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COMMERCIAL AIR TRANSPORT HAZARD WARNING AND AVOIDANCE SYSTEM

(Final Report)

VOLUME I - SUMMARY

by: G. W. Casserly and D. W. Richardson

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Prepared under Contract No: NAS 12-2108
by
POLHEMUS NAVIGATION SCIENCES, INC.
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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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COMMERCIAL AIR TRANSPORT
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Volume I - Summary

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1.0 INTRODUCTION

This volume of the report contains a summary of the major findings of a study of Hazard Warning and Avoidance System concepts for commercial aircraft. Two primary areas of interest were investigated, namely a definition of the problem and the operational requirements for such a system and secondly, the availability of current sensor and system technology as applied to possible solutions to the problem.

This project was initially motivated by a careful consideration of aircraft accident statistics. Using these statistics as a primary study input, three major hazard avoidance functions were identified, those being Independent Approach and Landing Monitor (IALM), Roll Out and Taxi Aid (ROTA), and High Ground Avoidance (HGA). All of these functions were related to the initial conclusion of the study, that the low visibility approach and landing situation represented the logical focus of attention .

An important aim of the study was the attempt to identify, if possible, a sensor which could provide all of these functions in a single integrated on-board system. The major effort in sensor technology was directed toward radar at X, Ku, Ka, and V bands with a lesser level of detail devoted to electro-optical and infra-red sensors. 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 was explored from the standpoint of cost penalties, and therefore, possible savings associated with aircraft delays, diversions and flight cancellations.

This volume has been configured in a format specifically designed for readability and ease of interpretation. Each of the succeeding sections of this volume is contained on two facing pages. The initial "thesis sentence" contained at the top of each left hand page sets the theme for the section and establishes the premise which is developed and concluded upon reaching the bottom of the facing right hand page. No section contains more than two pages and each left hand page introduces a new subject.

2.0 CONCLUSIONS

The major conclusions from this study of a Hazard Warning and Avoidance System are briefly summarized here.

Meteorology

- Dense fog is the severest limitation to optical visibility . Fog of 100 ft visibility is used as a design limit.
- Heavy rain, by itself, does not limit optical visibility. Rain of 16 mm/hr is used as a reasonable maximum design value.
- Heavy rain and dense fog can occur simultaneously, so a sensor must be able to see through the combination.

Accident Statistics

- There is a need for high-ground or runway orientation at distances of 7 to 10 miles from runway threshold.
- An approach and landing monitor coupled with a display of command guidance information could greatly contribute to accident avoidance EVEN IN "DAYTIME" CONDITIONS.

Economics

- Instrumentation that would increase landing capability from Cat I minima to Cat II minima could result in an average saving ranging from $6,000 to $13,000 per airplane per year. The regional carrier would derive the greatest benefit from Cat II capability.

Desired Characteristics

- The hazard warning and avoidance system should provide the functions of High Ground Avoidance (HGA), Independent Approach and Landing Monitor (IALM), and Roll-Out and Taxi Assistance (ROTA).
- In the IALM Mode, the system should provide command information which can be immediately interpreted.

- IALM capability should be provided at ranges up to 7-10 miles from runway threshold under adverse weather conditions.
- HGA capability should be provided at ranges up to 5-10 miles ahead of the aircraft velocity vector under adverse weather conditions.

Current Approach and Landing Aids

- ILS is the foremost of current aids. It suffers from path distortion due to multipath.
- Future ILS system concepts offer hope of improvement, but will not provide either redundancy or on-board monitoring capability.
- There is a need for an Independent Approach and Landing Monitor.

Sensor Performance

- The most promising concept for runway identification is a radar sensor in conjunction with runway enhancement by either reflectors or beacons.
- The high-ground avoidance function is best performed at either X band or Ku band. Ka band performance is marginal; V band performance is poor.
- The combined IALM and HGA functions are best performed at Ku band.
- The combined weather surveillance, IALM, HGA and ROTA functions are best performed at X band.

Recommendations

- Radar sensor experiments should be run at low grazing angles (1°-10°) over a range of frequencies and target signatures.
- Cockpit display concepts (content, format, location, etc.) should be investigated prior to finalization of a flight test configuration.

3.0 METEOROLOGICAL CONDITIONS AFFECTING VISIBILITY

Conditions of 100 ft visibility fog and 16 mm/hr rainfall represent a reasonable set of environmental design criteria for a Hazard Warning and Avoidance System.

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.

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 parameters such as the duration of the fog, frequency of occurrence, and the amount by which the visibility range is reduced i.e. the density of the fog. The attenuation through fog of various visibilities has been calculated and the results listed in Table I-1. 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. This severely restricts the range of optical systems in dense fog.

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 previously and the range of values derived from empirical formulae are listed in Table I-2. Under these conditions, 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. The attenuation of rainfall is shown in Table I-3. Not included in this brief discussion is the equally important consideration of the backscatter caused by rainfall.

Based on statistics averaged over a number of years, the amount of time per year the rainfall rate exceeds 16 mm/hr is generally quite small, even in areas of heavy rainfall. Generally, the duration of any one period of heavy rainfall tends to be short, which further minimizes the effect rainfall has on airline operations. Consequently, this study considered sensor performance only for rainfall rates of up to 16 mm/hr.

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 I-4. 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.

Typically dense smog has an attenuation of up to 17 dB/km at 0.6 microns, 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.

TABLE I-1. ATTENUATION IN FOG (dB/km)

Visible Range (ft)	ILS Category	Water Content (gm/m^3)	Radar				Optical	
			X 10 GHz	Ku 16 GHz	Ka 35 GHz	V 70 GHz	10 microns	0.5 micron
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

TABLE I-2. 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

TABLE I-3. 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 I-4. SNOWFALL VISIBILITY AND ATTENUATION (dB/km)

Snowfall Rate	Optical Visibility	Radar				Optical
Melted mm/hr	ft.	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

4.0 ACCIDENT ANALYSIS

Analysis of accidents involving certificated air carriers from 1958 through 1967 indicates a primary requirement for Hazard Warning and Avoidance System functions during approach and landing, to a range of 10 miles from the runway threshold.

Table I-5 presents one aspect of a statistical evaluation of aircraft accidents, 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.

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.

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 a relatively high percentage of the accidents reported 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 landing accidents (from 1 1/2 miles out to the end of the runway). 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.

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.

TABLE I-5. 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

5.0 ECONOMIC BENEFIT ANALYSIS

While the IALM provides cost benefits of varying degree to all potential users, based on the assumptions of this analysis, the greatest dollar savings accrue to the regional air carriers.

An analysis was made 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 at lower minimums) presents a potential way to avoid some of these penalties. The intent of this analysis was to evaluate the cost benefit of improved landing capability, with the emphasis placed upon the evaluation of the saving associated with improvement in terms of visibility increments. The magnitude of the saving is directly related to airline operating procedures and to the unique visibility characteristics of individual airports.

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 analysis considered the recorded visibility statistics for a number of U.S. airports and used them to estimate the average delay time and diversion probability for an aircraft attempting to land at a specific airport. The aircraft was 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 were considered in the analysis. The objective was to find the cost penalties related to the inability to land in individual intervals of visibility. The mean delay times per landing and the probabilities of diversion were 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.

A detailed discussion of this economic analysis appears in Section 3, Volume II, with the mathematic derivations and tabulated dollar results in Appendix A of Volume II. The analysis was performed for three basic route structures representing different types of aircraft and route lengths as shown below.

Aircraft #1:	A large four-engine jet,
Routes:	Transcontinental, intercontinental, 600 landings/year
Flight Plan:	May delay for two hours; diverts after a 2-hour delay
Aircraft #2:	A medium two or three-engine jet
Routes:	Regional, 2400 landings/year
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, 3000 landings/year
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.

Associated with each type of aircraft were different direct costs of delays, diversions and cancellations listed in Section 3 of Volume II.

The cost benefits of improved landing capability were obtained by combining the visibility data for an airport and the traffic arrival and landing rates at the airport with the delay, diversion and cancellation cost figures. Utilizing the visibility data alone, without the traffic data, would result in the assumption that the landing would be accomplished as soon as the weather clears. In reality, the delay may be further propagated because of accumulated traffic. 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.

An example of the results of the cost computations for the three route structures and eight airports is in Table I-6. The figures represent the dollar savings available from a full exploitation of Category II 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.

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. This fact directly contradicts the usual practice of spending a fixed per cent of the cost of the aircraft on avionic systems. 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.

TABLE I-6 .
ANNUAL COSTS ASSOCIATED
WITH THE VISIBILITY INTERVAL
3/16 MILE TO 1/2 MILE.

TABLE I-6. 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

6.0 DESIRED SYSTEM CHARACTERISTICS

An analysis of the operational requirements for the IALM, HGA and ROTA functions results in a primary system requirement for runway detection range capability of 7-10 miles under conditions of degraded visibility.

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. Table I-7 summarizes these system functions and their economic and/or safety motivations.

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 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.

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.

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. The HGA sensor is typically a radar equipment which measures the range and angular position of the terrain with respect to the flight vector. 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.

Table I-8 is included as a summary of some of the pertinent characteristics and/or requirements which have been developed in the detailed analysis. Naturally, these characteristics are not necessarily firm, but they do reflect the general character of the performance required of candidate systems.

TABLE I-7. 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.

TABLE I-8. DESIRED SYSTEM CHARACTERISTICS

Glide Slope Angle	2° - 10° *
Maximum Range Requirement High Ground Avoidance Approach and Landing Monitor	 5-10 miles 7-10 miles
Azimuth Coverage	± 30°
Azimuth Error	0.8°
Elevation Coverage	+ 5° - 15°
Elevation Error	0.4°
Offset Error at Threshold	± 40'
Scan Rate Azimuth Elevation	 2.3 per second 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.

7.0 SENSOR PERFORMANCE ANALYSIS

Radar sensors, which emerged much more strongly than optical sensors as candidates for the IALM, were studied in-depth in a background of equipment, environmental, and target characteristics.

A cursory study of optical sensors was performed for the 10 micron and 0.5 micron spectral regions. It was concluded that little is to be gained from instrumentation in these two regions over what a pilot can see visually. Radar sensing was studied at X, Ku, Ka, and V bands with promising results, and the study was pursued in depth.

The specific description of the equipment characteristics which were utilized in the study is contained in Table I-9 . The 10 kw peak power at V band was believed to be a currently practical upper limit. The beamwidths shown are based upon physical limits on antenna size of 1 meter in the horizontal direction and 30 centimeters in the vertical direction, imposed by space limitations in the nose of a typical commercial transport. The horizontal polarization was chosen over vertical polarization at X band because of better grass-to-concrete contrast. Circular polarization was used on the higher frequency bands to reduce the effect of backscatter from rain. A rain echo cancellation ratio of 15 dB was assumed. At all frequencies, a monopulse feature is required to produce adequate elevation accuracy for the IALM and HGA functions.

The environmental description included meteorological effects, excluding the attenuation caused by oxygen absorption. It was reasoned that oxygen absorption could be eliminated as a key factor in evaluating the various frequency bands if the specific frequencies were chosen to minimize its effects. Rainfall rates and durations were evaluated to establish 16 mm/hr of rainfall as a reasonable upper limit for design purposes. Fog of 100 ft visibility was similarly established as a reasonable upper limit. Theoretical values of attenuation were used for fog even though there is some evidence that they may be as much as twice the real or observed values. Snow was found to have an attenuation equal to or less than that of rainfall having the same water content. Fog of 100 ft visibility provides a more stringent limitation than heavy snowfall. The attenuation values for rain and fog are shown in Table I-10. Consideration was also given to the radar echo produced by backscattering from rain.

The detection of unenhanced runways depends upon the characteristics of backscattering from terrain at low grazing angles; a technical area in which quantitative information is relatively scarce. Work in this report is based upon estimated characteristics obtained by cautious extrapolation from data at larger grazing angles in the order of 10°. There is some risk in doing this and further exploration at low grazing angles is required to clarify the situation. In this report, a 20 dB value was used for the grass-to-concrete scattering ratio and 10 dB was used for the grass-to-asphalt scattering ratio.

TABLE I-9. 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)

TABLE I-10. 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

8.0 RADAR DETECTION OF RUNWAYS

For detection of runways, the IALM function will best operate at either X band or Ku band and, in addition, some form of runway enhancement is required.

Based on the analyses performed in this study, the detection of unenhanced runways by a radar sensor is not promising. This possibility was studied with respect to 4 basic requirements. They are:

1. Azimuth beamwidth narrow enough to allow the pilot to align the flight vector to within 0.4 degrees of the runway centerline.
2. A drop in signal amplitude of more than 3 dB as the radar beam sweeps across the runway.
3. Signal from terrain adjacent to the runway to be greater than 10 dB above receiver noise.
4. Signal from terrain adjacent to the runway to be greater than 10 dB above that from rain backscatter at the same range.

A sample of the results obtained from this analysis is shown in Table I-11. The results clearly indicate that the available ranges do not meet the 7-10 n m range requirement which has been established for the IALM function.

With reflector enhancement of the runway, it is possible to obtain the desired runway detection range. Reflector enhancement was studied with respect to the following basic requirements:

1. The radar azimuth beamwidth must be narrow enough to eliminate any large object from the pulse packet which contains the reflector.
2. The azimuth beamwidth must be narrow enough (2.0 degrees) to allow runway alignment OR, the monopulse feature must be used if the beamwidth is between 2 and 10 degrees.
3. The signal return from the reflector must be 10 dB above each of noise, terrain signal and rain backscatter.

Under these conditions, the detection ranges are shown in Table I-12. The table clearly shows that Ka and V bands fail to provide the required range capability in heavy rain and/or fog. Either X band or Ku band will furnish detection ranges which are commensurate with the desired performance.

With beacon enhancement the results also favor the use of either X band or Ku band. These results were obtained in terms of the beacon power required to produce a signal which is 10 dB above noise at a range of 10 n.m. The beacon is assumed to have 10 degree beamwidths in both azimuth and elevation. At V band, the power requirement is unreasonable. At Ka band, the power requirement is reasonable through 100 ft visibility fog but, again, it is too large in the presence of 16 mm/hr rain. At both X band and Ku band, the power requirements are reasonable. Table I-13 presents a summary of these results.

In summary, runway enhancement is required to meet the 7-10 n.m. range requirement and the radar should operate at either X band or Ku band.

TABLE I-11. DETECTION RANGE (nm) FOR UNENHANCED RUNWAYS (.1 μs PULSE WIDTH)

	Rain (mm/hr)				Fog (ft.Vis.)
	0	1	4	16	100
Best Freq.	Ka	Ka	Ku	Ku	Ku
Range (nm)	4.8	3.2	2.2	0.8	2.2

TABLE I-12. DETECTION RANGE (nm) FOR A 1000 m^2 REFLECTOR (0.1 μs PULSE WIDTH)

Frequency Band	Reflector Side Dim.	Rain (mm/hr)				Fog (ft Vis)
		0	1	4	16	100
X	68 cm	30	28	18	5.9	19
Ku	54	36	27	17	6.5	14
Ka	36	30	12	6.5	2.8	5.4
V	26	15	5.4	3.2	1.5	1.9

TABLE I-13. BEACON POWER (mW) REQUIRED TO FURNISH 10 dB SIGNAL-TO-NOISE RATIO AT 10 nm . .(10° BEACON BEAMWIDTH IN AZIMUTH & ELEVATION) (0.1 μs PULSE WIDTH)

Frequency Band	16 mm/hr Rain	100' Vis. Fog
X	0.95	0.47
Ku	148	2.0
Ka	3×10^8	1.26×10^3
V	——— Very Large ———	

9.0 RECOMMENDED FREQUENCY BAND

The best choice of radar frequency band for the combined IALM and HGA functions is Ku band. Further inclusion of weather surveillance and ROTA functions leads to the choice of an X-band system.

HGA. - The high-ground avoidance function was studied with respect to the following set of requirements.

1. Signals from terrain within 10 nm must be more than 20 dB above the receiver noise level even in the presence of heavy rain (16 mm/hr).

2. The triggering threshold is set 6 dB below the expected level of the terrain signal.

3. The signal from a rain front must not exceed the threshold.

A summary of the range at which high ground is detected appears in Table I-14 The detection range falls off rapidly with frequency. X band and Ku band performances are satisfactory but Ka band performance is only marginal. V band range capability is unacceptably low.

ROTA. - The primary requirement for roll-out and taxi assistance is one of resolution. The X band radar does not have sufficiently narrow beamwidth to provide the desired resolution unless some form of beam sharpening, such as monopulse feature, is used. The resolution of the other frequency bands is satisfactory for ROTA.

ILM and HGA Modes. For the performance of the high-ground avoidance and landing monitor functions the recommended system utilizes:

- Ku band frequency
- 1 m antenna aperture in azimuth
- runway enhancement by either reflectors or beacons
- 1 microsecond pulse length for HGA
- 0.1 microsecond pulse length for IALM

An alternative recommendation is made for the combined functions of IALM, HGA, weather surveillance and taxiway guidance functions in a single system. This composite system uses:

- X band frequency
- 1 m antenna aperture in azimuth
- runway and taxiway enhancement by either reflectors or beacons
- 5 microsecond pulse length in weather and HGA modes
- 0.1 microsecond pulse length in IALM & taxi modes

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.

TABLE I-14. DETECTION RANGE (nm) FOR HGA FUNCTION (1 μs PULSE LENGTH)

	Rain		Fog
Frequency Band	4 mm/hr	16 mm/hr	100' Visibility
X	22	12	18
Ku	13	5.1	11
Ka	4.8	1.9	4.0
V	1.8	0.9	1.1

10.0 SYSTEM CONFIGURATIONS

Within the currently available state of the art, there are several system configurations capable of performing the IALM, HGA, and ROTA functions required by various users.

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 aggressive 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 has already indicated the large benefit in reduced operating losses that could accrue to airline operators from the capability to operate at reduced minima. 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 some time 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.

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 centerline 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.

With runway and taxiway enhancement, an X band sensor can very easily meet the performance requirements of IALM and ROTA. There is no reason why the same X band sensor should not meet enroute weather radar requirements while also providing adequate performance in the HGA mode. 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.

11.0 RECOMMENDATIONS

There are two significant development efforts which require immediate implementation as the necessary next steps in the demonstration of an operational Hazard Warning and Avoidance System.

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, major emphasis has been placed on closing these information gaps as the necessary next step in an integrated plan.

This current study 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 inter-relate 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.

The sensor performance of an air-borne 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°. 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. 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.

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.

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 Program Flow Diagram, Figure I-1 .

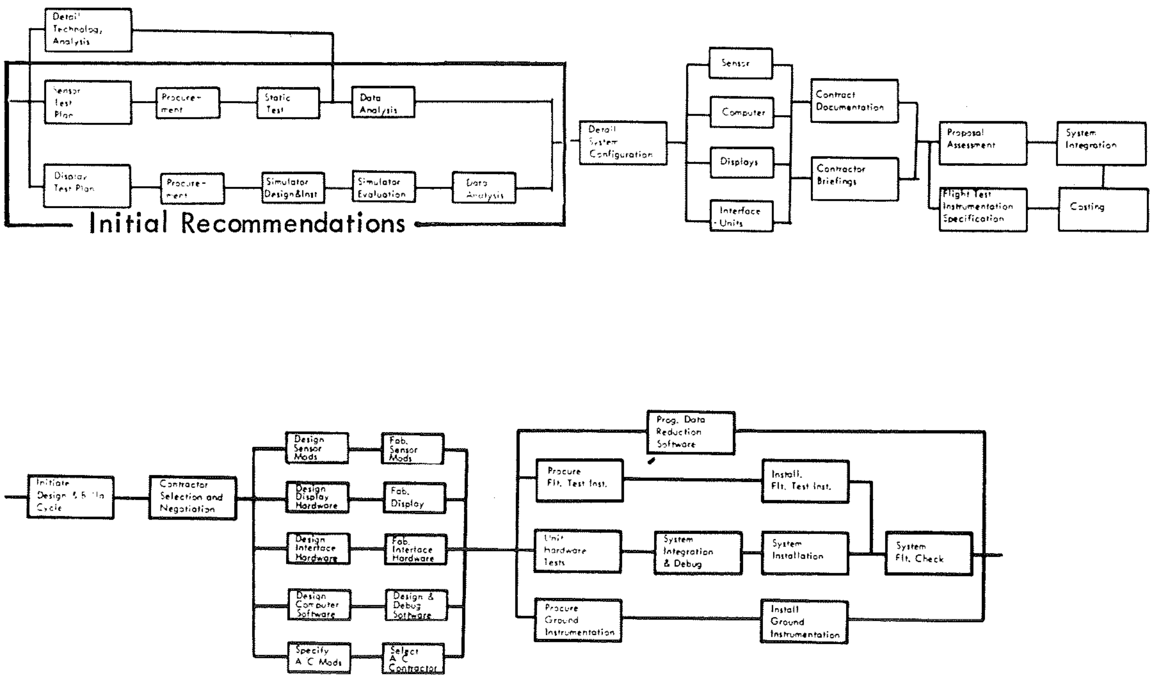

Figure I-1. Program Flow Diagram

Appendix A

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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