or a diversion to an alternate airport because of an inability to land. This economic impact is separate and above from the safety aspect of the problem. The inclusion of equipment to provide added landing capability (ability to operate at lower minimums) presents a potential way to avoid some of the penalties. The actual cost benefit achieved by such capability varies as the airline route structure, particular airport weather frequency statistics, and traffic density.

For the typical trunk, regional, and commuter airline route structures hypothesized for this study, annual per aircraft savings of as much as $25,000 for the trunk carrier, $53,000 for the regional carrier, and $45,000 for the commuter airline were computed, for a particular airport/weather situation assuming operation down to Category III, but only taking benefit for performance in weather below 1/2 mile visibility. Additional total savings could also be achieved for those situations where the minima are above 1/2 mile. The majority of the savings is felt in achieving operation down to 1/16 mile visibility, but a significant cost impact can be identified in getting from 1/2 mile to 3/16 mile conditions. Again, for the three carrier levels studied, annual per aircraft savings of $13,000 for the trunk, $27,000 for the regional, and $21,000 for the commuter carrier were postulated in lowering the operating minima from 1/2 to 3/16 mile. While many other combinations of route structures, weather statistics, and operating frequency can be studied, the foregoing figures identify the order of magnitude of equipment cost that could be considered on a cost benefit basis. One major conclusion of this particular analysis was the obvious cost effectiveness of a hazard warning and avoidance system just in reducing the operating minima at non-ILS runways.

8.5 Desired Characteristics (Section 4)

The hazard warning and avoidance system should provide capabilities for High Ground Avoidance (HGA), Independent Approach and Landing Monitor (IALM), and Roll Out and Taxi Aid (ROTA) functions. These system functions are predicated upon a series of safety and economic justifications. In the IALM mode it is desired that the system generate command information or error signals relative to a specified synthetic glide slope and localizer that are comparable in type and accuracy to that of a properly functioning ILS. Pilot workload and display interpretation requirements should be minimized; particularly during final approach conditions.

The primary characteristics of required system performance include:

Maximum Range	
HGA Mode	5-10 n. miles
IALM Mode	7-10 n. miles
Azimuth Coverage	$\pm 30^\circ$
Azimuth Error	0.8°
Elevation Coverage	$+ 5^\circ$ $- 15^\circ$
Elevation Error	0.4°
Offset Error at Threshold	$\pm$ 40'
Scan Rate	
Azimuth	2.3 cycles per sec.
Elevation	1.5 cycles per sec.
Glide Slope Angle	$2-10^\circ$
Cross Wind Component	22-28 knots (10° crab)

8.6 Current Approach and Landing Aids (Section 5)

Theoretically ILS can be developed to sufficient accuracy in the localizer and glide slope planes to be used for Category III landings. Unfortunately, it is still subject to local distortion, bends, etc. Quantitative range to touchdown information is not available to the pilot from existing ILS. Advanced scanning beam ILS concepts are under development, but their authorization and/or implementation have not yet been established. Neither of these ILS-type systems however will provide the back-up capability desired for an IALM, where independence from the ILS system is a design criteria.

VOR/DME is not currently authorized for use in Category I conditions. Such developments as Precision VOR when used with specialized airborne equipment, are capable of the accuracies required for Category I (and perhaps Category II) landings. Ground Controlled Approach (GCA) presently is not authorized for civilian use below Category I although it has been demonstrated within the military to be capable of Category II landings. Although accuracy improvements are possible, the inherent high costs of equipment and 24 hour GCA teams preclude the utilization of GCA for Category III.

8.7 Sensor Performance (Section 6)

Sensor performance was studied primarily with regard to the requirements related to runway detection in the ILM mode and high ground detection in the HGA mode. The study of radar sensors led to the summary recommendation of two major possible radar systems. The brief review of optical sensors which was performed did not identify any promising alternatives in either the visible spectrum or the infra-red spectrum.

Runway identification by radar means requires that the runway be enhanced by reflectors or beacons. Ka band provides the best capability for unenhanced runways but its limited clear weather range capability, 3 to 5 n.m., is seriously reduced by heavy rain. X band and Ku band provide the required 7-10 n.m. range capability when runway enhancement is used. X band is limited only in that it does not possess the resolution required to produce a radar map of the runway. The higher frequency bands, both Ka and V bands, have limited range capability when reflectors are used and they require excessive power levels in beacons, so neither is recommended.

For the detection of high ground, both X band and Ku band provide adequate performance. The range at Ka band is marginal and the range at V band is poor.

The roll out and taxi requirements for Category III operations tend to favor the higher frequency bands, Ka and V bands, because of their superior resolution properties.

In summary, two configurations are recommended for further pursuit. The first of these is a combined ILM and HGA radar system. The system uses

- Ku band frequency
- 1 m antenna aperture in azimuth
- runways enhanced by reflectors
- 1.0 and 0.1 μs pulse widths.

The second is a combined ILM, HGA, Weather and taxiway guidance radar system. This single composite system includes the features of

- X band frequency
- 1 m antenna aperture in azimuth
- runways enhanced by reflectors or beacons
- 5.0 and 0.1 μs pulse widths.

The former system offers slightly better performance when a separate weather radar is available. The latter system offers the possibility of combining the very important ILM and HGA functions with the existing concepts and hardware developed for weather radar applications.

8.8 System Configurations (Section 7)

Based on the sensor performance analysis of Section 6, there are several general system configurations available with the overall required system performance. Due to the various requirements of potential users of hazard warning and avoidance systems, several approaches were investigated. Without runway enhancement, high ground avoidance and some measure of approach monitoring capability can be provided. With some form of runway enhancement, the problem of runway detection and identification is minimized or eliminated. Using monopulse or interferometer techniques for elevation scanning, quantitative command guidance information can be generated and displayed relative to a synthetic glide slope. These systems can provide either monitoring information or actual guidance information, according to the concept of system application. Using concepts of display such as the Electronic Attitude Director Indicator, it is possible to generate either a synthetic runway perspective, or an actual radar or TV view of the runway attitude information, command signals relative to a theoretical glide slope, and a predicted touchdown point relative to the displayed runway.

With runway and taxiway enhancement, either an X band or Ku band sensor can very easily meet the performance requirements of IALM and ROTA. It also provides adequate performance in the HGA mode. As pointed out in Section 6, it is possible to utilize the same X band sensor for these functions that meets enroute weather radar requirements. In this way, with a single equipment that is conceivably not much more expensive than a weather radar, it is possible to provide in addition to the weather radar capability, IALM, ROTA, and HGA capabilities.

9.0 RECOMMENDATIONS FOR FUTURE DEVELOPMENT

9.1 Introduction

Provisions of the original Statement of Work for this study effort called for the development of a comprehensive program aimed at the acquisition and flight test of a demonstration hazard warning and avoidance system. During the conduct of this study, as the operational analysis and technology investigations were performed, marked information gaps in certain basic areas of interest began to appear. Therefore, as the overall development plan is discussed in this section, major emphasis has been placed on closing these information gaps as the necessary next step in an integrated plan.

Definitely this current study, as documented in this volume, has provided the depth of substantiating data necessary as a prerequisite for a decision to continue the development of the hazard warning and avoidance system. The problem has been identified and quantified in three areas - operational, economics and flight safety. Although all of these areas interrelate and interact, it has been shown that each of them would substantially benefit from the functions and capabilities afforded by the system concepts postulated in this study and in a manner that would responsibly benefit both the airline operators and the traveling public. In parallel, an extensive study into the technology of existing sensors has shown that, in general, performance of the required level as defined by the operational problem analysis, is currently available within today's state of the art. However, the sensor technology performance analysis has been based, in part, on an extrapolation into an area of uncertainty related to target signatures and low grazing angles which must be resolved as the logical next element of the development program. Similarly, the subject of flight deck information display content and format both affects and is affected by the entire system concept to such a degree that additional emphasis must be placed on this investigation concurrently with the sensor analysis.

9.2 Immediate Recommendations

"Recommended Development Program" (p.176) describes the overall plan recommended for the development and flight demonstration of a hazard warning and avoidance system. As a device to spotlight the relative importance of the two immediate areas of concern, namely, sensor performance and display concept, these two tasks will be discussed separately, and indeed, are identified as comprising a separate and distinct phase of the development cycle.

9.2.1 <u>Sensor Static Feasibility Tests (Ground Based)</u>. - The sensor performance of an airborne or self-contained IALM depends primarily upon the characteristics of the signals scattered back from the ground at grazing angles in the range of 1° to 10°. Data appearing in Section 2 of Volume III of this report show that very few quantitative measurements have been made of the scattering coefficient of various terrains at grazing angles of less than 10°.

Existing curves for X and Ku band frequencies can probably be extrapolated down to approximately 3° with reasonably accurate results. However, extrapolation at Ka band could give misleading data, while no base data of any significance at all exists for V band. Verification of the validity of extrapolation, or the establishment of a new set of empirical data at angles down to 1° for various frequencies is mandatory prior to a final selection of equipments suitable for flight test. Investigation of the effects of different techniques of polarization (vertical, horizontal, or circular) should also be conducted as they pertain to various frequencies.

The ability of a mapping radar to detect and display an airport runway depends upon the difference between the scattering coefficient of the runway and that of the adjacent ground. At a 10° grazing angle the scattering coefficient of grass is about 20dB above that of concrete and 10dB above that of asphalt. Due to the lack of test data, the performance of the frequency bands considered at angles down to 1° has not been verified. At Ka and V bands, for instance, the surface roughness of runways is becoming large as compared with the wavelength, which may invalidate a straight extrapolation of existing data. The problem of diminished contrast for an unenhanced runway in proximity to a paved intermediate area rather than grass, or a snow-covered runway, poses a series of unanswered questions concerning target signatures. In the case of runway enhancement techniques, the signature characteristics of various reflector/beacon devices also needs empirical verification. For this reason, a comprehensive series of experiments should be run using available equipments at the frequencies of interest and ground-based towers under the requisite conditions of grazing angle and target conditions, in order to establish a data base to be used for the final selection of frequency and runway enhancement to consider for ultimate flight test.

The following paragraphs describe the initial work necessary for the desired sensor performance tests:

Radar, IR, and Visual Spectrum sensor data generated during the Phase I feasibility study should be used to select candidate sensors for static and flight tests. Sensor test plans should be evolved and sensors will then be procured and static testing will be initiated.

These tests should be designed to provide data relating to the following aspects:

- Radar cross sections of various surfaces (asphalt, concrete, grass) as a function of frequency, polarization and grazing angle of very shallow grazing angles (as low as 1 degree). Included in this evaluation will be consideration of runway contrast such as snow cover, paved areas, etc.

  The effect of circular polarization on rain clutter cancellation at shallow grazing angles.

  The optimum polarization technique(s) for a landing monitor system.

The effect on signal return, background levels and attenuation of both visual and IR systems at shallow depression angles.

The effect of utilizing frequency agility techniques as a device for increasing runway contrast.

The relative performance improvement in both radar and IR spectrums of various target enhancement techniques.

The ability of both visual (electro-optical) and IR sensors to perform the Roll-out and Taxi Aid functions for Category IIIC operations.

In addition to obtaining basic sensor data, it will be necessary to assess the practicability of pilot display interpretation for purposes of runway identification. The ratio of runway width to radar beam width which allows identification of the runway (due to the absence of back scatter) should be determined.

9.2.2 Display System Simulation and Evaluation. - In great measure the utility and acceptance of any hazard warning and avoidance system, in particular one whose primary function is one of an Independent Approach and Landing Monitor, is dependent upon the proper processing and display of necessary situation and command information. A whole spectrum of issues and controversies always arises when the subject of cockpit displays is introduced. Some of these issues concern such areas as head-up vs. head-down, real world vs. symbolic presentation, moving PPI vs. touchdown tracking, situation vs. command information, etc. All of these issues must be investigated in a realistic and scientific manner prior to the establishment of a recommended flight test configuration.

The following paragraphs describe the initial work necessary for preliminary display system evaluation.

1. Define and model theoretically the dynamics of the landing phase for representative current and advanced commercial transports including such considerations as safe go-around which are dependent on handling characteristics, size and approach speed. Determine which equipments, computer programs, schedules and costs would be required and perform preliminary design of a simulation facility for the landing phase situation. Consider, wherever possible, the utilization of existing available simulation facilities. Incorporate flexibility to accommodate the full complement of sensor systems which have application as elements of an independent landing monitor. Survey existing displays and make recommendations for incorporating that computer/display system interface which most closely approximates the IALM system needs.

2. Determine from such existing information as EADI flight tests, Ames flight tests and others, the capability of the pilot to land, roll-out, and taxi aircraft using television cameras and cathode-ray tube displays. Devise an evaluation technique to determine relative pilot performance as a function of deterioration in display information resolution and content. Ascertain minimum information requirements for this type of display and establish sensor and processing specifications to provide these minimum requirements.

3. Based on the results of Item 2 above, one or more candidate display systems could be procured for the purposes of system simulation and evaluation. In particular, the following aspects will be considered:

- Display Symbology. This will include assessment of the ease of interpretation of the director and situation data.
- Display Response.
- Accuracy of the display itself and the accuracy with which command flight path can be achieved.
- Control motion in response to display command.
- Adequacy of display of aircraft vertical situation data.

In addition to an operational and functional assessment, a detailed assessment of the ease of interfacing and the degree of difficulty of changing symbology could be achieved. The operational and technical assessment would not be exhaustive but would allow final selection of the flight test display system(s).

9.3 Recommended Development Program

From the standpoint of an overview of all of the elements in an integrated development program, the recommended tasks have been identified and grouped in the following manner. The tasks gathered under Feasibility Tests have already been described in Section 9, p.173 of this report.

A brief outline of additional interrelated tasks is included herein.

9.3.1 Program Outline. -

Program Definition

Feasibility Tests - These tasks are considered necessary for immediate implementation in order to establish the primary system concept for future development efforts.

Sensor Static Feasibility Tests
Display System Simulation and Evaluation

System Definition - Once the basic system concept and sensor feasibility has been established, a detailed system configuration must be defined in order to scope the actual development program from a cost and schedule viewpoint.

Detailed Technology Analysis
Flight Test System Configuration Definition
Detailed Flight Test Planning
System Specification

Program Scope and Cost - These tasks should provide detailed and accurate estimates of the costs and schedules associated with an actual hardware system acquisition and test program.

Vendor Proposal Evaluation
Cost and Schedule Preparation

System Acquisition - The following tasks represent the necessary sequential elements contained in the creation of a hazard warning and avoidance system suitable for flight test evaluation.

Flight Test Instrumentation Design and Procurement
Test Aircraft Procurement and Modification
Hardware Procurement and Detail Design
Fabrication Assembly and Bench Check-Out of Hardware
Installation and Check-Out in Test Aircraft
Flight Proving of the System

System Evaluation - The system once built and checked out, should be subjected to extensive and carefully planned flight test evaluation under a varied and representative set of operational conditions.

Flight Test Evaluation of Alternative Configurations
Flight Test Data Reduction and Analysis

Figure II-34, Program Flow Diagram, illustrates an overall view of the logical relationship between all of the previously identified tasks.

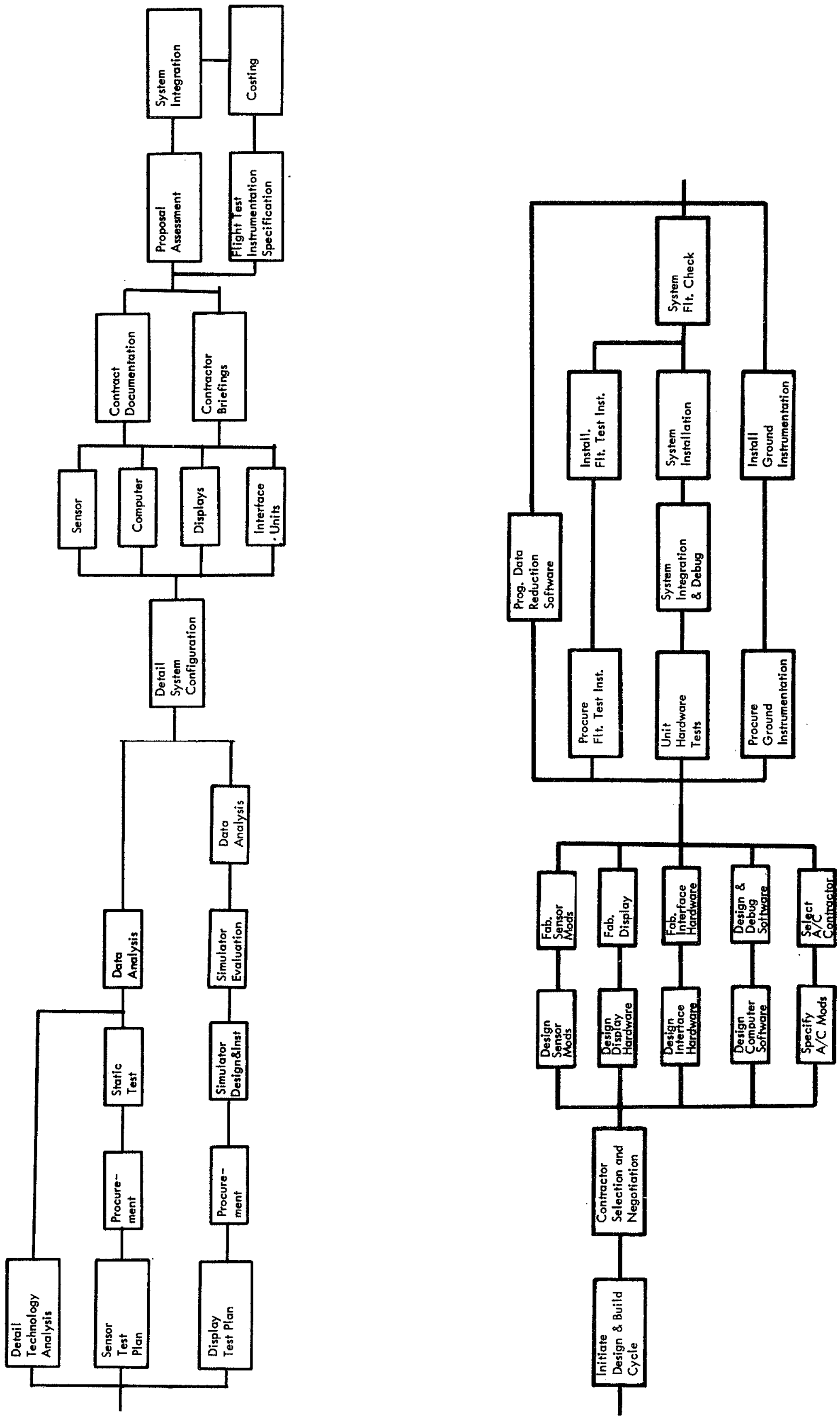


Figure II-34. Program Flow Diagram

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Appendix A

AN ANALYTICAL TREATMENT OF DELAYS & DELAY COSTS

In airline operations poor visibility results in delays, diversions, and cancellations. Each of these disruptions of normal operation carries with it an economic penalty. The purpose of this Appendix is to present the method by which visibility data for an airport can be used to generate information regarding delays, diversions and the cost associated with them.

The derivation begins with the development of equations for the delays and diversions due solely to bad weather. These equations are then extended to include the compounding of delay due to traffic accumulation during the bad weather. The entire derivation is structured to utilize visibility data in the form which is presented in Table VI of each of the Climatological Summaries (Ref. A-1). These tables list the number of occurrences during a ten-year period of visibilities at or below the listed levels. The tables further subdivide the data into time intervals of bad weather durations.

The derivation of the equations is shown below.

T_i	Time values between which visibility data is provided.
X_i	Visibility data; the number of occurrences in ten years of visibility below a specified level with a duration between T_{i-1} and T_i. These values come from Table VI in the Summaries.
W	The actual duration of a bad weather sample.
W_i	The average duration of bad weather between T_{i-1} and T_i.
L	The maximum aircraft loiter (or delay) capability.
M	The number of minutes in ten years.
i	Index of the tabular data ($0 \leq i \leq 11$)

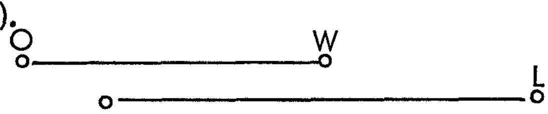
The first part of this derivation will be concerned only with values of L that are equal to some value of T_i. That is, 'n' can be found where $L = T_n$. T_i has these values;

$$T_i = 0, 15, 30, 45, 60, 90, 120, 180, 240, 360, 480, 600.$$

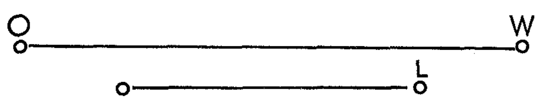
The equations will then be generalized for any value of L, where $0 < L < 600$.

The delays an aircraft may encounter can be classified in three categories. The aircraft is also assumed to divert if the delay exceeds its loiter capability (L).

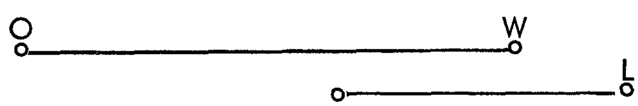
D_s - The average delay associated with relatively short periods of low visibility ($L > W$).



D_d - The average delay experienced before a diversion occurs (the aircraft has waited for L minutes but the weather did not clear) ($W > L$).



D_e - The average delay associated with periods of weather longer than the loiter time, but where the aircraft arrived late enough such that the weather cleared in time for landing ($W > L$).



In order to find the expressions for these delays, the following probabilities must be found.

$P(E)$	The probability of encountering the weather condition.
$P(D\|E)$	The probability of diversion given that weather of length $W > L$ is encountered.
$P(D)$	The probability of diversion.
$P(C\|E)$	The probability of being able to land given that weather of length $W > L$ is encountered.
$P(C)$	The probability of being able to land after weather of length $W > L$.

The derivation follows: Given values of T_i and X_i,

$$W_i = \frac{T_{i-1} + T_i}{2}$$

the average duration of weather in the interval between T_{i-1} and T_i.

<u>To find D_s:</u>

$L = T_n$, since $W < L$ the following holds for $i \leq n$.

$$P_i(E) = \frac{W_i X_i}{M},$$ the probability of encounter for the interval associated with i.

$$D_a = \frac{W_i}{2},$$ the average time spent in delays in that interval, given that it is encountered in a uniformly random manner.

$D_i = P_i(E) D_a$, the average delay associated with that interval.

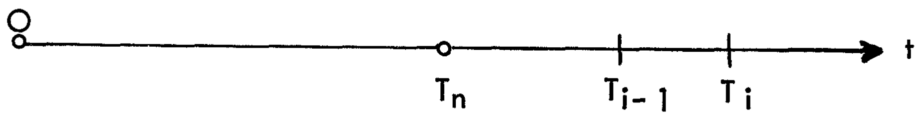
$$D_s = \sum_{i=1}^{n} P_i(E) D_a = \sum_{i=1}^{n} \frac{W_i^2 X_i}{2M}$$

To find D_d:

The following holds for $i > n$, since $W > L$

$$P_i(D|E) = \frac{W_i - L}{W_i}$$, the probability of diversion associated with that interval, given that it is encountered.

This expression for $P_i(D|E)$ is an approximation since it uses W_i, the average values for duration. The true value of $P_i(D|E)$ is derived below and shown to approximate the above.



The probability of diversion (given encounter) for a given weather duration 't' ($t = W > T_n = L$) is

$$P_t = \frac{t - T_n}{t}$$

The average probability over the interval is the integral of P_t divided by the length of the interval.

$$P_i(D|E) = \frac{1}{T_i - T_{i-1}} \int_{T_{i-1}}^{T_i} P_t \, dt = \frac{1}{T_i - T_{i-1}} \int_{T_{i-1}}^{T_i} \frac{t - T_n}{t} \, dt$$

$$P_i(D|E) = \frac{(T_i - T_{i-1}) - T_n \ln(T_i/T_{i-1})}{(T_i - T_{i-1})}$$

The first approximation of $\ln(x)$ is

$$\ln(x) \cong \frac{2(x-1)}{x+1}$$

so $$\ln(T_i/T_{i-1}) \cong \frac{2(T_i - T_{i-1})}{T_i + T_{i-1}}$$

$$\text{so } P_i(D|E) = 1 - \frac{2T_n}{T_i + T_{i-1}}$$

$$P_i(D|E) = \frac{\left(\frac{T_i + T_{i-1}}{2}\right) - T_n}{\left(\frac{T_i + T_{i-1}}{2}\right)}$$

$$\text{but } W_i = \frac{T_i + T_{i-1}}{2}, \quad L = T_n$$

$$\text{so } P_i(D|E) = \frac{W_i - L}{W_i}$$

The approximation is judged good enough since the error at the largest value of T_i/T_{i-1} (= 30/15 = 2) is four percent.

Continuing, to find D_d:

$$P_i(D) = P_i(D|E)\ P_i(E), \text{ for } i > n$$

$$= \frac{W_i - L}{W_i} \cdot \frac{W_i X_i}{M} = \frac{(W_i - L)X_i}{M}$$

$$P(D) = \sum_{n+1}^{11} \frac{(W_i - L)X_i}{M}$$ the probability of diversion.

It is assumed that the aircraft has been delaying L minutes before diverting, so the average delay experienced before diversion is

$$D_d = L\ P(D) = \frac{L}{M} \sum_{n+1}^{11} (W_i - L)\ X_i$$

To find D_e:

The following holds for $i > n$, since $W > L$.

$$P_i(C|E) = \frac{L}{W_i},$$ the probability of landing associated with that interval, given that weather lasting longer than L is encountered.

Again, this approximation, which uses the average weather duration, is supported by the reasoning used before.

$$P_i(C) = P_i(C|E)\ P_i(E)$$

$$= \frac{L}{W_i}\ \frac{W_i X_i}{M} = \frac{L}{M}\ X_i$$

Assuming a uniform distribution of arrival in the period W-L to W, the average delay is $\frac{L}{2}$ minutes.

$$\text{so} \quad D_i = \frac{L^2}{2M}\ X_i$$

$$\text{and} \quad D_e = \frac{L^2}{2M} \sum_{n+1}^{11} X_i$$

To find the total average delay per landing, D_T, the three components would be added.

$$D_T = \sum_{i=1}^{n} \frac{W_i^2 X_i}{2M} + \frac{L}{M} \sum_{n+1}^{11} (W_i - L)\ X_i + \frac{L^2}{2M} \sum_{n+1}^{11} X_i$$

And the probability of diversion is:

$$P(D) = \sum_{n+1}^{11} \frac{(W_i - L)\ X_i}{M}$$

<u>General Derivation</u>

This part of the derivation is concerned with finding the delays corresponding to arbitrary values of L ($0 < L < 600$) which may not correspond to the discrete values of T_i listed earlier.

A value of n may be found such that

$$T_n \leq L < T_{n+1}$$

$$D_s = \sum_{i=1}^{n} \frac{W_i^2 X_i}{2M} + F_1$$

$$D_d = F_2 + \frac{L}{M} \sum_{n+2}^{11} (W_i - L)\ X_i$$

$$D_e = F_3 + \frac{L^2}{2M} \sum_{n+2}^{11} X_i$$

and $$P(D) = P_1 + \sum_{n+2}^{11} \frac{(W_i - L)\, X_i}{M}$$

F_1, F_2, F_3, and P_1 are all functions of

L, X_{n+1}, T_n, and T_{n+1}

(The quantities with the subscript 'L' correspond to the interval between T_n and L.)

$$D_s = \sum_{i=1}^{n} P_i\,(E)\; D_a + P_L\,(E)\; D_L$$

$$P_L(E) = \frac{W_L\; X_L}{M}$$

$$D_L = \frac{W_L}{2}$$

W_L is the average duration of weather between T_n and L

$$W_L = \frac{T_n + L}{2}$$

X_L is the number of occurrences of weather in the interval between T_n and L

$$X_L = y\, X_{n+1} \quad , \quad y = \frac{L - T_n}{T_{n+1} - T_n} \quad ,$$ if we

assume that the occurrences X_{n+1} occur uniformly over the interval.

$$\text{So, } F_1 = P_L\,(E)\; D_L = \frac{(T_n + L)^2}{8M}\; X_{n+1}\; \frac{(L - T_n)}{T_{n+1} - T_n}$$

$$\text{and } D_s = \sum_{i=1}^{n} \frac{W_i^{\,2}\, X_i}{2M} + \frac{(T_n + L)^2}{8M}\; X_{n+1}\; \frac{(L-T_n)}{T_{n+1}-T_n} \qquad (1)$$

Let us also define $W_L{}^1$ and $X_L{}^1$, which correspond to the interval between L and T_{n+1}.

$$W_L{}^1 = \frac{L + T_{n+1}}{2}$$

$$X_L{}^1 = X_{n+1} - X_L = X_{n+1}\,(1-y) = X_{n+1}\frac{(T_{n+1} - L)}{T_{n+1} - T_n}$$

Using these values,

$$D_e = \frac{L^2}{2M}\left[X_{n+1}\left(\frac{T_{n+1} - L}{T_{n+1}-T_n}\right) + \sum_{n+2}^{11} X_i\right] \qquad (2)$$

$$D_d = L\,P(D) \qquad (3)$$

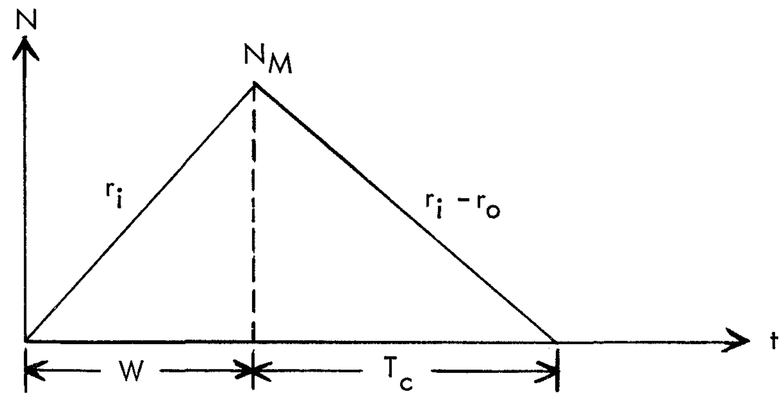
$$P\,(D) = \frac{\left(\frac{L+T_{n+1}}{2} - L\right) X_{n+1}\,\frac{T_{n+1} - L}{T_{n+1}-T_n}}{M} + \sum_{n+2}^{11} \frac{(W_i - L)X_i}{M} \qquad (4)$$

Equations 1, 2 and 3 can be used to find the average delays expected for an arbitrary value of L. (See Table A-1) These equations can be shown to be equivalent to the original equations (for $L = T_n$) by substituting values T_n and T_{n+1} for L. However, these equations take into account only the delay which occurs up to the time at which the weather clears. There is an additional delay component due to the fact that aircraft have accumulated during the bad weather and they must await their sequential turn before landing. A delay due to traffic accumulation can be experienced by those aircraft arriving in bad weather and those aircraft arriving after the weather clears but before the congestion is relieved.

Let us define these additional quantities:

r_i	average aircraft arrival rate in the terminal area.
r_o	maximum landing rate in IFR conditions.
N	the number of aircraft in the terminal area awaiting landing at any given time.
T_c	the length of time after the weather has cleared ($t > W$) required to land all waiting aircraft (reduce N to zero).

The graph below shows the relationship between N and time, t. Note that the slope of the first part of the curve is r_i, since no landings are occurring. The slope of the second part is $r_i - r_o$, since landings are occurring.



$N_M = r_i W$, the maximum value of N

$$T_c = \frac{N_M}{r_o - r_i} = \frac{r_i}{r_o - r_i} W$$

The two situations are as follows:

Situation One - an aircraft encounters the terminal area during the period of low visibility ($0 < t < W$)

Situation Two - an aircraft encounters the terminal area after the weather has cleared, but before all of the waiting aircraft have been landed ($W < t < W + T_c$)

Note that situation one is the situation actually used in the computation of delays and diversion probabilities earlier in this appendix. Situation two was not considered there, so a relationship between the two must be established.

In this appendix, the relationships were derived for computing the following quantities at a specific value of loiter capability, L.

D_s	the average delay due to short periods of low visibility ($L > W$).
D_e	the average delay due to arrival near the end of a long period of low visibility ($L < W$)
D_d	the average delay experienced before a diversion occurs ($L < W$).
P(D)	the probability of a diversion ($L < W$).

For Situation 1, we notice that the actual delay experienced, due to the poor weather alone, is further compounded by traffic congestion.

$$\text{Average delay due to weather} = \frac{W}{2}$$

$$\text{Average additional delay due to traffic} = 1/2 \ \frac{N_M}{r_o}$$

These values are based on the assumption that the aircraft may arrive at any time during W with equal probability. After the weather has cleared, the total time required to land all the aircraft that arrived during W and endured the delay is N_M/r_o. So the average delay

for situation one is:

$$D = \frac{W}{2} + \frac{1}{2}\frac{N_M}{r_o} = \frac{W}{2} + \frac{1}{2}\frac{r_i W}{r_o}$$

$$= \frac{W}{2}\ \frac{(r_o + r_i)}{r_o}$$

However the delay computations are made at the loiter capability, L, as if there were no additional delay due to traffic. Thus, to work with the weather statistics, it is necessary to suitably shorten the loiter capability of the aircraft to account for the additional delay due to traffic congestion. To accomplish this, we introduce a coefficient of delay propagation, CDP, defined as $CDP = \frac{r_o + r_i}{r_o}$ and a modified value of loiter

capability $L' = \frac{L}{CDP}$.

The modified loiter capability, L' is used to find the values of D_s, De, D_d and P (D). If situation two were not to be considered, then we could establish our final values for delay and probability as:

$$D_{s_1}' = D_s \ CDP \quad (5)$$

$$De_1 = De \ CDP \quad (6)$$

$$D_d{}' = D_d \ CDP \quad (7)$$

$$P(D)' = P(D) \quad (8)$$

However situation two exists and must be considered. The result will be different multipliers for D_s and D_e. The values of D_d' and $P(D)'$ will not change since it is assumed that the probability of diversion of an aircraft that arrived after the weather cleared is very small. This results from the fact that there would be a number of aircraft that arrived during the poor weather like the one that just arrived, and these others would divert before the last one leaving fewer aircraft ahead to delay the landing. Further, once the weather has cleared, it should be possible to accurately anticipate further delays and to avoid sending an aircraft to an airport where the probability of landing is extremely low.

As discussed earlier, the average delay per landing is the average delay given the encounter multiplied by the probability of the encounter.

$$D_1 = AD_1 \cdot P(E)$$

Likewise for situation two,

$$D_2 = AD_2 \cdot P(E_c)$$

where P(Ec) is the probability of encountering the terminal area during the period T_c. From these the delay multiplier, DM, is defined as:

$$DM = \frac{D_1 + D_2}{D_1} \; CDP$$

Let us evaluate D_1 and D_2.

$$D_1 = AD_1 \; P(E) = \frac{W}{2} \; \frac{(r_o + r_i)}{r_o} \; P(E)$$

$$D_2 = AD_2 \; P(E_c)$$

$$AD_2 = 1/2 \; \frac{N_M}{r_o}$$, since the average number of waiting aircraft during T_c is one-half N_M.

$$P(E_c) = \frac{T_c}{W} \; P(E),$$ that is, P(E) times the ratio of the periods of time that the probabilities refer to.

$$\frac{T_c}{W} = \frac{N_M}{r_o - r_i} \cdot \frac{1}{W} = \frac{r_i}{r_o - r_i}$$

so $$D_2 = \frac{W}{2} \; \frac{r_i}{r_o} \; \frac{r_i}{r_o - r_i} \; P(E)$$

So the total delay is $D_1 + D_2$

$$D = D_1 + D_2 = \frac{W}{2r_o} P(E) \left(r_o + r_i + \frac{r_i^2}{r_o - r_i} \right)$$

$$D = \frac{W}{2} \frac{r_o}{r_o - r_i} P(E)$$

So, the value of DM, which includes the effects of both situations, is

$$DM = \frac{D_1 + D_2}{D_1} \cdot CDP = \frac{\left(\frac{W}{2} P(E)\right) \frac{r_o}{r_o - r_i}}{\left(\frac{W}{2} P(E)\right) \frac{r_o + r_i}{r_o}} \quad \frac{r_o + r_i}{r_o}$$

$$DM = \frac{r_o}{r_o - r_i}$$

So the final values of delays and probability of diversion are:

$$D_s' = D_s \cdot DM \tag{9}$$

$$D_e' = D_e \cdot DM \tag{10}$$

$$D_d' = D_d \cdot CDP \tag{11}$$

$$P(D)' = P(D) \tag{12}$$

where D_s, D_e, D_d, and P(D) are determined at $L' = L/CDP$.

These formulations of delay times and diversion probabilities are used in the economic benefit analysis of Section 3.

Two tables follow which present different computations made on the basic visibility data which was taken from the Climatological Summaries. Table A-1 shows the results of computations of mean delay per landing and diversion probability for three values of loiter capability at thirty-one airports. The results reflect only the effect of the visibility statistics, which are shown on the table for each airport, and not the effects of delay propagation or operating procedures or costs. The second table, A-2, shows the results of a complete solution of the poor visibility cost problem, as developed in this appendix. The effects of delay propagation, operating procedures (route structures), and operating costs are included in these computations for eight airports in the years 1967 and 1970.

TABLE A-1. MEAN DELAYS AND DIVERSION PROBABILITIES RESULTING SOLELY FROM THE VISIBILITY STATISTICS (4 pages)

AIRPORT	VISIBILITY (miles)	NUMBER OF OCCURANCES IN TEN YEARS FOR THESE DELAY TIMES IN MINUTES 0-15-	30-	45-	60-	90-	120-	180-	240-	360-	480-	600	MEAN DELAY PER LANDING.- FOR MAXIMUM DELAY OF (minutes) 30.00	60.00	120.00	PROBABILITY OF DIVERSION AFTER DELAY OF 30.00	60.00	120.00
ANCHORAGE AL	1/2	175	148	116	63	110	65	84	38	37	12	8	0.326205	0.559067	0.858327	0.0090848	0.0066307	0.0037189
ANCHORAGE AL	3/8	142	135	108	61	102	61	77	36	33	11	7	0.299736	0.512866	0.785175	0.0083348	0.0060546	0.0033710
ANCHORAGE AL	1/4	108	112	96	57	91	54	65	35	28	9	6	0.262598	0.448692	0.685195	0.0072967	0.0052732	0.0029204
ANCHORAGE AL	3/16	77	77	54	38	51	43	34	26	15	4	2	0.153416	0.259828	0.389320	0.0042151	0.0029774	0.0015400
ANCHORAGE AL	1/8	68	74	52	31	42	39	32	21	8	4	1	0.124861	0.209109	0.307521	0.0033753	0.0023300	0.0011237
ANCHORAGE AL	1/16	23	17	19	8	19	9	2	5	1	0	1	0.027935	0.044934	0.062815	0.0007173	0.0004449	0.0002110
ANCHORAGE AL	0	6	3	2	0	0	1	0	0	1	0	0	0.002572	0.004379	0.006968	0.0000684	0.0000542	0.0000342
ATLANTA,GA.	1/2	108	72	58	52	71	46	47	34	34	20	20	0.305891	0.545042	0.893940	0.0089722	0.0071156	0.0047513
ATLANTA,GA.	3/8	99	66	55	47	64	44	46	32	33	19	19	0.290752	0.519266	0.852514	0.0085444	0.0067990	0.0045403
ATLANTA,GA.	1/4	74	54	57	38	70	36	45	28	32	21	16	0.275111	0.491482	0.806890	0.0080923	0.0064339	0.0043064
ATLANTA,GA.	3/16	34	29	32	20	24	20	31	19	20	9	10	0.156694	0.281801	0.466520	0.0046429	0.0037531	0.0024983
ATLANTA,GA.	1/8	28	26	24	18	18	16	28	19	15	8	9	0.135213	0.243754	0.404646	0.0040184	0.0032626	0.0021732
ATLANTA,GA.	1/16	9	5	4	6	6	4	6	2	2	4	1	0.028523	0.050992	0.083718	0.0008413	0.0006674	0.0004449
ATLANTA,GA.	0	1	1	4	0	1	1	3	0	2	1	0	0.009294	0.016673	0.027496	0.0002738	0.0002225	0.0001426
BALTIMORE	1/2	65	80	62	35	52	42	71	36	31	26	39	0.380952	0.693457	1.172880	0.0114348	0.0095026	0.0066792
BALTIMORE	3/8	60	70	57	32	49	40	67	33	30	25	37	0.360765	0.657442	1.113144	0.0108473	0.0090263	0.0063541
BALTIMORE	1/4	44	47	46	26	46	40	53	26	28	23	33	0.317435	0.579798	0.983418	0.0095825	0.0079854	0.0056525
BALTIMORE	3/16	18	25	27	21	29	36	30	10	27	18	24	0.229225	0.420575	0.717996	0.0069644	0.0058436	0.0042094
BALTIMORE	1/8	18	27	23	18	24	26	30	12	27	12	22	0.203697	0.374005	0.639277	0.0061901	0.0052076	0.0037417
BALTIMORE	1/16	3	9	8	11	10	14	10	10	15	7	10	0.103760	0.191259	0.328323	0.0031728	0.0026808	0.0019393
BALTIMORE	0	1	3	7	11	4	9	5	3	4	3	3	0.038993	0.069847	0.115471	0.0011550	0.0009212	0.0006274
BIRMINGHAM,	1/2	45	21	7	15	17	16	11	4	11	2	1	0.057805	0.100402	0.155865	0.0016456	0.0012178	0.0007016
BIRMINGHAM,	3/8	44	19	6	13	17	15	10	4	10	2	1	0.054238	0.094338	0.146528	0.0015472	0.0011465	0.0006616
BIRMINGHAM,	1/4	41	16	6	14	16	13	10	4	10	2	1	0.052923	0.092215	0.143999	0.0015144	0.0011265	0.0006616
BIRMINGHAM,	3/16	12	7	8	3	10	9	5	3	6	2	1	0.034667	0.061291	0.097803	0.0010082	0.0007786	0.0004791
BIRMINGHAM,	1/8	12	7	8	3	10	9	5	3	6	2	1	0.034667	0.061291	0.097803	0.0010082	0.0007786	0.0004791
BIRMINGHAM,	1/16	7	4	5	0	8	7	4	1	6	0	1	0.024143	0.042822	0.067954	0.0007059	0.0005447	0.0003251
BIRMINGHAM,	0	4	5	1	1	6	3	3	2	2	0	1	0.014978	0.026496	0.041918	0.0004363	0.0003337	0.0001996
BOSTON	1/2	94	105	59	58	80	49	69	37	32	14	10	0.286656	0.501091	0.790811	0.0082064	0.0062144	0.0037189
BOSTON	3/8	88	99	57	55	75	47	66	34	28	12	9	0.262935	0.458135	0.718958	0.0074977	0.0056354	0.0033196
BOSTON	1/4	63	83	45	50	61	43	57	38	22	12	7	0.234354	0.409485	0.643914	0.0067120	0.0050650	0.0029717
BOSTON	3/16	36	35	29	22	40	22	30	12	12	8	2	0.115712	0.200772	0.311954	0.0032897	0.0024355	0.0014031
BOSTON	1/8	39	31	29	22	39	22	27	13	12	7	2	0.111685	0.193580	0.300292	0.0031728	0.0023414	0.0013461
BOSTON	1/16	13	15	8	9	21	7	9	6	8	0	1	0.044126	0.076088	0.116556	0.0012477	0.0009012	0.0005076
BOSTON	0	1	3	3	1	3	1	5	0	0	0	0	0.006139	0.010053	0.013732	0.0001626	0.0001027	0.0000285
BUFFALO	1/2	125	84	73	44	62	48	39	25	24	12	9	0.220873	0.383288	0.603642	0.0062471	0.0047057	0.0028747
BUFFALO	3/8	118	79	68	40	61	45	36	24	23	12	9	0.212167	0.368973	0.582911	0.0060176	0.0045517	0.0028063
BUFFALO	1/4	91	66	52	40	47	34	31	20	20	9	8	0.175805	0.306003	0.485011	0.0049937	0.0037845	0.0023557
BUFFALO	3/16	34	30	23	27	29	27	19	11	11	4	7	0.109086	0.190762	0.301987	0.0031314	0.0023671	0.0014602
BUFFALO	1/8	29	29	20	23	24	22	22	7	10	4	5	0.093739	0.163570	0.257641	0.0026822	0.0020192	0.0012149
BUFFALO	1/16	8	17	10	5	8	12	4	5	5	1	1	0.034186	0.059292	0.092231	0.0009654	0.0007244	0.0004164
BUFFALO	0	2	6	0	1	3	0	2	2	0	0	0	0.005305	0.008946	0.013117	0.0001440	0.0000998	0.0000456
BURBANK	1/2	40	50	41	37	34	32	41	20	26	4	8	0.173137	0.304244	0.484984	0.0049909	0.0038330	0.0023329
BURBANK	3/8	40	49	38	34	32	29	40	19	24	3	8	0.161881	0.284528	0.453847	0.0046658	0.0035877	0.0021846
BURBANK	1/4	33	45	27	27	35	19	37	15	21	4	6	0.139833	0.246086	0.392518	0.0040383	0.0031029	0.0018937
BURBANK	3/16	31	37	28	22	21	21	28	19	9	2	6	0.108124	0.189072	0.298629	0.0030943	0.0023557	0.0013860
BURBANK	1/8	32	30	22	20	17	18	27	13	6	2	5	0.088370	0.154047	0.241722	0.0025211	0.0019022	0.0010951
BURBANK	1/16	22	20	13	8	9	8	16	10	2	2	3	0.051944	0.091328	0.145421	0.0014930	0.0011550	0.0006845
BURBANK	0	8	8	7	7	5	4	10	2	3	1	0	0.023700	0.040672	0.062083	0.0006645	0.0004820	0.0002510
CHICAGO, OH	1/2	62	55	38	29	32	33	40	26	25	8	11	0.193730	0.345055	0.561537	0.0056682	0.0044918	0.0028633
CHICAGO, OH	3/8	59	51	36	26	30	30	40	24	24	7	11	0.184238	0.328563	0.535528	0.0053987	0.0042893	0.0027379
CHICAGO, OH	1/4	41	42	25	19	25	34	37	19	22	7	10	0.167025	0.299233	0.488038	0.0049281	0.0039328	0.0024869
CHICAGO, OH	3/16	20	15	13	17	18	20	29	7	11	5	9	0.109059	0.195933	0.320975	0.0032398	0.0025838	0.0016655
CHICAGO, OH	1/8	19	11	10	17	19	17	24	7	10	7	7	0.100434	0.180618	0.296549	0.0029902	0.0023842	0.0015572
CHICAGO, OH	1/16	10	7	4	9	12	10	8	8	5	4	4	0.056474	0.101846	0.168025	0.0016869	0.0013518	0.0009012
CHICAGO, OH	0	3	3	4	4	7	5	8	4	5	2	2	0.035838	0.064714	0.106551	0.0010723	0.0008613	0.0005590
CINCINNATI	1/2	52	46	38	45	52	32	37	19	26	19	16	0.234910	0.420800	0.695355	0.0069373	0.0055441	0.0037874
CINCINNATI	3/8	50	46	35	43	49	29	35	18	25	18	15	0.221937	0.397619	0.657501	0.0065537	0.0052418	0.0035877
CINCINNATI	1/4	41	40	33	40	46	23	32	19	24	17	15	0.211461	0.379973	0.631791	0.0062671	0.0050451	0.0034965
CINCINNATI	3/16	23	22	20	20	29	13	23	14	15	13	7	0.133283	0.240102	0.398940	0.0039642	0.0031999	0.0021846
CINCINNATI	1/8	23	22	20	20	27	12	23	14	15	13	7	0.132085	0.238220	0.396822	0.0039328	0.0031856	0.0021846
CINCINNATI	1/16	10	8	5	11	11	7	10	7	9	5	3	0.061441	0.111107	0.184901	0.0018395	0.0014887	0.0010096
CINCINNATI	0	6	4	5	4	8	5	4	5	6	2	2	0.036544	0.065938	0.109017	0.0010909	0.0008784	0.0005875

AIRPORT	VISIBILITY	0-15	15-30	30-45	45-60	60-90	90-120	120-180	180-240	240-360	360-480	480-600	MEAN DELAY 30.00	MEAN DELAY 60.00	MEAN DELAY 120.00	PROB. DIV. 30.00	PROB. DIV. 60.00	PROB. DIV. 120.00
		NUMBER OF OCCURANCES IN TEN YEARS FOR THESE DELAY TIMES IN MINUTES											MEAN DELAY PER LANDING - FOR MAXIMUM DELAY OF			PROBABILITY OF DIVERSION AFTER DELAY OF		
CLEVELAND	1/2	160	65	42	19	36	21	28	22	24	11	7	0.167955	0.298115	0.487049	0.0048668	0.0038758	0.0025439
CLEVELAND	3/8	150	60	37	17	32	18	26	21	22	10	6	0.152475	0.270790	0.442633	0.0044205	0.0035250	0.0023101
CLEVELAND	1/4	91	45	27	17	23	16	20	21	18	10	6	0.134925	0.241551	0.399127	0.0039585	0.0031970	0.0021389
CLEVELAND	3/16	28	21	16	11	14	6	14	17	13	7	3	0.089413	0.161212	0.268416	0.0026537	0.0021618	0.0014545
CLEVELAND	1/8	26	17	17	10	13	5	15	16	12	6	3	0.083991	0.151298	0.251444	0.0024912	0.0020249	0.0013518
CLEVELAND	1/16	7	11	4	4	11	1	18	7	3	1	3	0.044030	0.078809	0.127492	0.0013005	0.0010267	0.0006217
CLEVELAND	0	4	9	3	5	1	1	3	3	1	1	0	0.012347	0.021331	0.033865	0.0003451	0.0002624	0.0001597
COLUMBUS, O	1/2	88	54	48	22	29	28	37	31	19	12	12	0.195745	0.350124	0.576189	0.0057438	0.0046230	0.0030345
COLUMBUS, O	3/8	84	51	45	21	28	27	35	29	18	11	11	0.183430	0.327735	0.538185	0.0053759	0.0043150	0.0028177
COLUMBUS, O	1/4	70	44	30	19	28	25	32	27	19	8	11	0.169800	0.304602	0.500978	0.0050094	0.0040298	0.0026295
COLUMBUS, O	3/16	30	17	23	11	17	19	26	17	15	8	9	0.130599	0.236573	0.393914	0.0039071	0.0031942	0.0021275
COLUMBUS, O	1/8	31	17	19	12	18	17	26	16	16	6	9	0.125513	0.227236	0.377711	0.0037546	0.0030601	0.0020306
COLUMBUS, O	1/16	17	13	11	12	10	16	14	12	8	4	7	0.083665	0.151122	0.250583	0.0024969	0.0020249	0.0013461
COLUMBUS, O	0	17	14	8	7	6	9	10	8	8	1	5	0.056848	0.102744	0.170998	0.0016926	0.0013832	0.0009240
DALLAS, TEX	1/2	23	15	11	15	16	18	15	6	4	6	2	0.064757	0.113364	0.178088	0.0018652	0.0014031	0.0008271
DALLAS, TEX	3/8	22	14	10	15	9	17	14	5	3	5	2	0.055848	0.097776	0.153945	0.0016071	0.0012149	0.0007130
DALLAS, TEX	1/4	21	15	11	13	10	16	13	5	3	5	2	0.054650	0.095718	0.151031	0.0015714	0.0011921	0.0007073
DALLAS, TEX	3/16	12	9	9	3	13	7	2	4	5	2	1	0.032068	0.056217	0.089328	0.0009212	0.0007016	0.0004449
DALLAS, TEX	1/8	11	7	10	3	10	6	2	3	5	2	1	0.029443	0.051800	0.083285	0.0008484	0.0006559	0.0004278
DALLAS, TEX	1/16	3	2	5	2	4	3	0	3	3	1	0	0.014614	0.025774	0.041496	0.0004235	0.0003280	0.0002110
DALLAS, TEX	0	1	1	1	4	1	1	0	3	2	0	0	0.008481	0.014924	0.024036	0.0002467	0.0001882	0.0001198
DAYTON,OHIO	1/2	53	58	39	42	51	31	34	23	32	14	25	0.261416	0.472065	0.791581	0.0077815	0.0063484	0.0044775
DAYTON,OHIO	3/8	51	52	36	40	46	30	32	22	29	13	24	0.245246	0.443120	0.743513	0.0073066	0.0059662	0.0042094
DAYTON,OHIO	1/4	45	39	29	36	36	28	33	22	24	13	24	0.231027	0.419602	0.708103	0.0069316	0.0057096	0.0040440
DAYTON,OHIO	3/16	18	19	21	22	18	16	24	17	22	8	18	0.168319	0.308350	0.526737	0.0051035	0.0042779	0.0030744
DAYTON,OHIO	1/8	15	20	21	20	17	17	21	19	21	7	18	0.164073	0.300671	0.513753	0.0049752	0.0041752	0.0030002
DAYTON,OHIO	1/16	7	7	12	10	14	16	14	16	13	10	6	0.107835	0.196933	0.331387	0.0032655	0.0026979	0.0018480
DAYTON,OHIO	0	4	5	7	8	10	11	8	10	12	7	2	0.070890	0.129064	0.215926	0.0021404	0.0017539	0.0011864
DENVER, COLO	1/2	46	39	26	30	28	16	23	12	5	1	0	0.071168	0.117498	0.169089	0.0018994	0.0012491	0.0005647
DENVER, COLO	3/8	43	34	23	27	27	15	21	11	4	1	0	0.064751	0.106814	0.153058	0.0017283	0.0011294	0.0005019
DENVER, COLO	1/4	32	21	25	20	25	15	16	9	4	1	0	0.056067	0.092584	0.132625	0.0015015	0.0009811	0.0004392
DENVER, COLO	3/16	14	13	10	12	9	5	11	3	3	0	0	0.026881	0.044538	0.064516	0.0007215	0.0004791	0.0002167
DENVER, COLO	1/8	11	11	10	10	10	5	10	4	2	0	0	0.025400	0.042020	0.060308	0.0006816	0.0004478	0.0001939
DENVER, COLO	1/16	2	6	6	5	1	3	6	3	0	0	0	0.011978	0.019865	0.028678	0.0003208	0.0002167	0.0000856
DENVER, COLO	0	4	1	0	0	1	2	3	2	0	0	0	0.005973	0.010508	0.015705	0.0001740	0.0001283	0.0000513
DETROIT	1/2	60	58	34	36	46	37	38	41	42	24	19	0.305388	0.555249	0.933992	0.0091718	0.0075605	0.0052418
DETROIT	3/8	56	55	31	32	45	36	38	40	38	22	19	0.290891	0.528993	0.889042	0.0087397	0.0072011	0.0049738
DETROIT	1/4	50	42	23	26	41	37	34	39	34	22	16	0.267389	0.487193	0.818259	0.0080610	0.0066450	0.0045574
DETROIT	3/16	16	22	21	17	27	27	36	28	20	19	11	0.198783	0.362273	0.606926	0.0060005	0.0049395	0.0033311
DETROIT	1/8	14	24	18	17	28	27	35	25	19	18	11	0.190783	0.347413	0.581135	0.0057538	0.0047256	0.0031828
DETROIT	1/16	5	17	16	8	9	14	24	9	13	7	6	0.098637	0.179105	0.299035	0.0029574	0.0024327	0.0016142
DETROIT	0	2	9	6	4	7	8	13	4	7	2	2	0.045019	0.080836	0.131465	0.0013347	0.0010638	0.0006559
HARTFORD,CON	1/2	66	95	66	36	58	45	83	38	53	17	23	0.364524	0.655795	1.083562	0.0107917	0.0087355	0.0057438
HARTFORD,CON	3/8	59	78	58	34	54	42	79	36	50	16	22	0.343819	0.619636	1.025180	0.0102099	0.0082763	0.0054472
HARTFORD,CON	1/4	46	57	41	38	45	35	75	33	45	15	17	0.302912	0.546148	0.901897	0.0090164	0.0072838	0.0047456
HARTFORD,CON	3/16	25	26	28	23	34	34	56	23	28	11	9	0.205569	0.369128	0.600905	0.0061046	0.0048540	0.0030173
HARTFORD,CON	1/8	23	23	25	25	37	28	49	21	28	10	9	0.193478	0.347365	0.566756	0.0057466	0.0045659	0.0028862
HARTFORD,CON	1/16	8	13	11	18	19	21	24	15	8	6	6	0.103209	0.184473	0.298436	0.0030530	0.0023956	0.0014887
HARTFORD,CON	0	5	9	4	11	11	11	10	7	6	5	2	0.055516	0.099359	0.161603	0.0016441	0.0012948	0.0008271
HOUSTON	1/2	103	99	71	49	72	52	72	51	53	37	30	0.449874	0.814778	1.365684	0.0134297	0.0110256	0.0076032
HOUSTON	3/8	97	97	70	48	70	52	69	48	50	36	28	0.429896	0.777635	1.301120	0.0128137	0.0104951	0.0072154
HOUSTON	1/4	82	92	66	42	65	50	63	39	53	35	25	0.403993	0.731573	1.226161	0.0120551	0.0098990	0.0068332
HOUSTON	3/16	44	50	38	29	42	32	38	38	43	18	15	0.272448	0.494102	0.826964	0.0081579	0.0066906	0.0045631
HOUSTON	1/8	38	45	38	28	33	28	33	31	39	16	13	0.238081	0.431452	0.722969	0.0071184	0.0058436	0.0040041
HOUSTON	1/16	21	14	21	15	18	17	16	15	10	6	1	0.083691	0.147325	0.234145	0.0024241	0.0018566	0.0011123
HOUSTON	0	4	9	7	3	3	5	4	4	1	0	0	0.014743	0.024764	0.036400	0.0003993	0.0002795	0.0001255
INDIANAPOLI	1/2	61	46	36	34	55	28	41	21	23	13	12	0.205911	0.366193	0.595210	0.0060290	0.0047313	0.0030801
INDIANAPOLI	3/8	62	45	34	32	51	26	39	21	21	13	11	0.195002	0.346878	0.564131	0.0057096	0.0044861	0.0029204
INDIANAPOLI	1/4	54	43	27	23	45	25	39	17	23	8	11	0.176725	0.315211	0.512636	0.0051905	0.0040954	0.0026352
INDIANAPOLI	3/16	23	14	14	18	24	15	22	10	14	3	10	0.110054	0.197836	0.326152	0.0032712	0.0026152	0.0017454
INDIANAPOLI	1/8	22	16	13	16	24	13	22	10	15	3	9	0.107193	0.192821	0.318013	0.0031870	0.0025525	0.0016997
INDIANAPOLI	1/16	6	6	9	11	12	8	10	5	8	2	2	0.048918	0.086542	0.138989	0.0014288	0.0011008	0.0006902
INDIANAPOLI	0	2	5	2	0	4	1	3	4	2	0	1	0.015395	0.027726	0.045458	0.0004563	0.0003679	0.0002339

AIRPORT	VISIBILITY	NUMBER OF OCCURANCES IN TEN YEARS FOR THESE DELAY TIMES IN MINUTES 0-15-	30-	45-	60-	90-	120-	180-	240-	360-	480-	600	MEAN DELAY PER LANDING - FOR MAXIMUM DELAY OF 30.00	60.00	120.00	PROBABILITY OF DIVERSION AFTER DELAY OF 30.00	60.00	120.00
LOS ANGELES	1/2	73	84	48	47	74	52	74	31	53	35	32	0.426960	0.775731	1.303409	0.0128123	0.0105407	0.0073180
LOS ANGELES	3/8	69	76	46	44	69	51	71	30	52	34	31	0.413078	0.751342	1.264004	0.0124144	0.0102327	0.0071127
LOS ANGELES	1/4	58	56	47	35	59	48	51	25	52	33	26	0.367054	0.669212	1.131117	0.0110626	0.0091689	0.0064568
LOS ANGELES	3/16	33	39	44	25	52	38	36	30	45	29	22	0.317462	0.580194	0.984241	0.0095982	0.0079911	0.0056696
LOS ANGELES	1/8	41	36	35	21	39	40	33	26	46	22	19	0.281640	0.515042	0.872310	0.0085216	0.0070984	0.0049795
LOS ANGELES	1/16	25	29	19	13	46	22	19	26	36	15	11	0.203446	0.370925	0.623920	0.0061402	0.0050593	0.0035193
LOS ANGELES	0	13	14	7	8	20	11	18	15	21	5	3	0.101060	0.183276	0.303206	0.0030359	0.0024612	0.0016028
LOUISVILLE K	1/2	36	20	18	15	16	13	20	15	20	6	5	0.112252	0.202392	0.335627	0.0033382	0.0027065	0.0017967
LOUISVILLE K	3/8	33	18	18	14	15	10	20	14	18	5	4	0.100375	0.180457	0.298035	0.0029746	0.0023985	0.0015743
LOUISVILLE K	1/4	25	15	17	11	15	14	19	10	16	5	4	0.093001	0.167030	0.274427	0.0027550	0.0022102	0.0014317
LOUISVILLE K	3/16	8	10	11	8	9	9	10	12	9	2	3	0.060628	0.108813	0.178500	0.0017953	0.0014374	0.0009240
LOUISVILLE K	1/8	7	8	8	8	10	8	10	9	7	2	3	0.053383	0.095648	0.156266	0.0015800	0.0012548	0.0008042
LOUISVILLE K	1/16	5	7	3	6	9	6	3	11	2	1	3	0.037282	0.066847	0.109263	0.0011051	0.0008755	0.0005704
LOUISVILLE K	0	1	0	0	1	2	0	2	1	1	0	1	0.008176	0.014983	0.025293	0.0002495	0.0002053	0.0001426
MIAMI,FLA.	1/2	40	25	19	10	12	10	13	11	10	3	0	0.060666	0.105824	0.167212	0.0017240	0.0013176	0.0007757
MIAMI,FLA.	3/8	38	24	18	10	11	9	12	10	9	3	0	0.056115	0.097760	0.154485	0.0015914	0.0012149	0.0007187
MIAMI,FLA.	1/4	35	23	17	9	13	7	13	9	9	3	0	0.055024	0.095932	0.151630	0.0015629	0.0011921	0.0007073
MIAMI,FLA.	3/16	11	12	5	3	16	7	9	6	3	2	0	0.034089	0.059072	0.089852	0.0009697	0.0007044	0.0003708
MIAMI,FLA.	1/8	13	10	5	4	15	6	9	6	3	2	0	0.033362	0.057880	0.088445	0.0009511	0.0006930	0.0003708
MIAMI,FLA.	1/16	3	6	1	5	5	4	5	2	1	0	0	0.012967	0.021769	0.031202	0.0003565	0.0002367	0.0000970
MIAMI,FLA.	0	2	3	1	0	2	2	1	0	0	0	0	0.002765	0.004396	0.005508	0.0000699	0.0000399	0.0000057
MILWAUKEE	1/2	91	79	53	52	45	52	64	40	47	21	21	0.345878	0.622706	1.031693	0.0102598	0.0083077	0.0055327
MILWAUKEE	3/8	86	76	51	51	44	51	61	38	45	20	21	0.334285	0.601814	0.997240	0.0099162	0.0080282	0.0053559
MILWAUKEE	1/4	63	68	41	48	46	50	55	34	46	18	20	0.316965	0.571291	0.946718	0.0094242	0.0076261	0.0050935
MILWAUKEE	3/16	18	32	14	25	34	40	29	26	31	7	13	0.197692	0.357081	0.588301	0.0059106	0.0047570	0.0031086
MILWAUKEE	1/8	15	31	14	25	35	40	29	26	31	6	13	0.195660	0.353081	0.580558	0.0058450	0.0046914	0.0030516
MILWAUKEE	1/16	5	12	10	9	14	7	11	9	7	7	4	0.070205	0.126989	0.212141	0.0020976	0.0017083	0.0011750
MILWAUKEE	0	2	7	3	2	4	4	3	2	5	1	1	0.022550	0.040629	0.067152	0.0006688	0.0005419	0.0003593
MINNEAPOLIS	1/2	60	40	35	20	28	16	24	7	13	3	8	0.107097	0.187388	0.300581	0.0030558	0.0023557	0.0015115
MINNEAPOLIS	3/8	53	37	33	17	27	15	22	7	12	2	7	0.096691	0.168699	0.269015	0.0027493	0.0021047	0.0013290
MINNEAPOLIS	1/4	33	30	17	5	24	15	19	6	10	2	7	0.083927	0.149111	0.241150	0.0024441	0.0019251	0.0012263
MINNEAPOLIS	3/16	20	12	6	10	11	15	10	5	5	3	2	0.049367	0.086927	0.137277	0.0014317	0.0010894	0.0006445
MINNEAPOLIS	1/8	15	11	8	9	10	14	9	4	3	3	1	0.040351	0.070088	0.108247	0.0011508	0.0008499	0.0004734
MINNEAPOLIS	1/16	2	3	4	3	6	5	5	1	1	1	1	0.017823	0.031079	0.048255	0.0005119	0.0003793	0.0002167
MINNEAPOLIS	0	1	0	0	2	2	0	2	0	0	0	0	0.002658	0.004294	0.005706	0.0000713	0.0000399	0.0000114
NASHVILLE	1/2	45	53	36	27	38	19	31	17	17	11	6	0.149737	0.263994	0.425891	0.0043221	0.0033624	0.0021561
NASHVILLE	3/8	42	48	34	24	34	18	28	17	17	11	5	0.141395	0.249850	0.404282	0.0040925	0.0031999	0.0020591
NASHVILLE	1/4	32	40	27	21	40	16	22	16	16	10	5	0.130775	0.231263	0.373802	0.0037959	0.0029546	0.0019165
NASHVILLE	3/16	10	12	22	7	19	13	20	12	10	6	4	0.088969	0.159068	0.259171	0.0026223	0.0020819	0.0013233
NASHVILLE	1/8	10	13	17	8	22	12	19	10	10	6	4	0.086109	0.153918	0.250470	0.0025396	0.0020078	0.0012834
NASHVILLE	1/16	3	8	8	7	10	7	14	4	10	3	2	0.054345	0.097589	0.159726	0.0016128	0.0012862	0.0008214
NASHVILLE	0	2	5	4	4	2	6	2	1	4	2	0	0.019160	0.034004	0.055051	0.0005590	0.0004392	0.0002795
NEW ORLEANS	1/2	83	62	55	30	73	36	52	30	44	17	24	0.316441	0.570489	0.948248	0.0094042	0.0076232	0.0052019
NEW ORLEANS	3/8	79	60	54	29	72	35	50	28	43	16	24	0.307425	0.554233	0.921511	0.0091361	0.0074065	0.0050650
NEW ORLEANS	1/4	72	60	54	29	71	34	44	29	40	17	23	0.297463	0.536057	0.891828	0.0088338	0.0071612	0.0049224
NEW ORLEANS	3/16	22	35	21	18	36	27	26	18	27	12	13	0.185110	0.335643	0.560639	0.0055456	0.0045317	0.0031029
NEW ORLEANS	1/8	21	33	21	19	35	24	26	19	26	12	11	0.176837	0.320061	0.533164	0.0052875	0.0043036	0.0029261
NEW ORLEANS	1/16	10	14	9	8	13	8	12	10	6	3	1	0.052190	0.092151	0.146673	0.0015158	0.0011664	0.0006959
NEW ORLEANS	0	3	5	5	1	6	4	2	1	1	0	0	0.009497	0.015561	0.021593	0.0002510	0.0001597	0.0000627
NEWARK N.J.	1/2	67	90	44	27	54	27	40	23	25	11	12	0.206820	0.366209	0.594327	0.0059876	0.0047142	0.0030630
NEWARK N.J.	3/8	61	81	39	26	49	24	36	21	23	9	11	0.186077	0.329221	0.533726	0.0053830	0.0042294	0.0027436
NEWARK N.J.	1/4	45	51	26	25	36	19	30	22	13	6	10	0.145962	0.258614	0.418757	0.0042422	0.0033225	0.0021332
NEWARK N.J.	3/16	19	14	23	13	18	16	19	13	7	4	9	0.097541	0.174607	0.286902	0.0028776	0.0022987	0.0015172
NEWARK N.J.	1/8	14	11	17	13	20	13	14	14	3	3	9	0.084194	0.150534	0.246893	0.0024840	0.0019707	0.0013119
NEWARK N.J.	1/16	5	11	7	3	13	6	7	7	2	0	9	0.053003	0.096563	0.163362	0.0015942	0.0013204	0.0009468
NEWARK N.J.	0	1	8	5	3	7	8	4	3	2	1	6	0.038121	0.069435	0.117326	0.0011465	0.0009497	0.0006788
NEW YORK,N.Y	1/2	132	118	88	73	60	61	80	50	42	17	22	0.375781	0.665442	1.079221	0.0109072	0.0085757	0.0054757
NEW YORK,N.Y	3/8	120	105	79	66	57	55	76	44	35	15	21	0.339584	0.600969	0.973145	0.0098520	0.0077287	0.0049167
NEW YORK,N.Y	1/4	82	67	55	34	52	41	70	26	26	13	19	0.268849	0.479370	0.780640	0.0078813	0.0062486	0.0039927
NEW YORK,N.Y	3/16	44	50	28	23	42	31	34	15	17	10	12	0.170977	0.304505	0.495150	0.0050066	0.0039499	0.0025610
NEW YORK,N.Y	1/8	43	27	23	19	29	26	16	15	14	8	9	0.129010	0.230493	0.377460	0.0037959	0.0030145	0.0020021
NEW YORK,N.Y	1/16	21	20	7	7	11	9	10	8	5	5	3	0.057115	0.102407	0.168372	0.0016826	0.0013518	0.0008898
NEW YORK,N.Y	0	3	6	0	6	5	5	5	3	3	0	1	0.020924	0.036785	0.057703	0.0006075	0.0004563	0.0002624

AIRPORT	VISIBILITY	NUMBER OF OCCURANCES IN TEN YEARS FOR THESE DELAY TIMES IN MINUTES 0-15	15-30	30-45	45-60	60-90	90-120	120-180	180-240	240-360	360-480	480-600	MEAN DELAY PER LANDING - FOR MAXIMUM DELAY OF 30.00	60.00	120.00	PROBABILITY OF DIVERSION AFTER DELAY OF 30.00	60.00	120.00
OAKLAND CALI	1/2	35	26	25	32	28	17	26	21	21	13	25	0.212210	0.388764	0.666763	0.0064325	0.0053987	0.0039642
OAKLAND CALI	3/8	32	25	25	29	26	16	25	21	19	13	24	0.203291	0.372684	0.639839	0.0061659	0.0051848	0.0038102
OAKLAND CALI	1/4	26	27	25	25	23	17	27	20	16	12	24	0.195227	0.358011	0.614343	0.0059206	0.0049852	0.0036448
OAKLAND CALI	3/16	12	22	20	17	21	17	22	17	14	10	20	0.164838	0.302570	0.518475	0.0050066	0.0042151	0.0030630
OAKLAND CALI	1/8	9	20	15	12	22	19	23	13	15	10	18	0.156341	0.287303	0.490952	0.0047584	0.0040013	0.0028747
OAKLAND CALI	1/16	10	6	14	16	19	16	16	9	14	8	17	0.134753	0.247850	0.425532	0.0041125	0.0034594	0.0025382
OAKLAND CALI	0	7	9	7	10	17	15	12	7	14	6	14	0.112594	0.207654	0.356696	0.0034466	0.0029090	0.0021275
PHILADELPHI	1/2	74	83	42	37	48	33	40	21	36	17	19	0.259909	0.467509	0.778790	0.0076817	0.0062429	0.0043064
PHILADELPHI	3/8	66	76	40	34	46	30	38	20	35	17	19	0.252128	0.454611	0.760138	0.0074749	0.0061031	0.0042437
PHILADELPHI	1/4	46	47	27	23	38	23	32	19	32	15	15	0.213066	0.386716	0.649999	0.0063798	0.0052504	0.0036562
PHILADELPHI	3/16	23	27	23	12	14	25	18	12	22	13	10	0.147512	0.269277	0.456114	0.0044447	0.0037104	0.0026010
PHILADELPHI	1/8	22	25	16	12	13	17	19	12	23	10	10	0.137529	0.251984	0.429046	0.0041638	0.0034965	0.0024698
PHILADELPHI	1/16	9	15	6	9	11	12	12	11	7	7	2	0.068403	0.123198	0.202403	0.0020349	0.0016342	0.0010552
PHILADELPHI	0	3	3	3	4	2	7	7	2	5	1	1	0.026726	0.047982	0.077777	0.0007943	0.0006303	0.0003822
PITTSBURGH	1/2	111	56	43	31	47	30	34	35	34	12	13	0.233952	0.419110	0.690436	0.0068931	0.0055299	0.0036790
PITTSBURGH	3/8	101	55	39	28	45	27	34	34	31	11	13	0.222172	0.398352	0.656737	0.0065523	0.0052647	0.0035022
PITTSBURGH	1/4	57	48	32	19	40	20	30	34	25	11	11	0.194649	0.350338	0.579890	0.0057680	0.0046658	0.0031143
PITTSBURGH	3/16	44	19	21	10	21	13	31	25	16	8	8	0.139967	0.253668	0.421575	0.0041909	0.0034223	0.0022473
PITTSBURGH	1/8	37	19	21	8	21	12	30	21	13	9	6	0.125214	0.226242	0.374107	0.0037346	0.0030316	0.0019678
PITTSBURGH	1/16	15	14	14	4	16	9	20	14	5	9	3	0.082376	0.148609	0.244797	0.0024527	0.0019821	0.0012777
PITTSBURGH	0	10	12	11	5	16	5	15	8	6	6	2	0.061206	0.109674	0.179425	0.0018081	0.0014402	0.0009297
PORTLAND, O	1/2	90	108	107	66	85	45	84	52	52	42	42	0.515561	0.932554	1.570001	0.0153562	0.0126283	0.0088980
PORTLAND, O	3/8	85	102	104	64	80	40	78	48	51	41	41	0.494155	0.894694	1.510197	0.0147331	0.0121492	0.0086242
PORTLAND, O	1/4	89	88	96	61	69	47	69	43	49	40	39	0.467622	0.847696	1.432483	0.0139673	0.0115389	0.0082021
PORTLAND, O	3/16	36	69	64	34	58	34	47	37	45	32	28	0.364567	0.664030	1.126641	0.0109543	0.0091148	0.0065024
PORTLAND, O	1 8	36	67	61	33	56	32	43	37	46	31	26	0.352407	0.642053	1.089862	0.0105921	0.0088182	0.0062971
PORTLAND, O	1/16	20	31	30	25	29	24	33	16	29	13	15	0.198339	0.360038	0.605183	0.0059477	0.0048911	0.0033938
PORTLAND, O	0	9	12	12	13	18	13	18	16	16	5	10	0.116941	0.213199	0.358797	0.0035321	0.0029118	0.0020078

TABLE A-2. US AIRPORT VISIBILITY DATA (16 pages)(.. A-17 thru A-32)

AIRPORT: ATLANTA,GA. YEAR: 1967

VISI-BILITY	NUMBER OF OCCURANCES IN TEN YEARS FOR THESE DELAY TIMES IN MINUTES 0-15	15-30	30-45	45-60	60-90	90-120	120-180	180-240	240-360	360-480	480-600
1/2	108	72	58	52	71	46	47	34	34	20	20
3/8	99	66	55	47	64	44	46	32	33	19	19
1/4	74	54	57	38	70	36	45	28	32	21	16
3/16	34	29	32	20	24	20	31	19	20	9	10
1/8	28	26	24	18	18	16	28	19	15	9	9
1/16	9	5	4	6	6	4	6	2	2	4	1
0	1	1	4	0	1	1	3	0	2	1	0

AVERAGE ARRIVAL RATE = 31.1, MAXIMUM IFR LANDING RATE = 72.0
COEFFICIENT OF DELAY PROPAGATION = 1.43, DELAY MULTIPLIER = 1.76

VISI-BILITY	MEAN DELAY PER LANDING - FOR MAXIMUM TOTAL DELAY OF 30.00	60.00	120.00	PROBABILITY OF DIVERSION AFTER TOTAL DELAY OF 30.00	60.00	120.00
1/2	0.324058	0.606949	1.076097	0.0096294	0.0080394	0.0057173
3/8	0.307755	0.576995	1.024477	0.0091620	0.0076672	0.0054851
1/4	0.290941	0.546132	0.970516	0.0086825	0.0072491	0.0051467
3/16	0.165203	0.311214	0.555858	0.0049612	0.0041866	0.0030947
1/8	0.142403	0.268533	0.480768	0.0042850	0.0036394	0.0027088
1/16	0.030125	0.056597	0.100571	0.0009015	0.0007574	0.0005491
0	0.009809	0.018496	0.032865	0.0002944	0.0002419	0.0001839

ROUTE STRUCTURE 1: LONG RANGE, 600 LANDINGS/YEAR
COST OF DELAY = $14.50/MINUTE, DIVERSION = $1700.

VISIBILITY RANGE	PER FLIGHT COSTS DELAY		DIVERSION		TOTAL		TOTAL PER YEAR
1/2 - 3/8	0.34	+	0.80	=	1.14	=	685.93
3/8 - 1/4	0.19	+	1.16	=	1.36	=	814.69
1/4 - 3/16	2.44	+	7.06	=	9.50	=	5700.53
3/16 - 1/8	0.42	+	1.33	=	1.74	=	1046.88
1/8 - 1/16	1.74	+	7.46	=	9.20	=	5519.82
1/16 - 0	0.36	+	1.23	=	1.59	=	952.35
0 -	0.16	+	0.63	=	0.79	=	473.49
TOTAL	5.66	+	19.67	=	25.32	=	15193.69

ROUTE STRUCTURE 2: MEDIUM RANGE, 2400 LANDINGS/YEAR
COST OF DELAY = $10.20/MINUTE, DIVERSION = $1460., CANCELATION = $1300.

VISIBILITY RANGE	PER FLIGHT COSTS DELAY		DIVERSION		CANCEL		TOTAL		TOTAL PER YEAR
1/2 - 3/8	0.08	+	0.26	+	0.30	=	0.64	=	1537.00
3/8 - 1/4	0.06	+	0.27	+	0.44	=	0.77	=	1856.68
1/4 - 3/16	0.52	+	2.11	+	2.67	=	5.30	=	12725.24
3/16 - 1/8	0.10	+	0.37	+	0.50	=	0.98	=	2340.20
1/8 - 1/16	0.40	+	1.93	+	2.82	=	5.15	=	12358.59
1/16 - 0	0.07	+	0.35	+	0.46	=	0.89	=	2134.25
0 -	0.04	+	0.16	+	0.24	=	0.44	=	1059.38
TOTAL	1.27	+	5.47	+	7.43	=	14.17	=	34011.34

ROUTE STRUCTURE 3: SHORT RANGE, 3000 LANDINGS/YEAR
COST OF DELAY = $ 4.10/MIN, HOLD TAKE OFF = $ 0.41/MIN, CANCEL = $1150.

VISIBILITY RANGE	PER FLIGHT COSTS DELAY		HOLD		CANCEL		TOTAL		TOTAL PER YEAR
1/2 - 3/8	0.01	+	0.02	+	0.43	=	0.46	=	1381.38
3/8 - 1/4	0.01	+	0.01	+	0.48	=	0.51	=	1515.99
1/4 - 3/16	0.06	+	0.16	+	3.52	=	3.74	=	11219.12
3/16 - 1/8	0.01	+	0.03	+	0.63	=	0.67	=	2013.91
1/8 - 1/16	0.04	+	0.12	+	3.31	=	3.48	=	10441.16
1/16 - 0	0.01	+	0.02	+	0.59	=	0.62	=	1870.04
0 -	0.00	+	0.01	+	0.28	=	0.30	=	885.52
TOTAL	0.14	+	0.39	+	9.25	=	9.78	=	29327.11

AIRPORT: ATLANTA,GA. YEAR: 1970

VISI-BILITY	NUMBER OF OCCURANCES IN TEN YEARS FOR THESE DELAY TIMES IN MINUTES 0-15-	30-	45-	60-	90-	120-	180-	240-	360-	480-	600
1/2	108	72	58	52	71	46	47	34	34	20	20
3/8	99	66	55	47	64	44	46	32	33	19	19
1/4	74	54	57	38	70	36	45	28	32	21	16
3/16	34	29	32	20	24	20	31	19	20	9	10
1/8	28	26	24	18	18	16	28	19	15	8	9
1/16	9	5	4	6	6	4	6	2	2	4	1
0	1	1	4	0	1	1	3	0	2	1	0

AVERAGE ARRIVAL RATE = 43.5, MAXIMUM IFR LANDING RATE = 72.0
COEFFICIENT OF DELAY PROPAGATION = 1.60, DELAY MULTIPLIER = 2.53

VISI-BILITY	MEAN DELAY PER LANDING - FOR MAXIMUM TOTAL DELAY OF 30.00	60.00	120.00	PROBABILITY OF DIVERSION AFTER TOTAL DELAY OF 30.00	60.00	120.00
1/2	0.336081	0.652013	1.227924	0.0097928	0.0082670	0.0059397
3/8	0.318983	0.619328	1.166105	0.0093156	0.0078802	0.0057059
1/4	0.301250	0.586640	1.109222	0.0088292	0.0074449	0.0053314
3/16	0.170734	0.333170	0.624448	0.0050404	0.0042901	0.0032401
1/8	0.147098	0.285685	0.537934	0.0043513	0.0037309	0.0028405
1/16	0.031164	0.060522	0.114344	0.0009165	0.0007805	0.0005623
0	0.010130	0.020090	0.036738	0.0002996	0.0002453	0.0001942

ROUTE STRUCTURE 1: LONG RANGE, 600 LANDINGS/YEAR
COST OF DELAY = $14.50/MINUTE, DIVERSION = $1700.

VISIBILITY RANGE	PER FLIGHT COSTS DELAY		DIVERSION		TOTAL		TOTAL PER YEAR
1/2 - 3/8	0.49	+	0.80	=	1.29	=	776.41
3/8 - 1/4	0.17	+	1.29	=	1.46	=	876.75
1/4 - 3/16	3.39	+	7.19	=	10.58	=	6350.67
3/16 - 1/8	0.56	+	1.37	=	1.93	=	1160.23
1/8 - 1/16	2.18	+	7.84	=	10.02	=	6009.00
1/16 - 0	0.48	+	1.27	=	1.75	=	1050.69
0 -	0.19	+	0.67	=	0.86	=	517.66
TOTAL	7.47	+	20.43	=	27.90	=	16741.40

ROUTE STRUCTURE 2: MEDIUM RANGE, 2400 LANDINGS/YEAR
COST OF DELAY = $10.20/MINUTE, DIVERSION = $1460., CANCELATION = $1300.

VISIBILITY RANGE	PER FLIGHT COSTS DELAY		DIVERSION		CANCEL		TOTAL		TOTAL PER YEAR
1/2 - 3/8	0.10	+	0.27	+	0.30	=	0.67	=	1616.47
3/8 - 1/4	0.07	+	0.28	+	0.49	=	0.83	=	2002.78
1/4 - 3/16	0.65	+	2.18	+	2.72	=	5.56	=	13332.20
3/16 - 1/8	0.13	+	0.38	+	0.52	=	1.03	=	2475.03
1/8 - 1/16	0.50	+	1.96	+	2.96	=	5.43	=	13025.20
1/16 - 0	0.08	+	0.37	+	0.48	=	0.93	=	2233.01
0 -	0.05	+	0.16	+	0.25	=	0.47	=	1126.55
TOTAL	1.59	+	5.61	+	7.72	=	14.92	=	35811.23

ROUTE STRUCTURE 3: SHORT RANGE, 3000 LANDINGS/YEAR
COST OF DELAY = $ 4.10/MIN, HOLD TAKE OFF = $ 0.41/MIN, CANCEL = $1150.

VISIBILITY RANGE	PER FLIGHT COSTS DELAY		HOLD		CANCEL		TOTAL		TOTAL PER YEAR
1/2 - 3/8	0.01	+	0.03	+	0.44	=	0.48	=	1454.23
3/8 - 1/4	0.01	+	0.01	+	0.50	=	0.53	=	1584.45
1/4 - 3/16	0.07	+	0.20	+	3.63	=	3.90	=	11696.91
3/16 - 1/8	0.01	+	0.04	+	0.64	=	0.70	=	2093.19
1/8 - 1/16	0.05	+	0.15	+	3.39	=	3.60	=	10801.09
1/16 - 0	0.01	+	0.02	+	0.62	=	0.65	=	1951.68
0 -	0.00	+	0.02	+	0.28	=	0.30	=	914.47
TOTAL	0.17	+	0.48	+	9.51	=	10.17	=	30496.03

AIRPORT: BALTIMORE YEAR: 1967

VISI-BILITY	NUMBER OF OCCURANCES IN TEN YEARS FOR THESE DELAY TIMES IN MINUTES 0-15-	30-	45-	60-	90-	120-	180-	240-	360-	480-	600
1/2	65	80	62	35	52	42	71	36	31	26	39
3/8	60	70	57	32	49	40	67	33	30	25	37
1/4	44	47	46	26	46	40	53	26	28	23	33
3/16	18	25	27	21	29	36	30	10	27	18	24
1/8	18	27	23	18	24	26	30	12	27	12	22
1/16	3	9	8	11	10	14	10	10	15	7	10
0	1	3	7	11	4	9	5	3	4	3	3

AVERAGE ARRIVAL RATE = 17.8, MAXIMUM IFR LANDING RATE = 41.6
COEFFICIENT OF DELAY PROPAGATION = 1.43, DELAY MULTIPLIER = 1.75

VISI-BILITY	MEAN DELAY PER LANDING - FOR MAXIMUM TOTAL DELAY OF 30.00	60.00	120.00	PROBABILITY OF DIVERSION AFTER TOTAL DELAY OF 30.00	60.00	120.00
1/2	0.399483	0.756123	1.367599	0.0121082	0.0104641	0.0080273
3/8	0.377979	0.716144	1.296797	0.0114797	0.0099371	0.0076309
1/4	0.331844	0.630312	1.144258	0.0101311	0.0087967	0.0067430
3/16	0.238870	0.455318	0.830303	0.0073439	0.0064265	0.0049826
1/8	0.212320	0.404580	0.738354	0.0065217	0.0057207	0.0044539
1/16	0.107807	0.206142	0.377623	0.0033351	0.0029466	0.0023108
0	0.041019	0.077348	0.137144	0.0012388	0.0010351	0.0007704

ROUTE STRUCTURE 1: LONG RANGE, 600 LANDINGS/YEAR
COST OF DELAY = $14.50/MINUTE, DIVERSION = $1700.

VISIBILITY RANGE	PER FLIGHT COSTS DELAY		DIVERSION		TOTAL		TOTAL PER YEAR
1/2 - 3/8	0.34	+	1.36	=	1.70	=	1020.25
3/8 - 1/4	0.67	+	3.05	=	3.72	=	2232.72
1/4 - 3/16	1.49	+	6.06	=	7.55	=	4527.09
3/16 - 1/8	0.41	+	1.82	=	2.23	=	1339.19
1/8 - 1/16	1.50	+	7.37	=	8.87	=	5324.36
1/16 - 0	0.81	+	5.30	=	6.11	=	3663.33
0 -	0.65	+	2.65	=	3.30	=	1978.98
TOTAL	5.86	+	27.61	=	33.48	=	20085.90

ROUTE STRUCTURE 2: MEDIUM RANGE, 2400 LANDINGS/YEAR
COST OF DELAY = $10.20/MINUTE, DIVERSION = $1460., CANCELATION = $1300.

VISIBILITY RANGE	PER FLIGHT COSTS DELAY		DIVERSION		CANCEL		TOTAL		TOTAL PER YEAR
1/2 - 3/8	0.09	+	0.35	+	0.52	=	0.95	=	2339.26
3/8 - 1/4	0.18	+	0.76	+	1.15	=	2.09	=	5014.38
1/4 - 3/16	0.33	+	1.59	+	2.29	=	4.22	=	10121.90
3/16 - 1/8	0.09	+	0.47	+	0.69	=	1.25	=	2991.81
1/8 - 1/16	0.33	+	1.85	+	2.79	=	4.96	=	11901.70
1/16 - 0	0.14	+	1.26	+	2.00	=	3.40	=	8169.00
0 -	0.16	+	0.70	+	1.00	=	1.85	=	4447.09
TOTAL	1.31	+	6.98	+	10.44	=	18.72	=	44935.13

ROUTE STRUCTURE 3: SHORT RANGE, 3000 LANDINGS/YEAR
COST OF DELAY = $ 4.10/MIN, HOLD TAKE OFF = $ 0.41/MIN, CANCEL = $1150.

VISIBILITY RANGE	PER FLIGHT COSTS DELAY		HOLD		CANCEL		TOTAL		TOTAL PER YEAR
1/2 - 3/8	0.01	+	0.02	+	0.61	=	0.64	=	1924.66
3/8 - 1/4	0.02	+	0.05	+	1.31	=	1.39	=	4156.13
1/4 - 3/16	0.04	+	0.10	+	2.73	=	2.87	=	8596.03
3/16 - 1/8	0.01	+	0.03	+	0.81	=	0.85	=	2542.43
1/8 - 1/16	0.04	+	0.10	+	3.19	=	3.33	=	9979.33
1/16 - 0	0.02	+	0.04	+	2.20	=	2.26	=	6774.91
0 -	0.02	+	0.05	+	1.19	=	1.26	=	3766.12
TOTAL	0.15	+	0.40	+	12.03	=	12.58	=	37739.61

AIRPORT: BALTIMORE YEAR: 1970

VISI-BILITY	NUMBER OF OCCURANCES IN TEN YEARS FOR THESE DELAY TIMES IN MINUTES 0-15-	30-	45-	60-	90-	120-	180-	240-	360-	480-	600
1/2	65	80	62	35	52	42	71	36	31	26	39
3/8	60	70	57	32	49	40	67	33	30	25	37
1/4	44	47	46	26	46	40	53	26	28	23	33
3/16	18	25	27	21	29	36	30	10	27	18	24
1/8	18	27	23	18	24	26	30	12	27	12	22
1/16	3	9	8	11	10	14	10	10	15	7	10
0	1	3	7	11	4	9	5	3	4	3	3

AVERAGE ARRIVAL RATE = 22.3, MAXIMUM IFR LANDING RATE = 41.6
COEFFICIENT OF DELAY PROPAGATION = 1.54, DELAY MULTIPLIER = 2.16

VISI-BILITY	MEAN DELAY PER LANDING - FOR MAXIMUM TOTAL DELAY OF 30.00	60.00	120.00	PROBABILITY OF DIVERSION AFTER TOTAL DELAY OF 30.00	60.00	120.00
1/2	0.406415	0.781872	1.449979	0.0122191	0.0106160	0.0082444
3/8	0.384386	0.740160	1.374373	0.0115838	0.0100812	0.0078368
1/4	0.337115	0.650685	1.212715	0.0102214	0.0089256	0.0069197
3/16	0.242341	0.468989	0.877340	0.0074063	0.0065210	0.0051131
1/8	0.215459	0.416602	0.779422	0.0065763	0.0058040	0.0045721
1/16	0.109249	0.211768	0.397565	0.0033619	0.0029910	0.0023739
0	0.041730	0.080362	0.146148	0.0012526	0.0010548	0.0007963

ROUTE STRUCTURE 1: LONG RANGE, 600 LANDINGS/YEAR
COST OF DELAY = $14.50/MINUTE, DIVERSION = $1700.

VISIBILITY RANGE	PER FLIGHT COSTS DELAY		DIVERSION		TOTAL		TOTAL PER YEAR
1/2 - 3/8	0.39	+	1.40	=	1.79	=	1073.51
3/8 - 1/4	0.75	+	3.15	=	3.90	=	2341.91
1/4 - 3/16	1.72	+	6.21	=	7.93	=	4760.50
3/16 - 1/8	0.48	+	1.86	=	2.34	=	1403.75
1/8 - 1/16	1.71	+	7.56	=	9.27	=	5564.39
1/16 - 0	0.90	+	5.43	=	6.33	=	3796.37
0 -	0.73	+	2.74	=	3.47	=	2083.71
TOTAL	6.68	+	28.36	=	35.04	=	21024.13

ROUTE STRUCTURE 2: MEDIUM RANGE, 2400 LANDINGS/YEAR
COST OF DELAY = $10.20/MINUTE, DIVERSION = $1460., CANCELATION = $1300.

VISIBILITY RANGE	PER FLIGHT COSTS DELAY		DIVERSION		CANCEL		TOTAL		TOTAL PER YEAR
1/2 - 3/8	0.10	+	0.36	+	0.53	=	0.99	=	2364.90
3/8 - 1/4	0.21	+	0.76	+	1.19	=	2.16	=	5186.86
1/4 - 3/16	0.38	+	1.61	+	2.35	=	4.34	=	10423.23
3/16 - 1/8	0.10	+	0.48	+	0.70	=	1.28	=	3070.14
1/8 - 1/16	0.37	+	1.87	+	2.86	=	5.09	=	12221.08
1/16 - 0	0.16	+	1.27	+	2.05	=	3.48	=	8341.76
0 -	0.17	+	0.71	+	1.04	=	1.92	=	4598.13
TOTAL	1.48	+	7.06	+	10.72	=	19.25	=	46206.10

ROUTE STRUCTURE 3: SHORT RANGE, 3000 LANDINGS/YEAR
COST OF DELAY = $ 4.10/MIN, HOLD TAKE OFF = $ 0.41/MIN, CANCEL = $1150.

VISIBILITY RANGE	PER FLIGHT COSTS DELAY		HOLD		CANCEL		TOTAL		TOTAL PER YEAR
1/2 - 3/8	0.01	+	0.03	+	0.62	=	0.66	=	1967.31
3/8 - 1/4	0.03	+	0.06	+	1.33	=	1.41	=	4242.08
1/4 - 3/16	0.04	+	0.12	+	2.77	=	2.92	=	8771.31
3/16 - 1/8	0.01	+	0.03	+	0.82	=	0.86	=	2593.09
1/8 - 1/16	0.04	+	0.11	+	3.23	=	3.39	=	10162.89
1/16 - 0	0.02	+	0.05	+	2.23	=	2.29	=	6873.73
0 -	0.02	+	0.06	+	1.21	=	1.29	=	3856.39
TOTAL	0.16	+	0.45	+	12.21	=	12.82	=	38466.79

AIRPORT: CHICAGO, OHARE YEAR: 1967

VISIBILITY	NUMBER OF OCCURANCES IN TEN YEARS FOR THESE DELAY TIMES IN MINUTES 0-15	15-30	30-45	45-60	60-90	90-120	120-180	180-240	240-360	360-480	480-600
1/2	62	55	38	29	32	33	40	26	25	8	11
3/8	59	51	36	26	30	30	40	24	24	7	11
1/4	41	42	25	19	25	34	37	19	22	7	10
3/16	20	15	13	17	18	20	29	7	11	5	9
1/8	19	11	10	17	19	17	24	7	10	7	7
1/16	10	7	4	9	12	10	8	8	5	4	4
0	3	3	4	4	7	5	8	4	5	2	2

AVERAGE ARRIVAL RATE = 55.1, MAXIMUM IFR LANDING RATE = 108.0
COEFFICIENT OF DELAY PROPAGATION = 1.51, DELAY MULTIPLIER = 2.04

VISIBILITY	MEAN DELAY PER LANDING - FOR MAXIMUM TOTAL DELAY OF 30.00	60.00	120.00	PROBABILITY OF DIVERSION AFTER TOTAL DELAY OF 30.00	60.00	120.00
1/2	0.208651	0.395467	0.714524	0.0061345	0.0051444	0.0037162
3/8	0.198258	0.376029	0.680192	0.0058380	0.0049048	0.0035549
1/4	0.179029	0.340270	0.619146	0.0053097	0.0045117	0.0032628
3/16	0.116223	0.221970	0.405579	0.0034884	0.0029751	0.0021454
1/8	0.106854	0.204286	0.374361	0.0032176	0.0027519	0.0019714
1/16	0.060006	0.114727	0.211321	0.0018102	0.0015605	0.0011150
0	0.038007	0.072883	0.134186	0.0011513	0.0009885	0.0007111

ROUTE STRUCTURE 1: LONG RANGE, 600 LANDINGS/YEAR
COST OF DELAY = $14.50/MINUTE, DIVERSION = $1700.

VISIBILITY RANGE	PER FLIGHT COSTS DELAY		DIVERSION		TOTAL		TOTAL PER YEAR
1/2 - 3/8	0.22	+	0.55	=	0.77	=	463.09
3/8 - 1/4	0.38	+	1.00	=	1.38	=	828.99
1/4 - 3/16	1.15	+	3.84	=	5.00	=	2997.79
3/16 - 1/8	0.15	+	0.60	=	0.75	=	449.12
1/8 - 1/16	0.87	+	2.95	=	3.82	=	2291.91
1/16 - 0	0.42	+	1.39	=	1.81	=	1083.05
0 -	0.71	+	2.45	=	3.15	=	1892.77
TOTAL	3.89	+	12.78	=	16.68	=	10006.70

ROUTE STRUCTURE 2: MEDIUM RANGE, 2400 LANDINGS/YEAR
COST OF DELAY = $10.20/MINUTE, DIVERSION = $1460., CANCELATION = $1300.

VISIBILITY RANGE	PER FLIGHT COSTS DELAY		DIVERSION		CANCEL		TOTAL		TOTAL PER YEAR
1/2 - 3/8	0.05	+	0.17	+	0.21	=	0.43	=	1023.10
3/8 - 1/4	0.12	+	0.26	+	0.38	=	0.77	=	1843.79
1/4 - 3/16	0.27	+	1.04	+	1.45	=	2.76	=	6619.72
3/16 - 1/8	0.04	+	0.15	+	0.23	=	0.42	=	1003.77
1/8 - 1/16	0.18	+	0.81	+	1.11	=	2.11	=	5053.97
1/16 - 0	0.08	+	0.39	+	0.53	=	0.99	=	2379.58
0 -	0.14	+	0.67	+	0.92	=	1.73	=	4160.12
TOTAL	0.89	+	3.49	+	4.83	=	9.20	=	22084.05

ROUTE STRUCTURE 3: SHORT RANGE, 3000 LANDINGS/YEAR
COST OF DELAY = $ 4.10/MIN, HOLD TAKE OFF = $ 0.41/MIN, CANCEL = $1150.

VISIBILITY RANGE	PER FLIGHT COSTS DELAY		HOLD		CANCEL		TOTAL		TOTAL PER YEAR
1/2 - 3/8	0.01	+	0.02	+	0.28	=	0.30	=	890.97
3/8 - 1/4	0.01	+	0.04	+	0.45	=	0.50	=	1510.72
1/4 - 3/16	0.03	+	0.08	+	1.77	=	1.88	=	5632.96
3/16 - 1/8	0.01	+	0.01	+	0.26	=	0.27	=	824.55
1/8 - 1/16	0.02	+	0.06	+	1.37	=	1.45	=	4340.63
1/16 - 0	0.01	+	0.02	+	0.66	=	0.69	=	2069.19
0 -	0.01	+	0.04	+	1.14	=	1.19	=	3583.24
TOTAL	0.10	+	0.27	+	5.92	=	6.28	=	18852.25

AIRPORT: CHICAGO, OHARE YEAR: 1970

VISI- BILITY	NUMBER OF OCCURANCES IN TEN YEARS FOR THESE DELAY TIMES IN MINUTES 0-15-	30-	45-	60-	90-	120-	180-	240-	360-	480-	600
1/2	62	55	38	29	32	33	40	26	25	8	11
3/8	59	51	36	26	30	30	40	24	24	7	11
1/4	41	42	25	19	25	34	37	19	22	7	10
3/16	20	15	13	17	18	20	29	7	11	5	9
1/8	19	11	10	17	19	17	24	7	10	7	7
1/16	10	7	4	9	12	10	8	8	5	4	4
0	3	3	4	4	7	5	8	4	5	2	2

AVERAGE ARRIVAL RATE = 70.2, MAXIMUM IFR LANDING RATE = 108.0
COEFFICIENT OF DELAY PROPAGATION = 1.65, DELAY MULTIPLIER = 2.86

VISI- BILITY	MEAN DELAY PER LANDING - FOR MAXIMUM TOTAL DELAY OF 30.00	60.00	120.00	PROBABILITY OF DIVERSION AFTER TOTAL DELAY OF 30.00	60.00	120.00
1/2	0.216598	0.424967	0.807980	0.0062120	0.0052506	0.0038581
3/8	0.205716	0.403820	0.768282	0.0059110	0.0050046	0.0036906
1/4	0.185370	0.363445	0.697101	0.0053730	0.0046065	0.0033960
3/16	0.119840	0.236122	0.456897	0.0035296	0.0030410	0.0022261
1/8	0.110059	0.216878	0.422798	0.0032554	0.0028146	0.0020392
1/16	0.061783	0.121409	0.238921	0.0018307	0.0015963	0.0011496
0	0.039073	0.077285	0.151331	0.0011644	0.0010096	0.0007355

ROUTE STRUCTURE 1: LONG RANGE, 600 LANDINGS/YEAR
COST OF DELAY = $14.50/MINUTE, DIVERSION = $1700.

VISIBILITY RANGE	PER FLIGHT COSTS DELAY		DIVERSION		TOTAL		TOTAL PER YEAR
1/2 - 3/8	0.28	+	0.58	=	0.86	=	516.29
3/8 - 1/4	0.52	+	1.01	=	1.53	=	919.78
1/4 - 3/16	1.45	+	4.02	=	5.47	=	3283.07
3/16 - 1/8	0.17	+	0.64	=	0.81	=	487.24
1/8 - 1/16	1.12	+	3.06	=	4.18	=	2507.15
1/16 - 0	0.55	+	1.42	=	1.97	=	1184.45
0 -	0.91	+	2.53	=	3.44	=	2066.74
TOTAL	5.00	+	13.27	=	18.27	=	10964.71

ROUTE STRUCTURE 2: MEDIUM RANGE, 2400 LANDINGS/YEAR
COST OF DELAY = $10.20/MINUTE, DIVERSION = $1460., CANCELATION = $1300.

VISIBILITY RANGE	PER FLIGHT COSTS DELAY		DIVERSION		CANCEL		TOTAL		TOTAL PER YEAR
1/2 - 3/8	0.07	+	0.17	+	0.22	=	0.45	=	1084.93
3/8 - 1/4	0.17	+	0.27	+	0.38	=	0.82	=	1966.21
1/4 - 3/16	0.34	+	1.05	+	1.52	=	2.91	=	6990.96
3/16 - 1/8	0.06	+	0.15	+	0.24	=	0.45	=	1076.45
1/8 - 1/16	0.23	+	0.82	+	1.16	=	2.21	=	5298.89
1/16 - 0	0.09	+	0.40	+	0.54	=	1.03	=	2470.01
0 -	0.17	+	0.68	+	0.96	=	1.81	=	4341.82
TOTAL	1.12	+	3.54	+	5.02	=	9.68	=	23229.27

ROUTE STRUCTURE 3: SHORT RANGE, 3000 LANDINGS/YEAR
COST OF DELAY = $ 4.10/MIN, HOLD TAKE OFF = $ 0.41/MIN, CANCEL = $1150.

VISIBILITY RANGE	PER FLIGHT COSTS DELAY		HOLD		CANCEL		TOTAL		TOTAL PER YEAR
1/2 - 3/8	0.01	+	0.02	+	0.28	=	0.31	=	929.29
3/8 - 1/4	0.02	+	0.05	+	0.46	=	0.53	=	1581.55
1/4 - 3/16	0.04	+	0.10	+	1.80	=	1.94	=	5821.81
3/16 - 1/8	0.01	+	0.02	+	0.26	=	0.28	=	852.42
1/8 - 1/16	0.02	+	0.07	+	1.40	=	1.50	=	4485.89
1/16 - 0	0.01	+	0.03	+	0.67	=	0.71	=	2136.95
0 -	0.02	+	0.05	+	1.16	=	1.23	=	3694.31
TOTAL	0.12	+	0.34	+	6.04	=	6.50	=	19502.21

AIRPORT: CLEVELAND YEAR: 1967

VISI-BILITY	NUMBER OF OCCURANCES IN TEN YEARS FOR THESE DELAY TIMES IN MINUTES 0-15-	30-	45-	60-	90-	120-	180-	240-	360-	480-	600
1/2	160	65	42	19	36	21	28	22	24	11	7
3/8	150	60	37	17	32	18	26	21	22	10	6
1/4	91	45	27	17	23	16	20	21	18	10	6
3/16	28	21	16	11	14	6	14	17	13	7	3
1/8	26	17	17	10	13	5	15	16	12	6	3
1/16	7	11	4	4	11	1	18	7	3	1	3
0	4	9	3	5	1	1	3	3	1	1	0

AVERAGE ARRIVAL RATE = 27.3, MAXIMUM IFR LANDING RATE = 56.8
COEFFICIENT OF DELAY PROPAGATION = 1.48, DELAY MULTIPLIER = 1.93

VISI-BILITY	MEAN DELAY PER LANDING - FOR MAXIMUM TOTAL DELAY OF 30.00	60.00	120.00	PROBABILITY OF DIVERSION AFTER TOTAL DELAY OF 30.00	60.00	120.00
1/2	0.181120	0.339187	0.606228	0.0052556	0.0043752	0.0031570
3/8	0.164419	0.307860	0.550554	0.0047704	0.0039794	0.0028758
1/4	0.144510	0.272165	0.490093	0.0042510	0.0035964	0.0026625
3/16	0.095045	0.180299	0.326879	0.0028407	0.0024244	0.0018180
1/8	0.089254	0.169470	0.306773	0.0026708	0.0022681	0.0017005
1/16	0.046902	0.088660	0.160788	0.0013968	0.0011896	0.0008132
0	0.013580	0.024944	0.043028	0.0003784	0.0003040	0.0002190

ROUTE STRUCTURE 1: LONG RANGE, 600 LANDINGS/YEAR
COST OF DELAY = $14.50/MINUTE, DIVERSION = $1700.

VISIBILITY RANGE	PER FLIGHT COSTS DELAY		DIVERSION		TOTAL		TOTAL PER YEAR
1/2 - 3/8	0.32	+	0.97	=	1.29	=	771.14
3/8 - 1/4	0.51	+	0.73	=	1.24	=	743.57
1/4 - 3/16	0.90	+	2.91	=	3.80	=	2281.40
3/16 - 1/8	0.09	+	0.40	=	0.49	=	294.75
1/8 - 1/16	0.57	+	3.05	=	3.63	=	2175.14
1/16 - 0	0.67	+	2.04	=	2.72	=	1630.61
0 -	0.24	+	0.75	=	1.00	=	597.68
TOTAL	3.30	+	10.86	=	14.16	=	8494.29

ROUTE STRUCTURE 2: MEDIUM RANGE, 2400 LANDINGS/YEAR
COST OF DELAY = $10.20/MINUTE, DIVERSION = $1460., CANCELATION = $1300.

VISIBILITY RANGE	PER FLIGHT COSTS DELAY		DIVERSION		CANCEL		TOTAL		TOTAL PER YEAR
1/2 - 3/8	0.08	+	0.27	+	0.37	=	0.71	=	1709.00
3/8 - 1/4	0.13	+	0.27	+	0.28	=	0.68	=	1635.39
1/4 - 3/16	0.22	+	0.79	+	1.10	=	2.11	=	5069.33
3/16 - 1/8	0.01	+	0.10	+	0.15	=	0.27	=	653.60
1/8 - 1/16	0.16	+	0.71	+	1.15	=	2.02	=	4854.98
1/16 - 0	0.11	+	0.61	+	0.77	=	1.49	=	3578.80
0 -	0.07	+	0.21	+	0.28	=	0.56	=	1341.91
TOTAL	0.78	+	2.97	+	4.10	=	7.85	=	18843.00

ROUTE STRUCTURE 3: SHORT RANGE, 3000 LANDINGS/YEAR
COST OF DELAY = $ 4.10/MIN, HOLD TAKE OFF = $ 0.41/MIN, CANCEL = $1150.

VISIBILITY RANGE	PER FLIGHT COSTS DELAY		HOLD		CANCEL		TOTAL		TOTAL PER YEAR
1/2 - 3/8	0.01	+	0.02	+	0.46	=	0.49	=	1462.02
3/8 - 1/4	0.02	+	0.04	+	0.44	=	0.49	=	1482.63
1/4 - 3/16	0.03	+	0.06	+	1.35	=	1.44	=	4317.17
3/16 - 1/8	0.00	+	0.00	+	0.18	=	0.19	=	557.48
1/8 - 1/16	0.02	+	0.05	+	1.24	=	1.31	=	3926.11
1/16 - 0	0.01	+	0.03	+	1.02	=	1.06	=	3190.53
0 -	0.01	+	0.02	+	0.35	=	0.38	=	1133.90
TOTAL	0.10	+	0.23	+	5.03	=	5.36	=	16069.88

AIRPORT: CLEVELAND YEAR: 1970

VISI-BILITY	NUMBER OF OCCURANCES IN TEN YEARS FOR THESE DELAY TIMES IN MINUTES 0-15-	30-	45-	60-	90-	120-	180-	240-	360-	480-	600
1/2	160	65	42	19	36	21	28	22	24	11	7
3/8	150	60	37	17	32	18	26	21	22	10	6
1/4	91	45	27	17	23	16	20	21	18	10	6
3/16	28	21	16	11	14	6	14	17	13	7	3
1/8	26	17	17	10	13	5	15	16	12	6	3
1/16	7	11	4	4	11	1	18	7	3	1	3
0	4	9	3	5	1	1	3	3	1	1	0

AVERAGE ARRIVAL RATE = 36.5, MAXIMUM IFR LANDING RATE = 56.8
COEFFICIENT OF DELAY PROPAGATION = 1.64, DELAY MULTIPLIER = 2.80

VISI-BILITY	MEAN DELAY PER LANDING - FOR MAXIMUM TOTAL DELAY OF 30.00	60.00	120.00	PROBABILITY OF DIVERSION AFTER TOTAL DELAY OF 30.00	60.00	120.00
1/2	0.189841	0.369362	0.698099	0.0053354	0.0044709	0.0032740
3/8	0.172359	0.335000	0.633354	0.0048422	0.0040667	0.0029837
1/4	0.150771	0.293941	0.557528	0.0043110	0.0036754	0.0027659
3/16	0.098581	0.193581	0.369470	0.0028791	0.0024768	0.0018879
1/8	0.092513	0.182311	0.346932	0.0027076	0.0023160	0.0017674
1/16	0.048695	0.094894	0.186238	0.0014165	0.0012231	0.0008466
0	0.014426	0.027547	0.049459	0.0003852	0.0003131	0.0002311

ROUTE STRUCTURE 1: LONG RANGE, 600 LANDINGS/YEAR
COST OF DELAY = $14.50/MINUTE, DIVERSION = $1700.

VISIBILITY RANGE	PER FLIGHT COSTS DELAY		DIVERSION		TOTAL		TOTAL PER YEAR
1/2 - 3/8	0.43	+	1.00	=	1.43	=	859.35
3/8 - 1/4	0.72	+	0.75	=	1.47	=	881.90
1/4 - 3/16	1.20	+	3.02	=	4.22	=	2531.63
3/16 - 1/8	0.12	+	0.41	=	0.53	=	319.01
1/8 - 1/16	0.73	+	3.17	=	3.90	=	2337.20
1/16 - 0	0.91	+	2.12	=	3.03	=	1817.78
0 -	0.32	+	0.80	=	1.11	=	666.03
TOTAL	4.43	+	11.26	=	15.69	=	9412.90

ROUTE STRUCTURE 2: MEDIUM RANGE, 2400 LANDINGS/YEAR
COST OF DELAY = $10.20/MINUTE, DIVERSION = $1460., CANCELATION = $1300.

VISIBILITY RANGE	PER FLIGHT COSTS DELAY		DIVERSION		CANCEL		TOTAL		TOTAL PER YEAR
1/2 - 3/8	0.10	+	0.27	+	0.38	=	0.75	=	1811.33
3/8 - 1/4	0.18	+	0.28	+	0.28	=	0.74	=	1783.07
1/4 - 3/16	0.29	+	0.81	+	1.14	=	2.24	=	5377.70
3/16 - 1/8	0.02	+	0.11	+	0.16	=	0.28	=	674.73
1/8 - 1/16	0.22	+	0.71	+	1.20	=	2.13	=	5110.25
1/16 - 0	0.13	+	0.63	+	0.80	=	1.56	=	3735.78
0 -	0.09	+	0.21	+	0.30	=	0.60	=	1441.85
TOTAL	1.03	+	3.02	+	4.26	=	8.31	=	19934.70

ROUTE STRUCTURE 3: SHORT RANGE, 3000 LANDINGS/YEAR
COST OF DELAY = $ 4.10/MIN, HOLD TAKE OFF = $ 0.41/MIN, CANCEL = $1150.

VISIBILITY RANGE	PER FLIGHT COSTS DELAY		HOLD		CANCEL		TOTAL		TOTAL PER YEAR
1/2 - 3/8	0.01	+	0.03	+	0.46	=	0.51	=	1522.02
3/8 - 1/4	0.02	+	0.05	+	0.45	=	0.52	=	1571.44
1/4 - 3/16	0.04	+	0.08	+	1.38	=	1.50	=	4493.59
3/16 - 1/8	0.00	+	0.00	+	0.18	=	0.19	=	575.15
1/8 - 1/16	0.02	+	0.07	+	1.26	=	1.35	=	4046.62
1/16 - 0	0.01	+	0.04	+	1.05	=	1.10	=	3300.70
0 -	0.01	+	0.03	+	0.36	=	0.40	=	1190.56
TOTAL	0.12	+	0.30	+	5.14	=	5.57	=	16700.07

AIRPORT: LOS ANGELES YEAR: 1967

VISI-BILITY	NUMBER OF OCCURANCES IN TEN YEARS FOR THESE DELAY TIMES IN MINUTES 0-15-	30-	45-	60-	90-	120-	180-	240-	360-	480-	600
1/2	73	84	48	47	74	52	74	31	53	35	32
3/8	69	76	46	44	69	51	71	30	52	34	31
1/4	58	56	47	35	59	48	51	25	52	33	26
3/16	33	39	44	25	52	38	36	30	45	29	22
1/8	41	36	35	21	39	40	33	26	46	22	19
1/16	25	29	19	13	46	22	19	26	36	15	11
0	13	14	7	8	20	11	18	15	21	5	3

AVERAGE ARRIVAL RATE = 41.3, MAXIMUM IFR LANDING RATE = 75.2
COEFFICIENT OF DELAY PROPAGATION = 1.55, DELAY MULTIPLIER = 2.22

VISI-BILITY	MEAN DELAY PER LANDING - FOR MAXIMUM TOTAL DELAY OF 30.00	60.00	120.00	PROBABILITY OF DIVERSION AFTER TOTAL DELAY OF 30.00	60.00	120.00
1/2	0.456526	0.878994	1.643760	0.0137141	0.0119576	0.0090227
3/8	0.441174	0.850164	1.590723	0.0132799	0.0115944	0.0087817
1/4	0.391087	0.755598	1.414592	0.0118229	0.0103265	0.0079117
3/16	0.337356	0.653463	1.225831	0.0102472	0.0089605	0.0069066
1/8	0.299243	0.579267	1.086012	0.0090897	0.0079717	0.0061656
1/16	0.216525	0.418156	0.789832	0.0065588	0.0057513	0.0042590
0	0.107817	0.207757	0.390613	0.0032543	0.0028399	0.0020571

ROUTE STRUCTURE 1: LONG RANGE, 600 LANDINGS/YEAR
COST OF DELAY = $14.50/MINUTE, DIVERSION = $1700.

VISIBILITY RANGE	PER FLIGHT COSTS DELAY		DIVERSION		TOTAL		TOTAL PER YEAR
1/2 - 3/8	0.35	+	0.83	=	1.18	=	707.25
3/8 - 1/4	1.04	+	2.99	=	4.03	=	2419.77
1/4 - 3/16	0.99	+	3.46	=	4.45	=	2667.37
3/16 - 1/8	0.74	+	2.55	=	3.29	=	1972.28
1/8 - 1/16	0.98	+	6.56	=	7.54	=	4521.43
1/16 - 0	1.96	+	7.57	=	9.53	=	5719.16
0 -	2.08	+	7.08	=	9.16	=	5496.60
TOTAL	8.14	+	31.04	=	39.17	=	23503.85

ROUTE STRUCTURE 2: MEDIUM RANGE, 2400 LANDINGS/YEAR
COST OF DELAY = $10.20/MINUTE, DIVERSION = $1460.. CANCELATION = $1300.

VISIBILITY RANGE	PER FLIGHT COSTS DELAY		DIVERSION		CANCEL		TOTAL		TOTAL PER YEAR
1/2 - 3/8	0.07	+	0.25	+	0.31	=	0.64	=	1526.92
3/8 - 1/4	0.19	+	0.87	+	1.13	=	2.19	=	5254.79
1/4 - 3/16	0.21	+	0.92	+	1.31	=	2.43	=	5840.46
3/16 - 1/8	0.15	+	0.66	+	0.96	=	1.78	=	4268.65
1/8 - 1/16	0.28	+	1.43	+	2.48	=	4.20	=	10070.14
1/16 - 0	0.36	+	1.95	+	2.86	=	5.18	=	12422.41
0 -	0.38	+	1.92	+	2.67	=	4.98	=	11947.49
TOTAL	1.65	+	8.01	+	11.73	=	21.39	=	51330.36

ROUTE STRUCTURE 3: SHORT RANGE, 3000 LANDINGS/YEAR
COST OF DELAY = $ 4.10/MIN, HOLD TAKE OFF = $ 0.41/MIN, CANCEL = $1159.

VISIBILITY RANGE	PER FLIGHT COSTS DELAY		HOLD		CANCEL		TOTAL		TOTAL PER YEAR
1/2 - 3/8	0.01	+	0.02	+	0.42	=	0.45	=	1342.23
3/8 - 1/4	0.03	+	0.05	+	1.46	=	1.54	=	4608.66
1/4 - 3/16	0.03	+	0.06	+	1.57	=	1.66	=	4968.64
3/16 - 1/8	0.01	+	0.05	+	1.14	=	1.20	=	3600.34
1/8 - 1/16	0.03	+	0.09	+	2.55	=	2.67	=	8014.81
1/16 - 0	0.04	+	0.11	+	3.35	=	3.50	=	10498.11
0 -	0.04	+	0.12	+	3.27	=	3.42	=	10272.59
TOTAL	0.18	+	0.50	+	13.75	=	14.44	=	43305.38

AIRPORT: LOS ANGELES YEAR: 1970

VISI- BILITY	NUMBER OF OCCURANCES IN TEN YEARS FOR THESE DELAY TIMES IN MINUTES										
	0–15–	30–	45–	60–	90–	120–	180–	240–	360–	480–	600
1/2	73	84	48	47	74	52	74	31	53	35	32
3/8	69	76	46	44	69	51	71	30	52	34	31
1/4	58	56	47	35	59	48	51	25	52	33	26
3/16	33	39	44	25	52	38	36	30	45	29	22
1/8	41	36	35	21	39	40	33	26	46	22	19
1/16	25	29	19	13	46	22	19	26	36	15	11
0	13	14	7	8	20	11	18	15	21	5	3

AVERAGE ARRIVAL RATE = 51.6, MAXIMUM IFR LANDING RATE = 75.2
COEFFICIENT OF DELAY PROPAGATION = 1.69, DELAY MULTIPLIER = 3.19

VISI- BILITY	MEAN DELAY PER LANDING – FOR MAXIMUM TOTAL DELAY OF			PROBABILITY OF DIVERSION AFTER TOTAL DELAY OF		
	30.00	60.00	120.00	30.00	60.00	120.00
1/2	0.472316	0.937271	1.860256	0.0138475	0.0121669	0.0092655
3/8	0.456106	0.905858	1.797113	0.0134079	0.0117954	0.0090209
1/4	0.403690	0.805107	1.593030	0.0119354	0.0104952	0.0081222
3/16	0.347620	0.695880	1.378436	0.0103432	0.0090998	0.0070837
1/8	0.308377	0.615962	1.216543	0.0091738	0.0080979	0.0063414
1/16	0.223342	0.444147	0.899893	0.0066207	0.0058524	0.0043583
0	0.111321	0.220779	0.445950	0.0032866	0.0028962	0.0021205

ROUTE STRUCTURE 1: LONG RANGE, 600 LANDINGS/YEAR
COST OF DELAY = $14.50/MINUTE, DIVERSION = $1700.

VISIBILITY RANGE	PER FLIGHT COSTS DELAY		DIVERSION		TOTAL		TOTAL PER YEAR
1/2 – 3/8	0.49	+	0.84	=	1.33	=	798.84
3/8 – 1/4	1.40	+	3.09	=	4.49	=	2692.23
1/4 – 3/16	1.30	+	3.57	=	4.88	=	2926.23
3/16 – 1/8	1.06	+	2.55	=	3.61	=	2165.55
1/8 – 1/16	1.14	+	6.82	=	7.96	=	4777.62
1/16 – 0	2.69	+	7.70	=	10.39	=	6231.86
0 –	2.78	+	7.29	=	10.07	=	6042.70
TOTAL	10.85	+	31.87	=	42.73	=	25635.07

ROUTE STRUCTURE 2: MEDIUM RANGE, 2400 LANDINGS/YEAR
COST OF DELAY = $10.20/MINUTE, DIVERSION = $1460., CANCELATION = $1300.

VISIBILITY RANGE	PER FLIGHT COSTS DELAY		DIVERSION		CANCEL		TOTAL		TOTAL PER YEAR
1/2 – 3/8	0.09	+	0.26	+	0.32	=	0.67	=	1604.05
3/8 – 1/4	0.23	+	0.89	+	1.17	=	2.29	=	5497.80
1/4 – 3/16	0.26	+	0.94	+	1.35	=	2.55	=	6116.22
3/16 – 1/8	0.20	+	0.67	+	0.96	=	1.84	=	4419.23
1/8 – 1/16	0.38	+	1.44	+	2.58	=	4.39	=	10541.90
1/16 – 0	0.47	+	1.98	+	2.91	=	5.36	=	12856.93
0 –	0.48	+	1.96	+	2.76	=	5.19	=	12460.03
TOTAL	2.11	+	8.13	+	12.05	=	22.29	=	53496.17

ROUTE STRUCTURE 3: SHORT RANGE, 3000 LANDINGS/YEAR
COST OF DELAY = $ 4.10/MIN, HOLD TAKE OFF = $ 0.41/MIN, CANCEL = $1150.

VISIBILITY RANGE	PER FLIGHT COSTS DELAY		HOLD		CANCEL		TOTAL		TOTAL PER YEAR
1/2 – 3/8	0.01	+	0.03	+	0.43	=	0.47	=	1396.59
3/8 – 1/4	0.03	+	0.06	+	1.50	=	1.59	=	4771.71
1/4 – 3/16	0.03	+	0.07	+	1.60	=	1.71	=	5134.90
3/16 – 1/8	0.02	+	0.07	+	1.15	=	1.24	=	3706.36
1/8 – 1/16	0.03	+	0.12	+	2.58	=	2.74	=	8214.48
1/16 – 0	0.05	+	0.14	+	3.40	=	3.59	=	10778.73
0 –	0.05	+	0.15	+	3.33	=	3.53	=	10584.36
TOTAL	0.23	+	0.64	+	13.99	=	14.86	=	44587.13

AIRPORT: MIAMI,FLA. YEAR: 1967

VISI-BILITY	NUMBER OF OCCURANCES IN TEN YEARS FOR THESE DELAY TIMES IN MINUTES										
	0-15-	30-	45-	60-	90-	120-	180-	240-	360-	480-	600
1/2	40	25	19	10	12	10	13	11	10	3	0
3/8	38	24	18	10	11	9	12	10	9	3	0
1/4	35	23	17	9	13	7	13	9	9	3	0
3/16	11	12	5	3	16	7	9	6	3	2	0
1/8	13	10	5	4	15	6	9	6	3	2	0
1/16	3	6	1	5	5	4	5	2	1	0	0
0	2	3	1	0	2	2	1	0	0	0	0

AVERAGE ARRIVAL RATE = 38.3, MAXIMUM IFR LANDING RATE = 64.8
COEFFICIENT OF DELAY PROPAGATION = 1.59, DELAY MULTIPLIER = 2.45

VISI-BILITY	MEAN DELAY PER LANDING - FOR MAXIMUM TOTAL DELAY OF			PROBABILITY OF DIVERSION AFTER TOTAL DELAY OF		
	30.00	60.00	120.00	30.00	60.00	120.00
1/2	0.068051	0.130421	0.236923	0.0019105	0.0015423	0.0010781
3/8	0.063052	0.120750	0.218824	0.0017651	0.0014213	0.0009955
1/4	0.061747	0.118283	0.215874	0.0017324	0.0013985	0.0009617
3/16	0.038103	0.072679	0.138669	0.0010777	0.0008810	0.0004896
1/8	0.037191	0.071115	0.135335	0.0010571	0.0008640	0.0004896
1/16	0.014803	0.027829	0.051459	0.0004052	0.0003200	0.0001591
0	0.003353	0.006141	0.011262	0.0000826	0.0000583	0.0000142

ROUTE STRUCTURE 1: LONG RANGE, 600 LANDINGS/YEAR
COST OF DELAY = $14.50/MINUTE, DIVERSION = $1700.

VISIBILITY RANGE	PER FLIGHT COSTS DELAY		DIVERSION		TOTAL		TOTAL PER YEAR
1/2 - 3/8	0.12	+	0.28	=	0.40	=	241.58
3/8 - 1/4	-0.02	+	0.12	=	0.10	=	60.25
1/4 - 3/16	0.30	+	1.62	=	1.92	=	1153.17
3/16 - 1/8	0.05	+	0.0	=	0.05	=	29.01
1/8 - 1/16	0.64	+	1.14	=	1.78	=	1066.84
1/16 - 0	0.33	+	0.50	=	0.83	=	497.58
0 -	0.14	+	0.05	=	0.19	=	112.44
TOTAL	1.56	+	3.71	=	5.27	=	3160.86

ROUTE STRUCTURE 2: MEDIUM RANGE, 2400 LANDINGS/YEAR
COST OF DELAY = $10.20/MINUTE, DIVERSION = $1460., CANCELATION = $1300.

VISIBILITY RANGE	PER FLIGHT COSTS DELAY		DIVERSION		CANCEL		TOTAL		TOTAL PER YEAR
1/2 - 3/8	0.02	+	0.08	+	0.11	=	0.21	=	515.88
3/8 - 1/4	0.01	+	0.01	+	0.04	=	0.07	=	159.89
1/4 - 3/16	0.15	+	0.33	+	0.61	=	1.09	=	2614.90
3/16 - 1/8	0.01	+	0.01	+	0.0	=	0.02	=	47.96
1/8 - 1/16	0.11	+	0.38	+	0.43	=	0.92	=	2211.70
1/16 - 0	0.06	+	0.19	+	0.19	=	0.44	=	1049.33
0 -	0.03	+	0.05	+	0.02	=	0.09	=	219.57
TOTAL	0.39	+	1.05	+	1.40	=	2.84	=	6819.21

ROUTE STRUCTURE 3: SHORT RANGE, 3000 LANDINGS/YEAR
COST OF DELAY = $ 4.10/MIN, HOLD TAKE OFF = $ 0.41/MIN, CANCEL = $1150.

VISIBILITY RANGE	PER FLIGHT COSTS DELAY		HOLD		CANCEL		TOTAL		TOTAL PER YEAR
1/2 - 3/8	0.00	+	0.01	+	0.14	=	0.15	=	448.12
3/8 - 1/4	0.00	+	0.00	+	0.03	=	0.03	=	92.59
1/4 - 3/16	0.02	+	0.04	+	0.60	=	0.66	=	1969.25
3/16 - 1/8	0.00	+	0.00	+	0.02	=	0.02	=	65.67
1/8 - 1/16	0.01	+	0.03	+	0.63	=	0.67	=	2011.60
1/16 - 0	0.01	+	0.02	+	0.30	=	0.33	=	978.73
0 -	0.00	+	0.01	+	0.07	=	0.08	=	234.55
TOTAL	0.04	+	0.12	+	1.77	=	1.93	=	5800.50

AIRPORT: MIAMI,FLA.   YEAR: 1970

VISI- BILITY	NUMBER OF OCCURANCES IN TEN YEARS FOR THESE DELAY TIMES IN MINUTES 0-15-	30-	45-	60-	90-	120-	180-	240-	360-	480-	600
1/2	40	25	19	10	12	10	13	11	10	3	0
3/8	38	24	18	10	11	9	12	10	9	3	0
1/4	35	23	17	9	13	7	13	9	9	3	0
3/16	11	12	5	3	16	7	9	6	3	2	0
1/8	13	10	5	4	15	6	9	6	3	2	0
1/16	3	6	1	5	5	4	5	2	1	0	0
0	2	3	1	0	2	2	1	0	0	0	0

AVERAGE ARRIVAL RATE = 46.0, MAXIMUM IFR LANDING RATE = 64.8
COEFFICIENT OF DELAY PROPAGATION = 1.71, DELAY MULTIPLIER = 3.45

VISI- BILITY	MEAN DELAY PER LANDING - FOR MAXIMUM TOTAL DELAY OF 30.00	60.00	120.00	PROBABILITY OF DIVERSION AFTER TOTAL DELAY OF 30.00	60.00	120.00
1/2	0.071732	0.144305	0.276409	0.0019324	0.0015672	0.0011130
3/8	0.066519	0.133779	0.255341	0.0017856	0.0014442	0.0010275
1/4	0.065099	0.130862	0.253370	0.0017523	0.0014214	0.0009896
3/16	0.040050	0.079458	0.169964	0.0010904	0.0009015	0.0005006
1/8	0.039027	0.077706	0.165264	0.0010695	0.0008839	0.0005006
1/16	0.015699	0.030678	0.063800	0.0004110	0.0003305	0.0001661
0	0.003662	0.007093	0.015047	0.0000841	0.0000603	0.0000152

ROUTE STRUCTURE 1: LONG RANGE, 600 LANDINGS/YEAR
COST OF DELAY = $14.50/MINUTE, DIVERSION = $1700.

VISIBILITY RANGE	PER FLIGHT COSTS DELAY		DIVERSION		TOTAL		TOTAL PER YEAR
1/2 - 3/8	0.16	+	0.29	=	0.45	=	270.46
3/8 - 1/4	-0.04	+	0.13	=	0.09	=	55.79
1/4 - 3/16	0.36	+	1.68	=	2.04	=	1224.41
3/16 - 1/8	0.07	+	0.0	=	0.07	=	40.89
1/8 - 1/16	0.89	+	1.15	=	2.04	=	1223.92
1/16 - 0	0.44	+	0.52	=	0.96	=	578.12
0 -	0.19	+	0.05	=	0.24	=	146.39
TOTAL	2.07	+	3.83	=	5.90	=	3539.96

ROUTE STRUCTURE 2: MEDIUM RANGE, 2400 LANDINGS/YEAR
COST OF DELAY = $10.20/MINUTE, DIVERSION = $1460.,   CANCELATION = $1300.

VISIBILITY RANGE	PER FLIGHT COSTS DELAY		DIVERSION		CANCEL		TOTAL		TOTAL PER YEAR
1/2 - 3/8	0.03	+	0.08	+	0.11	=	0.23	=	545.59
3/8 - 1/4	0.02	+	0.01	+	0.05	=	0.08	=	181.09
1/4 - 3/16	0.21	+	0.33	+	0.64	=	1.17	=	2801.55
3/16 - 1/8	0.01	+	0.01	+	0.0	=	0.02	=	52.85
1/8 - 1/16	0.14	+	0.39	+	0.43	=	0.97	=	2318.84
1/16 - 0	0.08	+	0.19	+	0.20	=	0.46	=	1115.84
0 -	0.04	+	0.05	+	0.02	=	0.10	=	246.55
TOTAL	0.51	+	1.07	+	1.45	=	3.03	=	7262.29

ROUTE STRUCTURE 3: SHORT RANGE, 3000 LANDINGS/YEAR
COST OF DELAY = $ 4.10/MIN, HOLD TAKE OFF = $ 0.41/MIN,   CANCEL = $1150.

VISIBILITY RANGE	PER FLIGHT COSTS DELAY		HOLD		CANCEL		TOTAL		TOTAL PER YEAR
1/2 - 3/8	0.00	+	0.01	+	0.14	=	0.15	=	464.03
3/8 - 1/4	0.00	+	0.00	+	0.03	=	0.03	=	98.14
1/4 - 3/16	0.02	+	0.06	+	0.60	=	0.68	=	2047.52
3/16 - 1/8	0.00	+	0.00	+	0.02	=	0.02	=	69.33
1/8 - 1/16	0.01	+	0.04	+	0.64	=	0.69	=	2083.20
1/16 - 0	0.01	+	0.02	+	0.31	=	0.34	=	1024.88
0 -	0.00	+	0.01	+	0.07	=	0.08	=	251.65
TOTAL	0.06	+	0.15	+	1.80	=	2.01	=	6038.74

AIRPORT: NEWARK N.J. YEAR: 1967

VISIBILITY	NUMBER OF OCCURANCES IN TEN YEARS FOR THESE DELAY TIMES IN MINUTES 0-15	15-30	30-45	45-60	60-90	90-120	120-180	180-240	240-360	360-480	480-600
1/2	67	90	44	27	54	27	40	23	25	11	12
3/8	61	81	39	26	49	24	36	21	23	9	11
1/4	45	51	26	25	36	19	30	22	13	6	10
3/16	19	14	23	13	18	16	19	13	7	4	9
1/8	14	11	17	13	20	13	14	14	3	3	9
1/16	5	11	7	3	13	6	7	7	2	0	9
0	1	8	5	3	7	8	4	3	2	1	6

AVERAGE ARRIVAL RATE = 22.3, MAXIMUM IFR LANDING RATE = 48.0
COEFFICIENT OF DELAY PROPAGATION = 1.46, DELAY MULTIPLIER = 1.87

VISIBILITY	MEAN DELAY PER LANDING - FOR MAXIMUM TOTAL DELAY OF 30.00	60.00	120.00	PROBABILITY OF DIVERSION AFTER TOTAL DELAY OF 30.00	60.00	120.00
1/2	0.222255	0.414851	0.738153	0.0064635	0.0053717	0.0037479
3/8	0.200029	0.373228	0.663606	0.0058136	0.0048269	0.0033576
1/4	0.156382	0.292704	0.520982	0.0045806	0.0038124	0.0026449
3/16	0.103487	0.195910	0.351100	0.0030983	0.0025879	0.0018848
1/8	0.089300	0.169024	0.303259	0.0026758	0.0022369	0.0015924
1/16	0.055819	0.106245	0.194751	0.0016919	0.0014709	0.0010971
0	0.040146	0.076415	0.139716	0.0012170	0.0010575	0.0007989

ROUTE STRUCTURE 1: LONG RANGE, 600 LANDINGS/YEAR
COST OF DELAY = $14.50/MINUTE, DIVERSION = $1700.

VISIBILITY RANGE	PER FLIGHT COSTS DELAY		DIVERSION		TOTAL		TOTAL PER YEAR
1/2 - 3/8	0.40	+	1.34	=	1.74	=	1045.62
3/8 - 1/4	0.83	+	2.45	=	3.28	=	1967.82
1/4 - 3/16	1.14	+	2.61	=	3.76	=	2253.30
3/16 - 1/8	0.18	+	1.01	=	1.19	=	714.46
1/8 - 1/16	0.71	+	1.70	=	2.42	=	1449.24
1/16 - 0	0.28	+	1.03	=	1.30	=	782.90
0 -	0.64	+	2.75	=	3.38	=	2030.45
TOTAL	4.18	+	12.89	=	17.07	=	10244.78

ROUTE STRUCTURE 2: MEDIUM RANGE, 2400 LANDINGS/YEAR
COST OF DELAY = $10.20/MINUTE, DIVERSION = $1460., CANCELATION = $1300.

VISIBILITY RANGE	PER FLIGHT COSTS DELAY		DIVERSION		CANCEL		TOTAL		TOTAL PER YEAR
1/2 - 3/8	0.09	+	0.37	+	0.51	=	0.97	=	2324.07
3/8 - 1/4	0.20	+	0.69	+	0.93	=	1.82	=	4365.86
1/4 - 3/16	0.24	+	0.86	+	0.99	=	2.09	=	5004.12
3/16 - 1/8	0.06	+	0.23	+	0.38	=	0.67	=	1603.66
1/8 - 1/16	0.17	+	0.53	+	0.64	=	1.35	=	3235.54
1/16 - 0	0.05	+	0.28	+	0.39	=	0.72	=	1725.71
0 -	0.13	+	0.71	+	1.04	=	1.88	=	4509.78
TOTAL	0.94	+	3.67	+	4.87	=	9.49	=	22768.73

ROUTE STRUCTURE 3: SHORT RANGE, 3000 LANDINGS/YEAR
COST OF DELAY = $ 4.10/MIN, HOLD TAKE OFF = $ 0.41/MIN, CANCEL = $1150.

VISIBILITY RANGE	PER FLIGHT COSTS DELAY		HOLD		CANCEL		TOTAL		TOTAL PER YEAR
1/2 - 3/8	0.01	+	0.03	+	0.63	=	0.66	=	1993.37
3/8 - 1/4	0.03	+	0.06	+	1.17	=	1.25	=	3749.79
1/4 - 3/16	0.03	+	0.06	+	1.41	=	1.51	=	4520.95
3/16 - 1/8	0.01	+	0.02	+	0.40	=	0.43	=	1285.26
1/8 - 1/16	0.02	+	0.06	+	0.88	=	0.95	=	2857.70
1/16 - 0	0.01	+	0.02	+	0.48	=	0.50	=	1490.34
0 -	0.01	+	0.04	+	1.22	=	1.27	=	3813.69
TOTAL	0.12	+	0.28	+	6.18	=	6.57	=	19711.08

AIRPORT: NEWARK N.J. YEAR: 1970

VISI-BILITY	NUMBER OF OCCURANCES IN TEN YEARS FOR THESE DELAY TIMES IN MINUTES										
	0-15-	30-	45-	60-	90-	120-	180-	240-	360-	480-	600
1/2	67	90	44	27	54	27	40	23	25	11	12
3/8	61	81	39	26	49	24	36	21	23	9	11
1/4	45	51	26	25	36	19	30	22	13	6	10
3/16	19	14	23	13	18	16	19	13	7	4	9
1/8	14	11	17	13	20	13	14	14	3	3	9
1/16	5	11	7	3	13	6	7	7	2	0	9
0	1	8	5	3	7	8	4	3	2	1	6

AVERAGE ARRIVAL RATE = 26.4, MAXIMUM IFR LANDING RATE = 48.0
COEFFICIENT OF DELAY PROPAGATION = 1.55, DELAY MULTIPLIER = 2.22

VISI-BILITY	MEAN DELAY PER LANDING - FOR MAXIMUM TOTAL DELAY OF 30.00	60.00	120.00	PROBABILITY OF DIVERSION AFTER TOTAL DELAY OF 30.00	60.00	120.00
1/2	0.226832	0.430274	0.788782	0.0065199	0.0054469	0.0038200
3/8	0.204163	0.387139	0.709415	0.0058647	0.0048956	0.0034220
1/4	0.159409	0.303191	0.556492	0.0046207	0.0038704	0.0026999
3/16	0.105113	0.202692	0.372363	0.0031245	0.0026205	0.0019277
1/8	0.090688	0.174749	0.322788	0.0026986	0.0022678	0.0016233
1/16	0.056615	0.109170	0.205847	0.0017035	0.0014881	0.0011125
0	0.040716	0.078521	0.147205	0.0012254	0.0010699	0.0008135

ROUTE STRUCTURE 1: LONG RANGE, 600 LANDINGS/YEAR
COST OF DELAY = $14.50/MINUTE, DIVERSION = $1700.

VISIBILITY RANGE	PER FLIGHT COSTS DELAY		DIVERSION		TOTAL		TOTAL PER YEAR
1/2 - 3/8	0.46	+	1.37	=	1.83	=	1096.43
3/8 - 1/4	0.96	+	2.48	=	3.45	=	2067.05
1/4 - 3/16	1.33	+	2.66	=	3.98	=	2389.50
3/16 - 1/8	0.19	+	1.05	=	1.24	=	741.81
1/8 - 1/16	0.81	+	1.76	=	2.56	=	1538.37
1/16 - 0	0.33	+	1.03	=	1.36	=	815.15
0 -	0.72	+	2.80	=	3.52	=	2110.49
TOTAL	4.79	+	13.14	=	17.93	=	10758.80

ROUTE STRUCTURE 2: MEDIUM RANGE, 2400 LANDINGS/YEAR
COST OF DELAY = $10.20/MINUTE, DIVERSION = $1460., CANCELATION = $1300.

VISIBILITY RANGE	PER FLIGHT COSTS DELAY		DIVERSION		CANCEL		TOTAL		TOTAL PER YEAR
1/2 - 3/8	0.10	+	0.37	+	0.52	=	0.99	=	2384.46
3/8 - 1/4	0.23	+	0.70	+	0.94	=	1.87	=	4479.89
1/4 - 3/16	0.26	+	0.88	+	1.00	=	2.14	=	5139.85
3/16 - 1/8	0.07	+	0.23	+	0.40	=	0.69	=	1661.19
1/8 - 1/16	0.19	+	0.54	+	0.66	=	1.40	=	3351.33
1/16 - 0	0.06	+	0.28	+	0.39	=	0.73	=	1750.63
0 -	0.15	+	0.72	+	1.06	=	1.92	=	4605.65
TOTAL	1.06	+	3.72	+	4.97	=	9.74	=	23372.99

ROUTE STRUCTURE 3: SHORT RANGE, 3000 LANDINGS/YEAR
COST OF DELAY = $ 4.10/MIN, HOLD TAKE OFF = $ 0.41/MIN, CANCEL = $1150.

VISIBILITY RANGE	PER FLIGHT COSTS DELAY		HOLD		CANCEL		TOTAL		TOTAL PER YEAR
1/2 - 3/8	0.01	+	0.03	+	0.63	=	0.68	=	2029.38
3/8 - 1/4	0.03	+	0.06	+	1.18	=	1.27	=	3821.02
1/4 - 3/16	0.04	+	0.07	+	1.44	=	1.54	=	4634.78
3/16 - 1/8	0.01	+	0.02	+	0.41	=	0.43	=	1302.98
1/8 - 1/16	0.02	+	0.06	+	0.90	=	0.98	=	2929.30
1/16 - 0	0.01	+	0.02	+	0.48	=	0.50	=	1513.16
0 -	0.02	+	0.04	+	1.23	=	1.29	=	3873.20
TOTAL	0.13	+	0.31	+	6.26	=	6.70	=	20103.82

AIRPORT: NEW YORK,N.Y. JFK YEAR: 1967

VISI- BILITY	NUMBER OF OCCURANCES IN TEN YEARS FOR THESE DELAY TIMES IN MINUTES 0-	15-	30-	45-	60-	90-	120-	180-	240-	360-	480-600
1/2	132	118	88	73	60	61	80	50	42	17	22
3/8	120	105	79	66	57	55	76	44	35	15	21
1/4	82	67	55	34	52	41	70	26	26	13	19
3/16	44	50	28	23	42	31	34	15	17	10	12
1/8	43	27	23	19	29	26	16	15	14	8	9
1/15	21	20	7	7	11	9	10	8	5	5	3
0	3	6	0	6	5	5	5	3	3	0	1

AVERAGE ARRIVAL RATE = 41.2, MAXIMUM IFR LANDING RATE = 64.0
COEFFICIENT OF DELAY PROPAGATION = 1.64, DELAY MULTIPLIER = 2.81

VISI- BILITY	MEAN DELAY PER LANDING - FOR MAXIMUM TOTAL DELAY OF 30.00	60.00	120.00	PROBABILITY OF DIVERSION AFTER TOTAL DELAY OF 30.00	60.00	120.00
1/2	0.421997	0.826536	1.549567	0.0120085	0.0100134	0.0073671
3/8	0.381388	0.747043	1.402715	0.0108527	0.0090429	0.0066112
1/4	0.299103	0.587367	1.120308	0.0086319	0.0072882	0.0053018
3/16	0.190662	0.372380	0.719559	0.0054801	0.0046540	0.0032804
1/8	0.142958	0.280828	0.540706	0.0041511	0.0035250	0.0025378
1/16	0.063630	0.123495	0.238143	0.0018278	0.0015797	0.0011546
0	0.023445	0.045182	0.088301	0.0006700	0.0005728	0.0003696

ROUTE STRUCTURE 1: LONG RANGE, 600 LANDINGS/YEAR
COST OF DELAY = $14.50/MINUTE, DIVERSION = $1700.

VISIBILITY RANGE	PER FLIGHT COSTS DELAY		DIVERSION		TOTAL		TOTAL PER YEAR
1/2 - 3/8	0.81	+	2.60	=	3.41	=	2048.67
3/8 - 1/4	1.82	+	4.50	=	6.32	=	3792.51
1/4 - 3/16	2.29	+	6.95	=	9.25	=	5548.34
3/16 - 1/8	1.30	+	2.55	=	3.86	=	2313.50
1/8 - 1/16	1.98	+	4.76	=	6.74	=	4043.12
1/16 - 0	0.81	+	2.70	=	3.51	=	2104.35
0 -	0.64	+	1.27	=	1.91	=	1145.21
TOTAL	9.65	+	25.34	=	34.99	=	20995.69

ROUTE STRUCTURE 2: MEDIUM RANGE, 2400 LANDINGS/YEAR
COST OF DELAY = $10.20/MINUTE, DIVERSION = $1460., CANCELATION = $1300.

VISIBILITY RANGE	PER FLIGHT COSTS DELAY		DIVERSION		CANCEL		TOTAL		TOTAL PER YEAR
1/2 - 3/8	0.22	+	0.64	+	0.98	=	1.84	=	4426.02
3/8 - 1/4	0.55	+	1.18	+	1.70	=	3.44	=	8246.36
1/4 - 3/16	0.58	+	1.76	+	2.63	=	4.97	=	11916.72
3/16 - 1/8	0.24	+	0.78	+	0.97	=	1.99	=	4777.02
1/8 - 1/16	0.41	+	1.32	+	1.80	=	3.54	=	8485.43
1/16 - 0	0.18	+	0.67	+	1.02	=	1.87	=	4492.00
0 -	0.11	+	0.40	+	0.48	=	0.99	=	2374.32
TOTAL	2.30	+	6.75	+	9.58	=	18.63	=	44717.86

ROUTE STRUCTURE 3: SHORT RANGE, 3000 LANDINGS/YEAR
COST OF DELAY = $ 4.10/MIN, HOLD TAKE OFF = $ 0.41/MIN, CANCEL = $1150.

VISIBILITY RANGE	PER FLIGHT COSTS DELAY		HOLD		CANCEL		TOTAL		TOTAL PER YEAR
1/2 - 3/8	0.02	+	0.07	+	1.12	=	1.21	=	3616.59
3/8 - 1/4	0.06	+	0.16	+	2.02	=	2.25	=	6739.88
1/4 - 3/16	0.06	+	0.18	+	3.03	=	3.27	=	9807.39
3/16 - 1/8	0.03	+	0.07	+	1.30	=	1.40	=	4195.23
1/8 - 1/16	0.04	+	0.13	+	2.24	=	2.41	=	7224.99
1/16 - 0	0.02	+	0.05	+	1.16	=	1.23	=	3699.31
0 -	0.01	+	0.03	+	0.66	=	0.70	=	2112.88
TOTAL	0.25	+	0.70	+	11.52	=	12.47	=	37396.27

AIRPORT: NEW YORK,N.Y. JFK   YEAR: 1970

VISI-BILITY	NUMBER OF OCCURANCES IN TEN YEARS FOR THESE DELAY TIMES IN MINUTES 0-15-	30-	45-	60-	90-	120-	180-	240-	360-	480-	600
1/2	132	118	88	73	60	61	80	50	42	17	22
3/8	120	105	79	66	57	55	76	44	35	15	21
1/4	82	67	55	34	52	41	70	26	26	13	19
3/16	44	50	28	23	42	31	34	15	17	10	12
1/8	43	27	23	19	29	26	16	15	14	8	9
1/16	21	20	7	7	11	9	10	8	5	5	3
0	3	6	0	6	5	5	5	3	3	0	1

AVERAGE ARRIVAL RATE = 49.6, MAXIMUM IFR LANDING RATE = 64.0
COEFFICIENT OF DELAY PROPAGATION = 1.77, DELAY MULTIPLIER = 4.44

VISI-BILITY	MEAN DELAY PER LANDING - FOR MAXIMUM TOTAL DELAY OF 30.00	60.00	120.00	PROBABILITY OF DIVERSION AFTER TOTAL DELAY OF 30.00	60.00	120.00
1/2	0.451926	0.942559	1.895904	0.0121350	0.0101761	0.0075847
3/8	0.408411	0.851997	1.720846	0.0109677	0.0091917	0.0068052
1/4	0.318374	0.663750	1.374446	0.0087181	0.0074042	0.0054485
3/16	0.203363	0.419008	0.894462	0.0055345	0.0047341	0.0033594
1/8	0.151743	0.315688	0.666818	0.0041919	0.0035830	0.0025983
1/16	0.067957	0.137726	0.290507	0.0018445	0.0016058	0.0011844
0	0.025050	0.050105	0.111568	0.0006772	0.0005872	0.0003819

ROUTE STRUCTURE 1: LONG RANGE, 600 LANDINGS/YEAR
COST OF DELAY = $14.50/MINUTE, DIVERSION = $1700.

VISIBILITY RANGE	PER FLIGHT COSTS DELAY		DIVERSION		TOTAL		TOTAL PER YEAR
1/2 - 3/8	1.18	+	2.68	=	3.86	=	2318.13
3/8 - 1/4	2.66	+	4.67	=	7.33	=	4397.41
1/4 - 3/16	3.32	+	7.19	=	10.51	=	6306.78
3/16 - 1/8	1.98	+	2.62	=	4.59	=	2756.83
1/8 - 1/16	3.00	+	4.86	=	7.86	=	4716.13
1/16 - 0	1.20	+	2.76	=	3.96	=	2375.29
0 -	0.95	+	1.31	=	2.27	=	1360.20
TOTAL	14.29	+	26.09	=	40.38	=	24230.76

ROUTE STRUCTURE 2: MEDIUM RANGE, 2400 LANDINGS/YEAR
COST OF DELAY = $10.20/MINUTE, DIVERSION = $1460., CANCELATION = $1300.

VISIBILITY RANGE	PER FLIGHT COSTS DELAY		DIVERSION		CANCEL		TOTAL		TOTAL PER YEAR
1/2 - 3/8	0.32	+	0.65	+	1.01	=	1.99	=	4765.13
3/8 - 1/4	0.83	+	1.20	+	1.76	=	3.79	=	9084.93
1/4 - 3/16	0.86	+	1.77	+	2.72	=	5.35	=	12838.45
3/16 - 1/8	0.35	+	0.80	+	0.99	=	2.14	=	5124.77
1/8 - 1/16	0.61	+	1.34	+	1.84	=	3.79	=	9087.05
1/16 - 0	0.27	+	0.67	+	1.04	=	1.99	=	4771.11
0 -	0.15	+	0.41	+	0.50	=	1.06	=	2534.44
TOTAL	3.39	+	6.84	+	9.86	=	20.09	=	48205.87

ROUTE STRUCTURE 3: SHORT RANGE, 3000 LANDINGS/YEAR
COST OF DELAY = $ 4.10/MIN, HOLD TAKE OFF = $ 0.41/MIN, CANCEL = $1150.

VISIBILITY RANGE	PER FLIGHT COSTS DELAY		HOLD		CANCEL		TOTAL		TOTAL PER YEAR
1/2 - 3/8	0.03	+	0.10	+	1.13	=	1.26	=	3790.23
3/8 - 1/4	0.09	+	0.25	+	2.06	=	2.39	=	7180.23
1/4 - 3/16	0.08	+	0.27	+	3.07	=	3.42	=	10270.65
3/16 - 1/8	0.05	+	0.10	+	1.32	=	1.47	=	4399.50
1/8 - 1/16	0.05	+	0.19	+	2.27	=	2.52	=	7564.72
1/16 - 0	0.03	+	0.08	+	1.17	=	1.28	=	3845.72
0 -	0.02	+	0.04	+	0.68	=	0.74	=	2212.14
TOTAL	0.36	+	1.02	+	11.70	=	13.09	=	39263.19

Appendix B

NEW TECHNOLOGY

After a diligent review of the work performed under this contract, no new innovation, discovery, improvement or invention was made.

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