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HEAD-UP DISPLAYS

A Study of Their Applicability in Civil Aviation

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This study was suggested by Dr. Walton L. Jones, Director of the Biotechnology and Human Research Division of the NASA Office of Advanced Research and Technology. Dr. Jones has had long experience in human factors problems associated with aircraft, and his suggestion for the study was prompted by the increasing attention which the head-up display has been receiving from research workers and operational personnel in the field of civil aviation. Specifically, Dr. Jones' concern was to survey current developments and trends and to enumerate the pros and cons of head-up displays. This report is an attempt to draw up such a balance sheet.

The technical monitor for this study was Mr. Allan Merkin, Manager, Aeronautical Systems, Biotechnology and Human Research Division. Mr. Merkin provided innumerable helpful suggestions on sources of information, and he was unsparing in his efforts to arrange interviews with persons active in head-up display research in NASA and in other Government departments and agencies. The authors are deeply grateful to Mr. Merkin for the generous gift of his time and for his counsel on the technical and administrative problems which arose during the course of the study.

The authors had the privilege to talk with more than sixty persons who are engaged in display research and civil aviation operations, both in this country and abroad. It is impossible to name them all here. While they must be acknowledged collectively, the authors owe each an individual debt of gratitude.

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SUMMARY AND CONCLUSIONS

The following is a synopsis of the report by chapter and a listing of the major conclusions. So that the conclusions may be understood in the context and in the sequence in which they are reached, they have been incorporated within the synopsis. For ease of identification the conclusions are underlined.

CHAPTER I

The head-up display (HUD) is a device which presents information about the actual and desired situation of an aircraft in such a way that the pilot can view both the display and the natural external scene at the same time. The name derives from the fact that the display is visible to the pilot while he is "head-up", looking out of the cockpit.

The distinguishing features of the head-up display are:

- The display is presented as a collimated image, which is to say an image focused at optical infinity.
- Because the image is collimated and because it is projected on a transparent surface, the display is superimposed on (and appears to be at the same distance as) the external visual background.
- The image is luminous, i.e., it is visible because it emits light not because it reflects light.
- The display is positioned so that it will lie in the pilot's central (foveal) field of view when he is looking ahead outside the aircraft.

While the HUD has found extensive application in military aviation, it has not gained acceptance (except in theory) in civil aviation. However, there is a strong interest in the HUD as a solution to current and projected operational problems in civil aviation. Therefore, this study was undertaken with three objectives in mind:

1. To take stock of the situation.
2. To provide information on developments and trends in the field.
3. To assess the potential of the HUD for civil aviation uses.

Basically, this is an analytic study of the research literature and published commentary on the subject of aircraft operating problems and the head-up display. Supplementary information gained from interviews with research workers, pilots, and display experts (both in the U.S. and abroad) has been used to round out the picture of current thinking on head-up displays.

CHAPTER II

Three general requirements which will govern the acceptance and use of the HUD in civil aviation are safety, practicality (operational utility), and economy. A review of safety statistics shows that commercial and large general aviation aircraft may be treated as a single class, although the safety problem for the latter is somewhat more severe. The safety record also shows that the problems exist in both VFR and IFR conditions and that they stem largely from human errors in perceiving and interpreting information from external visual sources and from instruments. The HUD, which purports to facilitate the process of assimilating information from these two sources, could contribute both to the overall safety of civil aviation operations and to the efficiency of pilot performance. The final acceptance of the HUD in civil aviation will be governed by how the industry equates these potential benefits with cost considerations.

CHAPTER III

Operational problems and requirements can be identified for several specific areas of civil aviation. The major problem, and the area where the HUD could make the greatest potential contribution, is in approach and landing. The nature of the pilot's task and his guidance and control problems are analyzed extensively for this phase of light. A similar, but not so detailed, analysis is presented for other flight phases which pose guidance and control difficulties. These are takeoff, missed approach, and taxiing in very low visibilities. Also considered are the effects of aircraft-peculiar variables such as type of propulsion, size, and flight characteristics. Particular emphasis is placed on the problems expected to be encountered with jumbo jet and supersonic transport aircraft.

CHAPTER IV

The nature of the pilot's visual task and the visual cues he uses for guidance in approach and landing are examined. To control the approach and landing path the pilot needs information on the displacement, rate of displacement, and acceleration (rate at which displacement rate is changing) of the aircraft with respect to the desired path in the horizontal and vertical dimensions -- making a total of six variables. Successful accomplishment of these control tasks by visual reference alone depends primarily upon the pilot's ability to see and interpret cues derived from the relative position and movement of the horizon, the extended runway centerline, the zero-velocity point (X-point), and the aiming point on the runway. Supplementary information in the form of instrumental indications of altitude, rate of descent, and airspeed may be needed to corroborate these visual judgments. The effect of reduced visibility is to obscure or confuse the requisite visual cues, creating control problems -- primarily in the vertical dimension. This leads to the conclusion that some way is needed to enhance the visual cues or to replace them so as to assure the safety of VFR as well as IFR approach and landing.

CHAPTER V

Present aids and solutions to these long-recognized visual problems are examined to determine their shortcomings and to identify specific areas where the HUD could make a contribution. The conclusions are that the present approach and runway lighting system is adequate for lateral guidance, except in very low visibilities such as those associated with Category III of IFR. The approach and runway lights, however, do not provide adequate reference for vertical flight path control. The Visual Approach Slope Indicator (VASI) represents a valuable addition to the system by extending the visual glide slope out several thousand feet from the threshold, but the VASI loses its effectiveness in low visibilities, where the need for guidance is the greatest. Further the VASI is not sufficiently flexible to provide vertical guidance when the pilot must alter the approach path to compensate for variations in aircraft size, weight, and trim condition or for variations in runway length and surface conditions. The ILS, which is the prime source guidance in IFR, is deficient in three respects. It has inherent errors which make it unsuitable as the sole source of guidance. The quality of ILS information deteriorates rapidly below 100 feet of altitude, and the ILS is unusable altogether below 50 feet where the final steps of the landing are undertaken. Finally, the placement of the ILS glide slope often results in the pilot being directed along an instrument approach path which is unlike that he is accustomed to in VFR. The consequence is a conflict between instrument and visual reference at the moment of breakout in low visibility approaches. Present panel instruments are deficient for several reasons. They are not adequately integrated; their scale factors are sometimes inappropriate for the precision with which the pilot must control the aircraft; they are not properly located in relation to the area of prime interest during landing; and they are often mismatched in illumination both among themselves and in relation to the external visual scene. Of these, the chief problem is location, which forces the pilot to abandon instrument guidance at the moment of going head-up on the approach. This transition is a serious safety problem because of the time lost in visual adaptation and accommodation and in psychological adjustment and orientation to an external frame of reference. The operating procedures adopted to compensate for deficiencies in present ground aids and aircraft equipment are not wholly adequate, and they often serve to complicate the existing guidance and control problems.

CHAPTER VI

The role of the HUD in solving the problems identified in the preceeding three chapters is outlined. The conclusions as to the applicability and usefulness of the HUD are:

1. In VFR the HUD would be of value as a substitute for, or supplement to, the VASI in furnishing vertical flight path guidance. The HUD would also aid in lateral control. Further, the addition of certain instrument information would provide corroboration of the visual guidance available from the HUD and external sources. A final useful addition would be guidance for the execution of the flare and decrab maneuvers.

2. In IFR Categories I and II the HUD would be of enormous value in that it would enable the pilot to retain instrument guidance while in a head-up position. This would not only eliminate the transition problem, which is the major danger in present Category I/II operations, it would assist the pilot in interpreting and using visual reference from the decision height on to touchdown. This application represents the primary justification for adopting the HUD in civil aviation.

3. The use of the HUD in Category III is problematical. The question is not so much one of display technology as it is of finding suitable information to present on the display. Providing an improved ILS is developed and a redundant, independent source of guidance can be found to replace the visual reference lost in blind landing, the HUD would be a valuable device for Category III use. Additional factors which complicate the assessment of the potential role of the HUD in near-zero visibility operations are the current controversies over manual vs. automatic control of the approach and landing and the consequent lack of certainty about the proper role of the pilot in these conditions. Still, the main problem, and the one upon which the potential application of the HUD rests, is that of developing a satisfactory independent landing monitor.

4. Other roles for the HUD include providing guidance for rollout and taxi, for takeoff, and for missed approach. None of these uses constitute a sufficient reason for adopting the HUD, but they are strong ancillary arguments since these modes of operation could easily be added to a HUD used primarily for approach and landing.

CHAPTER VII

The study concludes with an examination of certain technical and practical problems which must be solved before the HUD can gain final acceptance in civil aviation. These concerns may be classed as technological, human factors, doctrinal, and commercial. To some extent they represent disadvantages of the HUD, not as a concept, but as an operational device. On the other hand, they may be regarded as no more than the normal difficulties to be overcome in developing any device for the improvement of safety and efficiency in aviation. The overall judgment is that the potential value of the HUD justifies the expenditure of effort necessary to resolve the remaining implementation problems.

CHAPTER I

INTRODUCTION

BACKGROUND

The head-up display (HUD) is a device which presents information about the actual and desired situation of an aircraft in such a way that the pilot can view both the display and the natural external scene at the same time. The name derives from the fact that the display is visible to the pilot while he is "head-up", looking out of the cockpit.

In common usage the term head-up display has come to have the narrower meaning of a device whereby a collimated virtual image is projected on a transparent surface within the pilot's external field of view. Nearly all the head-up displays developed for aircraft have been of this type, and it is in this sense that head-up display and HUD are used in this report.

The distinguishing features of the head-up display are:

- The display is presented as a collimated image, which is to say an image focused at optical infinity.
- Because the image is collimated and because it is projected on a transparent surface, the display is superimposed on (and appears to be at the same distance as) the external visual background.
- The image is luminous, i.e., it is visible because it emits light not because it reflects it.
- The display is positioned so that it will lie in the pilot's central (foveal) field of view when he hs looking ahead outside the aircraft.

Specifically excluded by this definition, therefore, are three other types of displays which are sometimes called "head-up." One is the so-called peripheral vision display, which is designed so as not to be seen in the pilot's central cone of sight ahead of the aircraft but at the edge of his visual field -- that is, in the extrafoveal rather than the foveal field of view. Also excluded are instruments mounted either inside or outside of the aircraft within the area framed by the windshield. Because they are located at relatively short distances from the pilot's eyes and because they are not collimated, such displays do not appear at the same focal distance as the external background. They are simply situated in proximity to the center of the pilot's attention for ease of reference. Finally, the definition implicitly excludes visual aids, such as the VASI, which are not in the aircraft but on the ground. All three types of displays are not head-up in the classical sense, and they are not covered in this report.

Historically, the head-up display evolved from the gunsights used in military aircraft of the World War II period. These devices employed an illuminated reticle to produce an image which was collimated and projected on a small plate of glass situated in the pilot's line of aim to a target. Essentially they were static sighting devices whose purpose was to aid in estimating deflection angle and range.

About 1953 the Royal Aircraft Establishment at Farnborough, England undertook experiments with a head-up display in which a CRT was used in place of an illuminated reticle as the image source so as to get a display of greater flexibility. The original intent was to develop an improved gunsight for the higher speed aircraft with more complex weaponry then coming into use. A second military application envisaged at that time was a display for low altitude high speed flight. The interest at RAE Farnborough soon widened to other flight regimes, notably approach and landing where the HUD was suggested as a possible solution to the problem of operation in low visibility. A prototype approach and landing display was evaluated first at Farnborough and then by the Blind Landing Experimental Unit (BLEU) of the Royal Aircraft Establishment, Bedford. (Refs. 1,2)* Numerous investigations of the military and civilian uses of the HUD have been carried out at these two facilities in the intervening 17 years, and they are still major centers of HUD research.

The development of head-up displays in the United States began slightly later than in England and followed similar lines. The original impetus came from the desire to develop improved displays for military aircraft, particularly for weapon delivery and terrain following, and much of the early research was performed under military auspices. Initial invesitgations of a HUD for use in civil aviation were carried out by the Sperry Gyroscope Company as an outgrowth of their Zero-Reader display, which had been developed in the early 1950s. Sperry experimented with a variety of techniques in the period 1955-1960, and company-sponsored flight tests were conducted for several prototypes. (Refs. 1, 3, 4) While none of these were accepted for airline use, the Sperry program helped to refine the HUD concept and contributed to the solution of some of the basic technological problems.

A third major program which had a substantial influence on the early development of the head-up display concept was the Army Navy Instrumentation Program (ANIP). Initiated in 1953,

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* References are listed at the end of each chapter. A more extensive bibliography is provided in Appendix B.

ANIP sought to develop improved instrumentation for military aircraft. The emphasis was on an integrated, panel-mounted display known as the contact analog, which was to serve as a substitute for flight by visual reference. (Ref. 5) Although not concerned with the head-up display *per se*, ANIP did much to advance the understanding of what visual cues the pilot uses to control an aircraft and thereby helped define the form and content of future head-up displays.

From these beginnings the evolution of head-up displays proceeded with increasing momentum during the 1960s. Today many head-up displays are produced and marketed by U.S. firms, among which are Autonetics, Bendix, Conductron, Kaiser, Norden, Singer, and Sperry. In Europe the major HUD manufacturers include Specto (Smiths) and Elliott in England, CSF in France, and SAAB in Sweden. The fact remains, however, that the mainstream of HUD development has been in military fighter and attack aircraft. Head-up displays have been developed or are in the process of design for the F-111A, F-111B, A-7D/E, F-14, and F-15 aircraft in the U.S. and for the Harrier, Hunter, Meteor, Jaguar, and Sea Vixen aircraft in England. Within the past two or three years interest has also developed in head-up displays for military transport aircraft -- C-141, C-5A and the British Belfast.

In civil aviation the head-up display is still largely an experimental device. No U.S. airline now uses a head-up display on aircraft in passenger or cargo service, and no aircraft manufacturer offers a head-up display as a part of the standard instrumentation for commercial or general aviation. Interest in the HUD, however, is quite high -- especially as an aid for approach and landing in conditions of reduced visibility. The first government program to evaluate the HUD for civil aviation was conducted with a Sperry display by the FAA at the National Aviation Facilities Experimental Center (NAFEC) 1964-65. Subsequent flight testing of various head-up displays has been carried out by the FAA and NASA, and further trials are planned by both agencies. In addition, programs to develop and evaluate head-up displays for civil aviation have been undertaken privately by several display and aircraft manufacturers. (See, for example, Reference 7.) The HUD is being considered for use in the next generation of commercial aircraft represented by the Boeing 747, Douglas DC-10, Lockheed 1011, and the SST.

STUDY OBJECTIVES

In light of recent advances in display technology and extensive interest in the applications of the HUD in civil aviation, this study was undertaken with three objectives in mind:

- To take stock of the situation
- To provide information on developments and trends in the field.
- To assess the potential of the HUD for civil aviation uses.

To attain these objectives this report addresses itself to the following specific questions:

- What are the operating problems which the HUD could be expected to solve?
- What role could the HUD play in each of these situations?
- What are the performance requirements for the HUD in each of these roles?
- What is the present state of HUD technology?
- What are the related technical and practical concerns which will influence future development and use of the HUD?
- What are the major topics for further research.

METHOD

Basically, this study is a review and analysis of the technical literature published on the topic of head-up displays during the past fifteen years or so. The volume of documents is considerable, amounting to over 500 reports, articles, and scientific papers totalling several thousand pages. The principal source materials consist of reports of research studies, simulation experiments, and flight tests. Other valuable sources of information are design studies for particular displays and manufacturers' technical descriptions and publicity materials. Finally, because the head-up display has been the subject of lively debate for a long time, there are numerous articles in technical and trade journals and reports of conference proceedings which provide informed comment on technical subjects and on the more general matters of display philosophy and usage.

The bibliography appended to this report is not a complete listing of all the documents reviewed. It is limited to those which, in the author's estimation, are significant and valuable to an understanding of the subject. Among the items eliminated are minor technical notes, magazine articles of general interest only, reports dealing with engineering details of specific systems, documents containing information available in better form in other reports, and documents obtainable only from private sources.

With a body of literature so large and with such a variety of sources, the author makes no pretense to have studied it all in detail, nor even to have unearthed it all. It was neccessary to skim rather quickly through some materials, especially those dating back beyond ten years ago and those of marginal relevance. Undoubtedly some documents were overlooked, and apology is offered if any significant work seems to have been slighted or omitted.

To supplement the information available in the literature, interviews were held with persons active in head-up display research. Visits were made to NASA, FAA, Army, Navy, and Air Force research and flight test centers to discuss work in progress and to obtain background information on previous projects. The author was also privileged to spend three weeks in England and France visiting government and industry research facilities with an interest in head-up displays. A list of the organizations and agencies visited in the course of the study is provided in Appendix A.

Acknowledgement must also be made to Captain Harvey M. Thompson, Director of Flight, and Captain Edward Burke -- both of Allegheny Airlines -- for their assistance in making available a somewhat unusual but highly valuable source of information. Captains Thompson and Burke arranged for the author to ride in the cockpit on several regularly scheduled Allegheny flights so as to observe at first hand the problems of aircraft operation under a variety of weather conditions. This experience aided measurably in understanding the pilot's visual tasks and in assessing the potential of the head-up display.

SCOPE OF THE REPORT

To set the question of head-up displays within the overall context of civil aviation operations, the report begins with an examination of general operational requirements and of specific requirements for critical flight phases (Chapters II and III).

Chapter IV presents an analysis of the pilot's visual tasks and perceptual problems in critical flight phases. This is followed in Chapter V by an inventory of the present aids and methods of satisfying these requirements, with particular emphasis on their inadequacies and limitations.

These four chapters form the background for a discussion in Chapter VI of the roles which the head-up display could play and the way it might be expected to solve specific operational problems. Chapter VII covers several diverse topics -- display equipment requirements, HUD technology, and some technical and practical concerns which are not, strictly speaking, display problems but which will influence the future development and application of head-up displays. The report concludes with a summary of the capabilities and limitations of head-up displays and with a statement of the problems which remain to be solved by future research.

The scope of this report is necessarily broad since head-up displays cannot be treated as an isolated problem of technology. To assess the applicability of the HUD in civil aviation involves more than just examining the technical feasibility of a particular type of device for use in aircraft. It is also necessary to consider how the HUD is to be used and how it must fit in with other elements of the incredibily complex system of civil aviation. This is the reason for devoting almost half the report to topics which have little to do with the narrow question of display technology, but which are highly relevant to the role of the HUD and its practical value.

The report, therefore, deals with system problems and with the human factors associated with the use of the HUD in civil aviation. This is a result of the author's conviction that the chief concern is not so much whether a HUD can be developed to meet certain specifications, but what kind of display is needed to serve the pilot's needs and how is it to be used. This is not to minimize the problems of display engineering but to indicate that they are secondary to the questions of display philosophy and usage.

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1. Naish, J.M., "Display Research and Its Application to Civil Aircraft", Journal of the Royal Aeronautical Society, Vol. 69, pp 662-679, October 1965. (For the reader interested in the historical development of the head-up display concept this report is highly recommended, chiefly because it includes a transcript, pp 669-679, of the discussion which followed the presentation of the paper at a meeting of the Royal Aeronautical Society. Participants in this colloquim included nearly all the major figures active in head-up display research in England.)

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CHAPTER II

GENERAL REQUIREMENTS

Any system or item of equipment intended for use in civil aviation must satisfy three general requirements. It must be safe. It must be practical. It must be economical.

Safety is the first and dominant concern for everyone and everything connected with civil aviation. Safety is the touchstone in designing aircraft and aircraft equipment. Safety of operation is the basic principle of training programs for flight and ground personnel. Safety is the basis for most of the rules and procedures of civil air carriers. Safety underlies the regulatory structure established by the International Civil Aviation Organization and the Federal Aviation Administration. It is not too sweeping a statement to assert that everything done in an aircraft, both in flight and on the ground, ultimately reverts for justification to the question of safety. Every item of equipment, every human action, every procedure or practice must either promote safety or -- as a minimum -- not jeopardize human life and property.

It is therefore proper to set down safety as the first requirement for the head-up display and to inquire how the head-up display can serve the ends of safety. One of the arguments most often advanced in favor of the HUD is that it will promote safety by taking some of the risk out of operations such as approach, landing, or missed approach (especially in conditions of reduced visibility) where the overall safety of the existing system of instrumentation and guidance is most severly taxed. Those who are skeptical of the HUD also have reference to safety in pointing out its shortcomings. They contend that the reliability, integrity, accuracy, and other constituents of safety have not been sufficiently established for the HUD to warrant its use in civil aviation. (See, for example, Ref. 1)

How safe is the head-up display? No one really knows. Is it the key to safer operation in low visibility? It is hard to say. The reason is that safety is not a system characteristic which can be proven by logical deduction. It can only be inferred from empirical evidence. The safety of a system can only be demonstrated by statistics based on operating experience. In the case of the HUD such empirical evidence does not yet exist because the HUD has not been subjected to the trial of day-to-day usage.

While it is true that a considerable number of hours of flight experience have been amassed with experimental systems, this is not the same as regular operations. Test aircraft equipment is tuned to finer tolerances, maintenance practices are more specialized, pilots are more experienced and skilled, and the tolerable element of risk is higher in flight testing then in regular commercial service or in general aviation.

The military services also have experience with head-up displays, and some of it has been under conditions more nearly like those characteristic of civil aviation. However, here too, caution is required. Safety, although a major concern in military systems, is not always the prime concern. In combat operations accomplishing the mission comes first, and this will permit taking risks which are unacceptable in civil aviation. This is not to say that the military services are indifferent toward safety. Rather, their priorities are not the same as those of civil aviation, and the more strenuous uses to which military aircraft are put (both for combat and training purposes) dictate lower margins of safety. Since the operation is essentially riskier, the safety of military crewmen is assured in a different way. For instance, fighter and attack aircraft are equipped with ejection systems. If all else fails, the crew can escape from the aircraft. The same is not true of civil aviation, discounting those few general aviation aircraft which may be equipped with parachutes. Military transport aircraft come much closer to civil aircraft in their operating philosophy; but as noted in Chapter I, no experience with head-up displays has yet been accumulated in military transport operation. For these reasons it seems prudent not to go too far in extrapolating from military experience.

It is reasonable to conclude that the case of the head-up display will have to be tried in large measure on the question of safety. In the subsequent examination of head-up displays in this report safety is a paramount factor to be considered.

The question of the head-up display involves more, however, than safety of flight. To play a role in civil aviation, the HUD must also gain acceptance on practical grounds; and practicality implies many things. First and foremost there is the matter of utility. The HUD must be a working part of the total aircraft system. It must either extend the operational capability of the aircraft or enable the pilot to accomplish tasks within the present operational envelope more easily, more accurately or more consistently. To put it another way, the HUD must qualify on the same grounds as every other item of instrumentation which has been introduced into the cockpit over the years -- it must lead to some improvement in system performance.

There are other aspects of practicality to be considered. If the HUD is to be used as a supplement to or a substitute for existing flight instruments, it must have at least the same degree of validity and integrity as that which is now in the cockpit. If the HUD is to permit correct and precise control of the aircraft flight plan, it must be accurate. If it is to serve as the pilot's primary flight reference, the HUD must perform as needed and when needed, i.e., it must be reliable. Finally, it must be possible to keep the HUD in an operating state and (in case of failure) to return it to an operating state with a modicum of maintenance activity. That is, the HUD must exhibit the two characteristics of good maintainability -- high MTBF and low MTTR.

The criterian of practicability, therefore, embraces several system engineering characteristics. Among these are:

Utility - the usefulness and operability of the HUD;

Integrity - the "truthfulness" of the HUD as a flight instrument;

Accuracy - the precision with which the HUD indicates the flight situation;

Reliability - the degree of confidence one may have in the HUD continuing to function correctly;

Maintainability - the activity necessary to keep the HUD in, or restore it to, working order.

Integrity, accuracy, and reliability were mentioned earlier as factors relating to the safety of the head-up display, and it may seem logically inconsistent to cite them again here as elements of practicality. Actually, there is a case to be made for including them under either heading. For example, the reliability of the head-up display affects its safety. If the display fails during a landing, the pilot may be placed in a situation from which he cannot extricate himself, with resulting jeopardy or even catastrophe for the passengers and the aircraft. On the other hand, reliability also has an impact on the usefulness and practicality of the HUD. A display that does not work properly is simply so much excess baggage in the cockpit. The pilot cannot use it. And it poses an extra burden of work and cost for the ground crews to maintain it. It is plainly unsafe <u>and</u> impractical to place one's confidence in a display which fails too frequently. The same can be said for accuracy and integrity, and there is little to be gained in contending that they are either safety factors or practical factors when they are so clearly both.

Safety and practicality are not mutually exclusive standards. They are merely two ways of looking at a system. In one case the question is "What risks do I run in using the system?" In the other, "Will the system make my tasks easier or will it allow me to accomplish something I cannot now do at all?" If some of the evidence is pertinent to both questions, so much the better. If safety and practicality involve some of the same considerations, it is merely a reflection of the way in which system characteristics are interrelated, sometimes to the point where they cannot be neatly extricated.

The third general requirement to be set alongside safety and practicality is economy. Before the directors of an airline or the owners of general aviation aircraft buy the head-up display, even if wholly persuaded of its merits on the grounds of safety and practicality, it is reasonable to expect them to ask how much it will cost.

The head-up display is a relatively expensive instrument. It may run between $15,000 and $35,000 per unit, depending upon the complexity of the display and the quantity purchased. Moreover, for the foreseeable future the HUD is not intended as a replacement for any of the existing cockpit instruments, but as a supplement to them. This means that the HUD is an extra item of expense which cannot be offset by savings on other cockpit equipment. Further, the HUD is a complex piece of equipment, calling for specialized maintenance procedures and tools. Thus, the HUD represents an add-on cost in out fitting the aircraft initially and in maintaining it in good working order. It seems likely, therefore, that the reluctance of commercial and general aviation to accept the HUD stems, at least in part, from a very real concern about its cost.

Cost, however, is not a concern which is unique to civil aviation. Cost is also an important factor in decisions on the procurement of military systems. One of the puzzling facts about the head-up display is that of the two major potential users of the head-up display, the military services and the civilian air carriers, one seems to have accepted the HUD concept wholly and the other has been reluctant to give it even a limited trial. The usual explanation is that "things are different between military and civilian operations". This may be true, but only to a degree. An enlightening comparison of military and civilian aviation has been offered by C.O. Miller (Ref. 2), the major elements of which are set forth in Table I.

Although Miller was addressing the subject of system safety, two of his major points apply generally to the differences between military and civil aviation points of view. First, the purpose, motivation, and business relationship present in the air carrier system produce a cost consciousness far greater and less flexible than in the military. This means that proof of cost saving through increased operating efficiency or improved system safety is more essential in the commercial air carrier system. Second, there is a definite lack of a systems approach in the relationship among the equipment manufacturer, the airline operator, and the Federal Aviation Administration. Each tends to view the operation of the system with a parochial interest -- sales for the manufacturer, proftable operation for the air carrier, and regulatory responsibility for the FAA. Since it is the air carrier who must purchase the equipment -- head-up display or whatever -- it is natural that the acquisition and operating costs should be related to the air carriers' prime concern, the profitability of air transportation service.

A simple calculation will illustrate the point. Assuming that a head-up display certificated for commercial air carrier use would cost about $35,000 per unit (including the pro-rated cost of special maintenance equipment) and assuming that 100 units would be needed to equip a fleet and have a suitable reserve of spares, the initial acquisition would be on the order of $3.5 million. This amount is about the same as the purchase price of a medium-size jet aircraft. To justify such an expenditure the airline would have to find some realistic way of equating the potential revenue of an additional aircraft in the fleet (less purchase and operating costs) with the benefits expected to accrue from using the head-up display (also less purchase and operating costs). The benefits of the HUD might take the form of increased operating efficiency for the

TABLE I

ITEM	MILITARY	CIVILIAN
1. Objective	National defense	Air transportation service to the community at a profit
2. Size of Operation	USAF alone flies about 7 million hours per year	US carriers operate a little over 3 million hours per year
3. System Elements a. Personnel	Relatively low paid; Transient assignments; Average skill level lower	Can be highly selective; Stable employment at relatively high cost and skill level
b. Operational Procedures	Can and will compromise safety as mission requirements dictate; Procedures planned early in program life cycle	Safety is foremost consideration; Criteria do not fluctuate appreciably; Procedures often not developed until after aircraft delivery
c. Test and Acceptance Programs	A negotiated effort to specific requirements for a given program; Usually more rigid than previous programs	Adherence to minimum standards; Evaluated by a regulatory agency not necessarily the customer
4. Business Relationship Between Contractor and Customer	A major system rarely developed and sold except in response to a specific proposal request; Development costs not a high risk to the contractor	Private enterprise in relatively pure sense; Product is developed on company funds; Capital risk is extensive; Extreme competition on price
5. Management Concept	Total package managed by a single command at least through acquisition phase and early operations; Integrated transition between acquisition and operation phases; Contractors deal with only one customer at a time	Relatively sharp dividing line between acquisition and operation; Varied customer desires produce very complicated baselines for system control
6. Specifications/ Standards	Usually highly rigid and comprehensive — almost to a fault	FAA provides minimum standards which are exceeded only as dictated by the conscience and technical excellence of the contractor or operator
7. Motivation for Safety (in order)	(1) Mission accomplishment (2) Economics (3) Moral	(1) Economics (2) Moral (3) Mission accomplishment

(Adapted from Miller, Ref. 2)

aircraft so equipped or the less tangible (and harder to prove) advantage of improved safety. Somehow the trade-off would have to be made. It would be surprising that a management as cost-conscious as an airline, with experience in calculating cost and revenue down to the seat-mile, would accept the head-up display without some very sound evidence as to its value.

The cost of the head-up display may be an even more significant consideration in general aviation. Although it is hard to generalize bacause of the variety of motives for which general aviation aircraft are owned and operated, it can be said that general aviation is not a revenue-producing activity. The aircraft are flown either for pleasure, for convenience, or -- in a few cases -- for the purpose of economizing on air travel costs. The financial resources of general aircraft owners, either individually or collectively, are less than those of commercial air carriers. With smaller budgets and with no offsetting revenue from the aircraft, general aviation tends to be skeptical of any new item of equipment (especially one as costly as the head-up display). Unless it can be shown that the advantages in terms of safety and increased operating capability are significant and clear-cut, it is likely that general aviation will regard the head-up display as a prohibitively expensive item. A representative of the National Business Aircraft Association has stated that NBAA members tend toward the view that the head-up display is "nice to have but not necessary". (Ref. 3) This attitude is probably characteristics also of other portions of the general aviation community.

To summarize, the head-up display must satisfy the three general requirements of safety, practicality, and economy if it is to gain acceptance in civil aviation. From some of the discussion in this chapter, particularly that concerning cost, it may seem that these three requirements pose a dilemna. That is, the question may appear to be how to weigh safety and practicality vs. economy. This is too simple a view. Safety, practicality, and economy are not antagonistic, even though they are not always fully compatible. Nor are they the only factors to be considered. They are but three elements in a complex equation. They are three general criteria by which to judge the merits of the head-up display, but they are not the only criteria. Attention must now be directed to more specific and technical questions, relating to the applicability of the HUD to civil aviation. The next chapter deals with some of the problems of aircraft operation in specific flight phases and environmental conditions and sets forth some additional requirements for the head-up display.

However, before embarking on a discussion of technical subjects, a brief examination of some statistics is in order to establish the magnitude of the safety problem and to identify areas where the head-up display might make contributions of greatest significance.

Table II is a summary of aviation accidents in 1967 and 1968, the last two years for which figures are available. Of the 127,164 aircraft in use in 1968, about 98% were general aviation aircraft. General aviation also accounted for nearly all the accidents (95.6% in 1967 and 98.6% in 1968). Likewise, fatal accidents occurred in similar proportion, general aviation accounting for about 98% in both years. Comparison of accident rates per 100,000 hours of operation, however, shows a dramatic difference between general and commercial aviation. The accident rate in general aviation is about 20 times that in commercial aviation.

TABLE II

	1967	1968
ACTIVE AIRCRAFT		
General Aviation (est.)	114,186[1]	124,237[1]
Air Carrier	2,595	2,927
Total	116,781	127,124
ACCIDENTS (all types)		
General Aviation	6,115	4,968[2]
Air Carrier	70	72
Total	6,185	5,040
FATAL ACCIDENTS[3]		
General Aviation	603	692
Air Carrier	12	16
Total	615	708
ACCIDENT RATE (per 100,000 hrs.)		
General Aviation	27.6	20.6[2]
Air Carrier	1.18	1.11
FATAL ACCIDENT RATE (per 100,000 hrs.)		
General Aviation	2.7	2.9
Air Carrier	0.203	0.246

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[1] Includes gliders, helicopters, balloons and blimps.

[2] As of 1 January 1968, the definition of accident was made more restrictive, with the result that some minor accidents included in statistics for 1967 were excluded in 1968.

[3] Refers to the number of accidents involving a fatality, not the number of persons killed.

(Based on NTSB and FAA statistics)

These comparisons are somewhat deceptive, however, since the general aviation category includes such a wide variety of aircraft and implies a very broad range of pilot skills, maintenance practices, and types of operation. Table III, which presents accidents by flight phases, segregates small from large fixed-wing aircraft and excludes other general aviation vehicles such as gliders, helicopters, balloons, and blimps. The large fixed-wing category (maximum gross takeoff weight over 12,500 lbs.) includes mostly corporate and business aircraft and represents a class much more like air carriers in terms of size, maintenance practices, amount of instrumentation, pilot experience and skill, and type of use.

Table III shows that the larger general aviation aircraft and air carriers had roughly the same number of accidents in 1967 and 1968 and that these accidents were similarly distributed with respect to the flight phase when they occurred. In all cases but one (air carrier in-flight accidents 1968), approach and landing accidents outnumber those in any other category. Approach and landing account for between 40% and 60% of the accidents for all kinds of aircraft in both years. The only other phase close to landing in the number and percentage of accidents is flight, which in the definition used by the National Transportation Safety Board in compiling these statistics includes descent from altitutde and the initial portion of the approach. If this is taken into account, approach and landing is the most dangerous portion of flying. This is borne out by other NTSB figures which indicate that over half of all accidents occur within 5 miles of the airport. (Refs. 4,5)

Three additional statistical findings are of interest. Over 90% of all accidents occur in VFR conditions. About 85%

TABLE III

FLIGHT PHASE	1967			1968		
	General Aviation[1]			General Aviation[1]		
	Small Fixed Wing[2]	Large Fixed Wing	Air Carrier	Small Fixed Wing[2]	Large Fixed Wing	Air Carrier
STATIC	54	1	0	30	0	6
TAXI	364	0	5	199	2	5
TAKEOFF	955	12	6	812	9	4
FLIGHT[3]	1206	18	28	1179	7	29
LANDING[4]	3186	23	31	2380	24	28
UNKNOWN	45	2	0	65	0	0
TOTAL	5810	56	70	4665	42	72

[1] Accidents involving gliders, helicopters, balloons, and blimps are excluded.

[2] Less than 12,500 lbs. maximum gross takeoff weight.

[3] Includes climb to cruise, cruise, and descent to approach.

[4] Includes final approach.

(Based on NTSB and FAA statistics)

of all accidents happen in daylight hours. Pilot error is a cause or a contributing factor in about 80% of the cases. These generalizations hold true for commercial as well as general aviation, and they have been substantially the same over the past few years.

Three major points emerge from these statistics. First, in terms of the safety record, large general aviation aircraft are not distinguishable from commercial air carriers. By inference it can be concluded that whatever may be said about the problems of commercial aviation will apply to large general aviation aircraft as well. Further, whatever solutions the head-up display may offer for particular operating problems will be relevant to both of these classes of aircraft. Second, it is clear from the safety record that most of the operating problems are related to approach and landing. This is no surprise since the research literature and informed comment in the aviation industry stress the problems of approach and landing above all other phases of flight. The safety record may therefore be taken as additional confirmation of the prime importance of approach and landing problems. Third, these problems exist in both the VFR and IFR regimes, although certainly to different degrees. Approach and landing in conditions of reduced visibility have received by far the greatest share of attention, and most of the industry effort has been directed toward improving IFR systems; but the safety record clearly shows that approach and landing in VFR also poses serious problems. For these reasons this study will address itself to both commercial and general aviation applications of the head-up display and will concentrate on both VFR and IFR approach and landing.

An additional indication of the nature of the problems to considered and of their consequences is afforded by a recently lished analysis of 20 airline accidents. (Ref. 7) A summary of this analysis is presented in Table IV. In most of the accidents considered the investigators stated or strongly implied that the "human factor" contributed to the accident. In about half of the cases the probable cause was a combination of events, each of little consequence by itself, but dangerous when taken together. The human factor entered through the crew's inability to perceive or observe certain elements of information or their failure to comprehend the meaning in time for corrective action. The basic problem, as characterized by the author of the referenced study, was "information transfer and processing". That is, a failure occurred in the link between man and his source of information either outside or inside the cockpit.

TABLE IV

CARRIER & AIRCRAFT	LOCATION & DATE	ACCIDENT REPORT STATEMENT OF PROBABLE CAUSE	HUMAN FACTORS	COMB. OF FACTORS	SENSORY ILLUSION	ALT. READING	SINK RATE	MOTION CUES	EXCESS YAW	UNK. MALFUNCTION
American Electra	New York 2-8-59	Misread altimeter. Human tendency to assume conformance.	●		●	●				
American B-707	New York 8-15-59	Crew failed to recognize and correct development of excess yaw, which resulted in subsequent loss of control.		●					●	
Delta CV-880	Atlanta 5-23-60	A large amount of yaw to the right was present along with considerable skid or slip. The aircraft stalled, for reasons undetermined, at an altitude too low to effect recovery.	●	●					●	
Sabena B-707	Brussels 2-15-61	It was impossible in the time available, and under the circumstances in which the crew found itself, to identify with certainty the failures with which it was confronted.								●
KLM DC-8	Portugal 5-30-61	Not possible to establish. It was recommended that it be more essential than ever that the entire complex of cockpit equipment and cockpit procedures should be such as to ensure the timely detection of any defects in instruments or pilot errors.	●	●						●
Air France Caravelle	Morocco 9-11-61	Pilot made the error of 1000 ft at the beginning of the descent, then gave his full attention to reading the pointer.	●			●				
KLM DC-8	Lisbon 10-29-61	Pilot-in-command's dereliction with respect to approval of an excessively low approach.							●	●
American B-707	New York 3-1-62	Crew failed to detect malfunction, distracted by departure procedures. Excellent weather conditions.	●	●				●		
Northwest B-720B	Miami 2-12-63	Causal area involved man-machine environment relationships. A classic illustration of the man-machine	●		●					

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6. Flight Safety Foundation statistics based on figures published by the National Transportation Safety Board and the Federal Aviation Administration for the years 1967 and 1968.

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CHAPTER III

SPECIFIC OPERATIONAL PROBLEMS AND REQUIREMENTS

Specific operational problems and requirements are discussed in this chapter under three main headings: Approach and Landing, Other Flight Phases, and Aircraft-Peculiar Requirements. No attempt is made to offer a rigorous and complete analysis of aircraft operations nor to present a comprehensive list of requirements. Rather, the intent is to identify only the major elements of the flight situation which affect control of the aircraft and which consequently influence pilot performance. The purpose of this discussion is to single out problem areas and to describe the circumstances where the head-up display might contribute to safer or more effective aircraft control. These are requirements in the sense that they represent desired, or desirable, uses for the head-up display. An examination of how the head-up display might meet these requirements is deferred until Chapter VI.

APPROACH AND LANDING

The Site

A discussion of the approach and landing problem must begin with a description of the site, the runway itself. This is the pilot's visual target, and it constitutes the single most important element of the approach and landing situation.

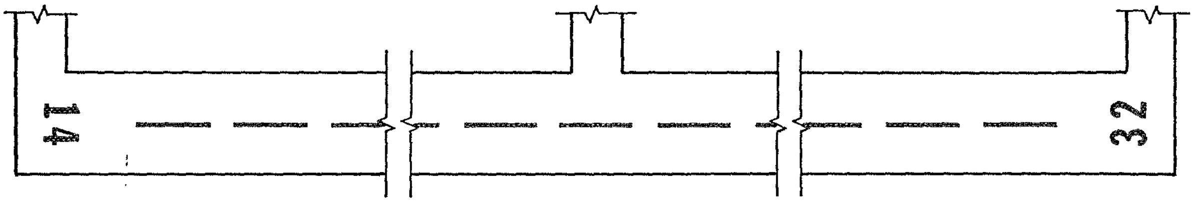
There is no such thing as a standard runway. There are only minimum standards for runways, depending upon the type of aircraft which may use them and the conditions of visibility in which they may be used. These standards are set down by the Federal Aviation Administration in the form of recommendations to the public in the interest of safety, regularity, or efficiency of aircraft operations. (Ref. 1) Generally, there are three types of runways:

1. Basic Runway - used for operations under Visual Flight Rules.
2. Instrument Runway - served by a non-visual navigation aid and intended for landings under instrument weather conditions.
3. All-Weather Runway - served by non-visual precision approach aids, such as ILS, and characterized by special operational requirements.

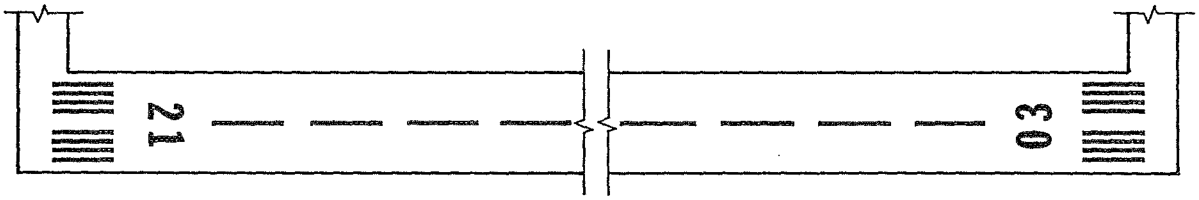
The configuration of the three types of runways and their characteristic markings are shown in Figure 1.

Despite the apparent regularity, there is actually a great deal of variation in runway characteristics. Runway length may range from 5,000 to 10,000 feet, or even longer in a few cases. Runway width may be between 100 and 200 feet. The consequences of this are that the shape of the runway, as viewed from the pilot's vantage point on the approach, varies in its critical dimensions. That is, while the runway always assumes an apparent trapezoidal shape when viewed in perspective, the height of the trapezoid (runway length) and the width of the base (runway width at the approach end) are not necessarily the same from one runway to another.

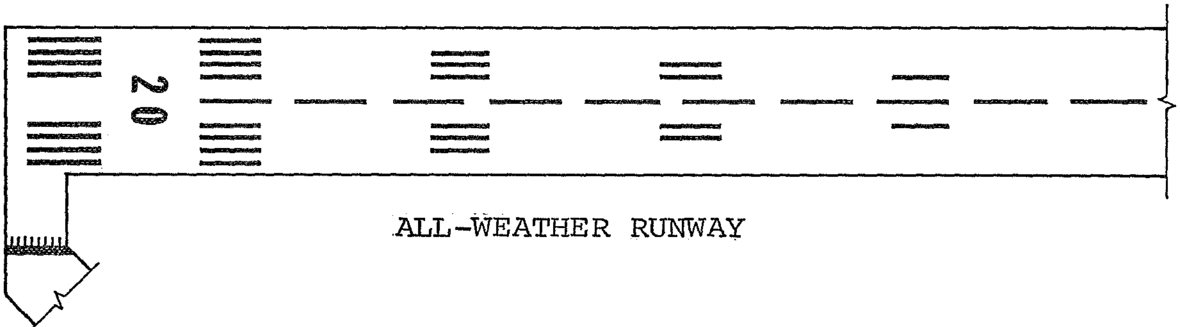
If this were the only source of variation in apparent runway geometry, there would be no problem. However, the apparent size of the runway is also a function of other parameters which are highly important in managing the approach. These parameters which the pilot has under his control, in contrast to those of



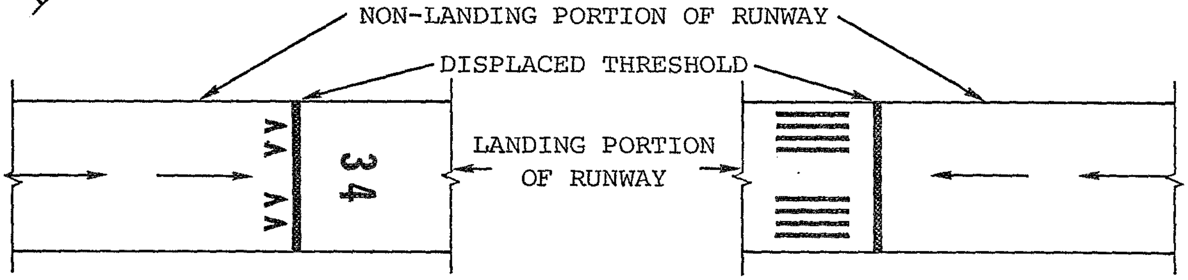
BASIC RUNWAY



INSTRUMENT RUNWAY



ALL-WEATHER RUNWAY



BASIC RUNWAY

INSTRUMENT AND
ALL-WEATHER RUNWAY

DISPLACED THRESHOLD MARKINGS

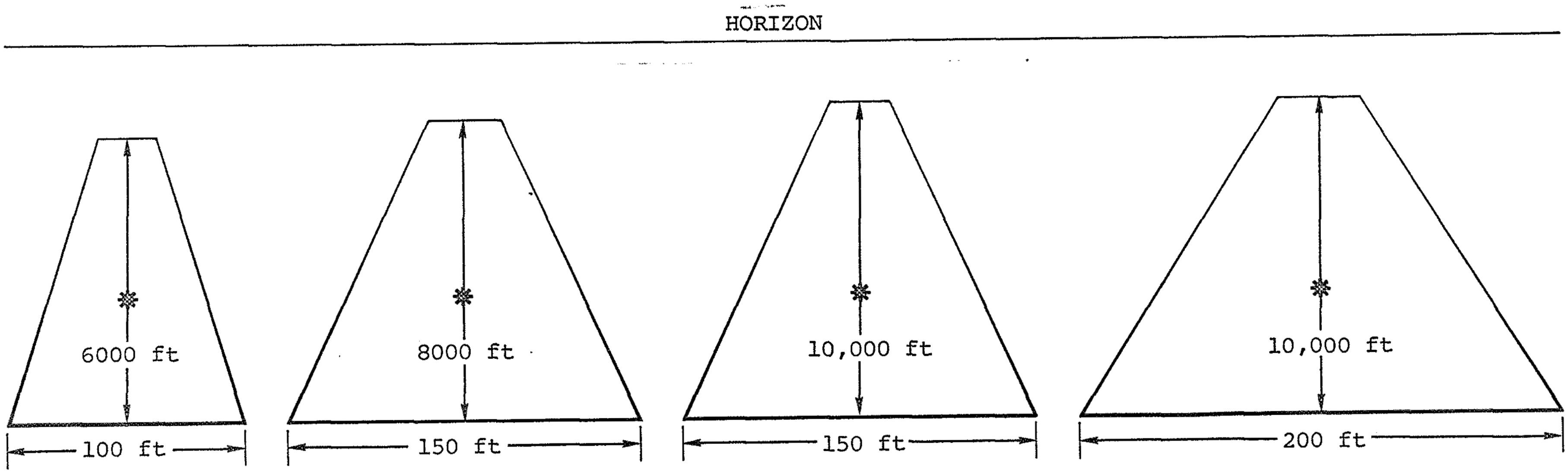
(Adapted from FAA, Ref.1)

Figure 1

the runway which he does not. Among these are the distance to the runway, the angle of the approach slope, and altitude. Thus, the variability of runway length and width introduces an element of ambiguity in the pilot's visual reference. Without knowledge of the actual physical dimensions of the runway and some experience with a runway of this size, the pilot cannot be certain, <u>from visual reference alone</u>, whether the apparent shape of the runway is due to runway variables or to the altitude, distance to the runway, and angle of the approach slope. Illustrations of this ambiguity of shape are given in Figures 2 and 3.

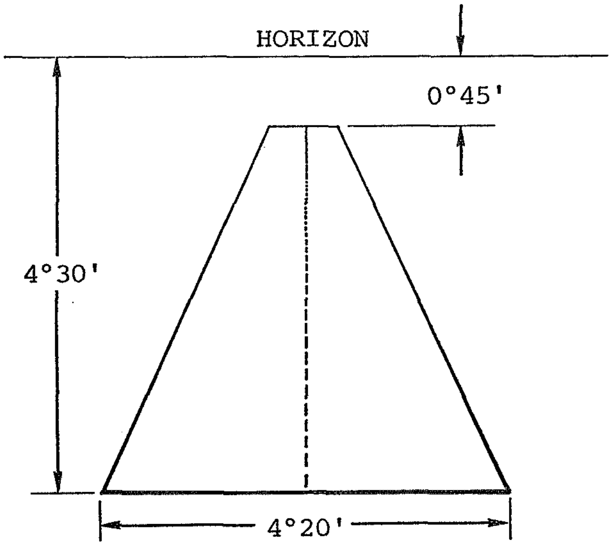
Many reports in the literature which discuss approach and landing make reference to a so-called "standard" runway. As pointed out, the "standard" runway does not exist. Usually what is meant is the All-Weather Runway shown in Figure 1 above. For the sake of simplicity and consistency with this practice, this report will use the All-Weather Runway as the basic model for subsequent analysis of the approach and landing problem. The All-Weather Runway, which is shown in perspective view in Figure 4, shall be assumed to be 10,000 feet long and 150 feet wide. In fact, it may be 7,000 to 10,000 feet in length. It is generally 150 feet wide, although some may be wider (up to 200 feet). According to FAA standards, the All-Weather Runway is marked with reflective white paint intended to make the landing area more conspicuous and to provide enhanced visual indications for approach and landing. These markings, shown in Figure 4, include the threshold, runway direction number, centerline, landing zone bars, and side stripes. (Ref. 2)

It must be emphasized that, while the All-Weather Runway will be used as a model, it is not the most common type of runway. Probably no more than 15% of the runways used by civil



All sketches depict the runway as seen at a distance of 2000 feet from the threshold on a 3° glide slope to a point (❋) 1000 feet beyond the threshold.

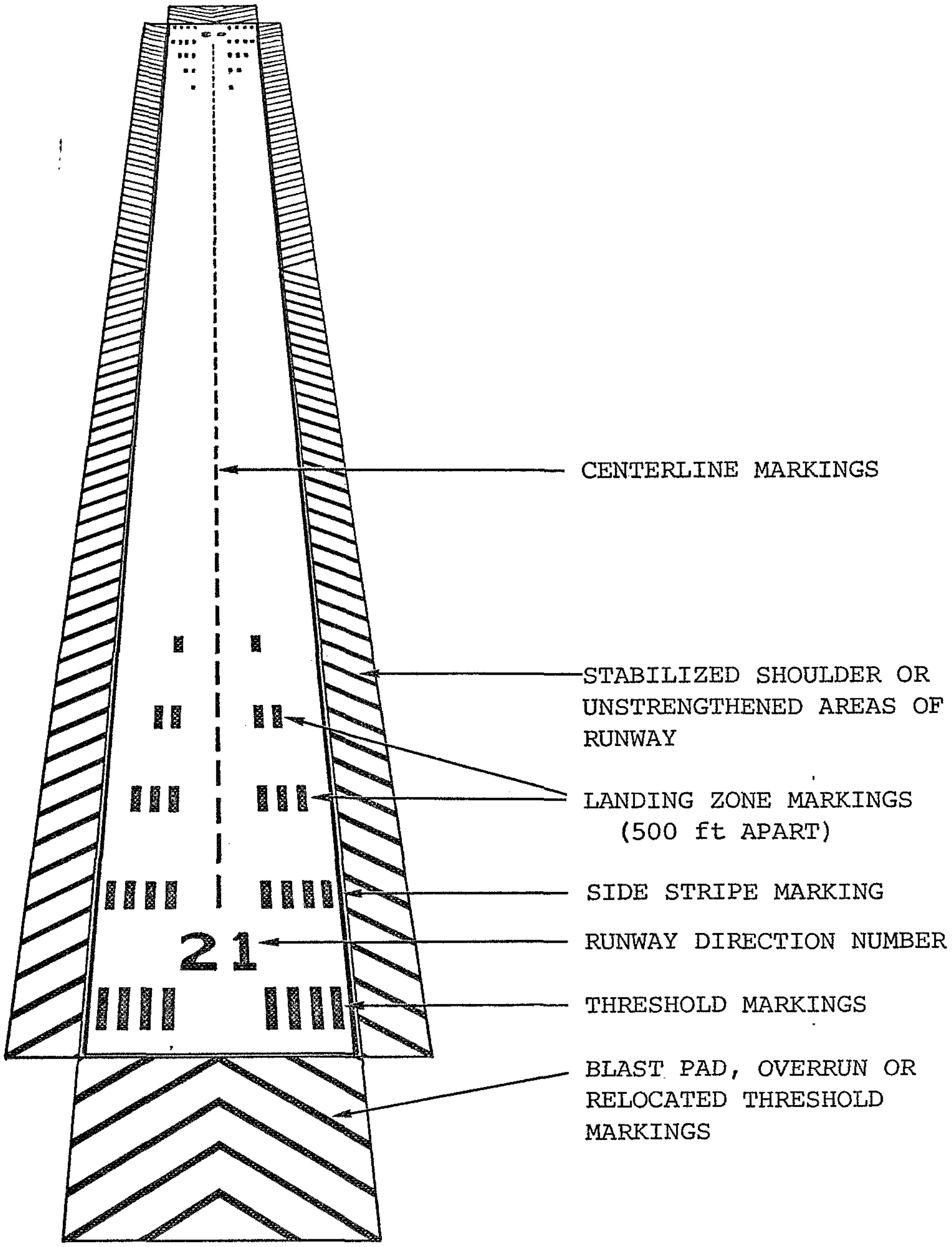
Figure 2



Runway geometry as seen under each of the following conditions

	A	B	C	D
RUNWAY LENGTH	6000 ft	8000 ft	10,000 ft	10,000 ft
RUNWAY WIDTH	100 ft	150 ft	150 ft	200 ft
DISTANCE TO RUNWAY	1300 ft	2000 ft	2000 ft	2700 ft
ALTITUDE	100 ft	130 ft	157 ft	210 ft
GLIDE SLOPE	2 1/2°	2 1/2°	3°	3 1/4°

Figure 3



(Adapted from White, Ref. 2)

Figure 4

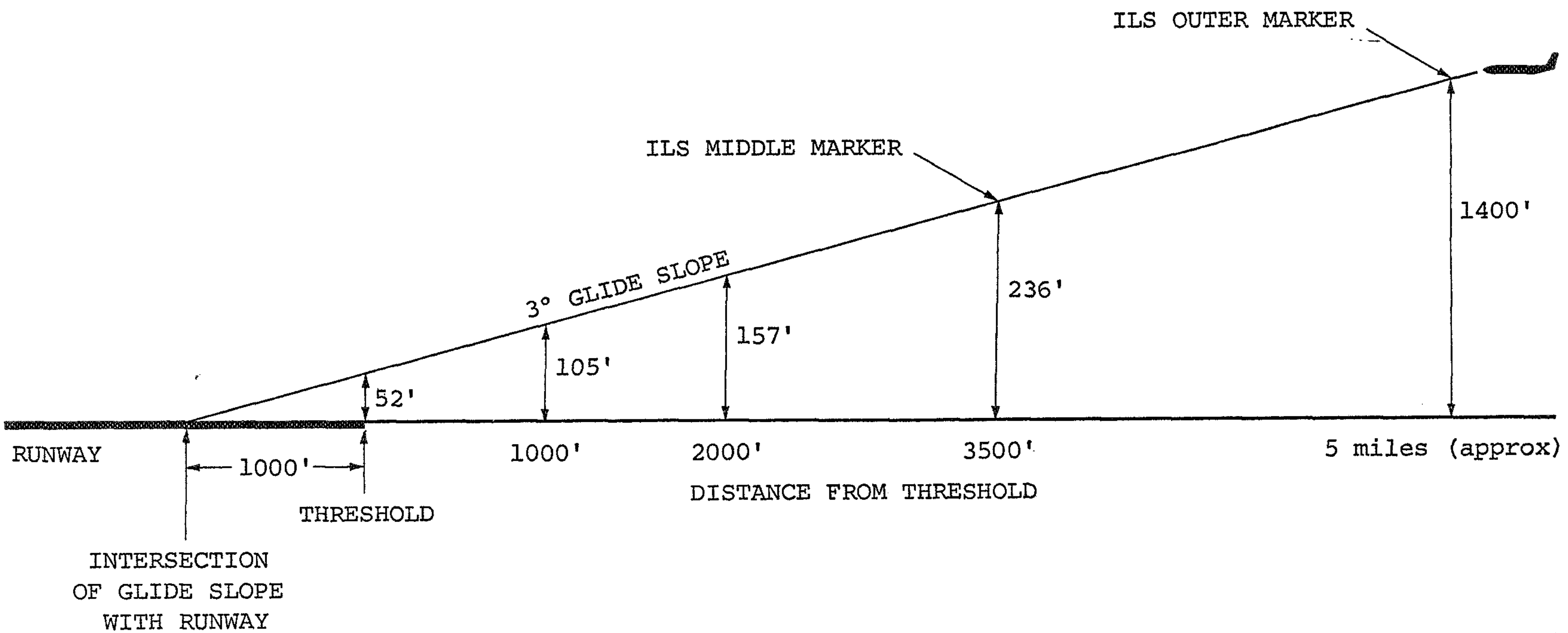
aircraft are of the all-weather type. Aside from the reasons of consistency with the literature, this runway has been selected as a model because it represents a best-case condition. That is, the All-Weather Runway is the best that the pilot can expect to encounter, and any subsequent discussion of the visual problems in using this type of runway will apply equally to other runway types of lesser quality.

The Approach

Approach is a broad term which may cover a portion of the decent from en route altitude and penetration of the terminal area as well as the final approach to the runway. This discussion is confined to the final approach, which under VFR conditions refers to the flight path of the aircraft in the direction of landing along the extended runway centerline from the base leg to the runway. The final approach for IFR is the flight path of the aircraft inbound to the airport on a final instrument approach course, beginning at the final approach fix and extending to the airport. (Ref. 1)

Essentially, both the VFR and IFR final approaches are straight line flight paths to the runway commencing at a distance of between 4 and 7 miles from the runway and at an altitude between 1000 and 2000 feet above the runway elevation. The variation in distance from the runway and altitude at which the final approach is begun is the result of differences in airport sites, the aircraft, the type of approach (VFR or IFR) and the angle of the approach slope. A typical approach geometry is illustrated in Figure 5. Table V shows some of the important parameters of the approach.

The pilot's tasks in controlling the aircraft on the



(Angles and distances not to scale)

Figure 5

TABLE V

A. SLANT RANGE TO RUNWAY AIMPOINT (ft)

ALTITUDE (ft)	GLIDE SLOPE		
	2 1/2°	2 3/4°	3°
300	6879	6258	5733
200	4586	4172	3822
150	3440	3129	2866
100	2293	2086	1911
50	1146	1043	956

B. ALTITUDE AT SELECTED DISTANCES FROM THRESHOLD* (ft)

DISTANCE (ft)	GLIDE SLOPE		
	2 1/2°	2 3/4°	3°
3500	197	216	236
2000	131	144	157
1000	87	96	105
0	44	48	52

* Aiming point is assumed to be 1000 ft beyond threshold

C. RATE OF DESCENT (ft/min)

SPEED (kts)	GLIDE SLOPE		
	2 1/2°	2 3/4°	3°
90	400	440	475
100	442	486	530
110	485	535	585
120	530	583	636
130	575	630	690
140	620	680	742
150	665	730	795

D. TIME FROM 200 ft ALTITUDE UNTIL OVER THRESHOLD (sec)

SPEED (kts)	GLIDE SLOPE		
	2 1/2°	2 3/4°	3°
90	23.5	20.9	18.6
100	21.2	18.7	16.7
110	19.2	17.0	15.2
120	17.2	15.6	13.9
130	16.2	14.4	12.9
140	15.1	13.4	12.0
150	14.1	12.5	11.2

approach can be divided into two classes: control in the vertical plane and control in the horizontal plane. The major elements of control in the vertical plane are airspeed, angle of attack, altitude, rate of descent, and flight path angle. Approach speeds vary for different aircraft and for the same aircraft with changes in weight. For large jet transports approach speeds of 130-140 knots are typical. Approach speeds for smaller, propeller aircraft are generally lower; 110-120 knots is typical, but approach speeds may be under 100 knots for aircraft with gross landing weights of 12,000 to 15,000 pounds.

Speed, rate of descent, and flight path angle are interrelated such that, given a speed and rate of descent, a certain flight path angle will result. Thus, from Table Vc it can be seen that an approach speed of 140 knots and a rate of descent of 620 feet per minute will produce a flight path angle (glide slope) of 2-1/2°. Conversely, a given speed and glide slope will determine the rate of descent. Again referring to Table Vc a speed of 120 knots on a 3° glide slope will produce a rate of descent of 636 feet per minute (or about 10-1/2 feet per second).

Speed also plays a part in determining another important factor of aircraft control in the vertical dimension, angle of attack. Angle of attack is the angle formed by the chord of the airfoil (wing) and the relative air velocity (relative wind). Angle of attack, pitch attitude, and flight path angle are related as follows:

$$\alpha = \Theta = \Gamma$$

where: α = angle of attach
Θ = pitch attitude
Γ = flight path angle

More importantly, a given speed (thrust) and pitch attitude will produce a particular angle of attack, and hence flight path angle.

Angle of attack is especially important in transport jet aircraft because of their characteristic high angle of attack in the approach configuration. That is, approach in a jet aircraft is conducted in a nose-up attitude while on a descending flight path. Thus, for approach on a 3° glide slope a large jet may fly at 5° to 6° angle of attack (a 2° to 3° nose-up attitude). This approaches the unstable, semi-stall condition sometimes called "flying the back side of the power curve." Raising the nose causes the aircraft to decelerate to a lower speed where more power is required to stablilize. If no more power is available, the aircraft can accelerate only by losing altitude. (Ref. 3) To put it another way, any mismanagement of power or undetected loss of speed on the approach can result in an increased angle of attack (assuming the aircraft does not change pitch attitude) and a consequent increase in the rate of descent (a steepening of the flight path angle). If this occurs at low altitude, it can result in landing short of the runway. For example, an increase of 2° in angle of attack will increase the rate of descent by about 5 feet per second. If this took place on a 3° glide slope at an altitude of 200 feet and were allowed to go uncorrected, it would result in a touchdown about 275 feet short of the runway.

To summarize, control of the aircraft in the vertical plane during the approach is a precise and demanding task, probably one of the most in civil aviation. It calls for very delicate management of speed and rate of descent (or angle of attack and flight path) in a circumstance which allows very little margin for error and time for reaction. At typical jet approach speeds the time for the aircraft to descend from an altitude of 200 feet to the point where it crosses the runway threshold is on the order of 12-14 seconds. During this time the aircraft has travelled a distance along the ground of about 3000 feet.

The other aspect of managing the aircraft in the approach is control in the horizontal plane. This involves two major elements: holding a proper roll attitude (wings level) and maintaining the lateral alignment of the flight path (ground track) with the extended runway centerline. The latter task, while probably not as difficult as control in the vertical plane, can be extremely complicated if the approach is made in a crosswind. The crab angle which the pilot must hold to compensate for a crosswind introduces difficulty in the task of estimating ground track and alignment with the runway centerline, particularly under conditions of reduced visibility. Moreover, since wind speed and direction are seldom constant during the approach, the pilot must continually reassess and counteract the effect of crosswind.

The problem of aircraft control in wind is further complicated by wind shear and backing. Captain D. M. White, an airline pilot, offers the following discussion of the difficulties associated with these phenomena. (Ref. 4)

> "Wind shear is the change of velocity of the wind in direction or speed with either horizontal distance or vertical distance, or both. It is expressed in knots per hundred feet. For example, if the velocity changed from a 10-knot headwind at 100 feet to a 5-knot headwind on the surface, this would be a 5-knot shear. Wind shear will affect an airplane on both landing and takeoff and may be experienced along a cold front or a pressure trough, in the vicinity of thunder-

storms, when nocturnal inversions occur, and particularly where there is a tight pressure gradient or a steep temperature inversion near the surface.

"Due to the intertia of a large airplane, anytime it traverses an area where it encounters a change from one wind velocity to that of another in less time than it takes for the aircraft mass to become adjusted in speed to the new environment, there will be a resultant change in the plane's airspeed. For example, if an airplane were descending at 140 knots IAS with a direct 20-knot tailwind, its ground speed would be 160 knots. If it instantaneously encountered a calm wind condition, due to the inability of the aircraft to immediately overcome it inertia, the ground speed would tend to remain at 160 knots also. If the aircraft is not properly decelerated, there will be a resultant increased angle of attack, a high flight path over the threshold, excessive airspeed to be bled off, and a landing well down the runway from the desired touchdown point.

"Conversely, if an aircraft were descending at 140 knots airspeed with a 20-knot headwind, its ground speed would be 120 knots. If it instantaneously experienced a calm wind condition, the ground speed would tend to remain substantially the same, but the indicated airspeed would tend to drop off toward 120 knots. To overcome the intertia of a large turbo jet in this case, there must be an application of power to regain airspeed plus a special effort to keep the nose up, or the airplane will sink below the glide slope and land short of the touchdown aim point.

"Most of the wind shear encountered is not of this instantaneous nature, and in most nonsevere wind shears, rapid reduction or application of power, as the case may be, has prevented an incident or an accident.

> "Interrelated with wind shear, there may also be the problem of the backing of the wind. In the free atmosphere, the wind blow approximately parallel with the isobars, the lower pressure being to the left. Descending below the gradient level, surface friction will not only reduce the wind speed, but will cause the direction to flow somewhat across the isobars toward the lower pressure. This counter-clockwise backing of the wind will occur from about 3,000 feet to approximately 300 feet, and as high as a 70-degree change has been noted. A descending aircraft under these conditions would be experiencing a constantly changing effective wind component that, when coupled with a definite wind shear, could easily further compound the problem by causing lateral displacement from the centerline."

Although horizontal and vertical control have been treated here as separate aspects of the pilot's overall management of the approach, they are obviously interrelated. Aircraft dynamics are such that any perturbation in one axis of control produces effects in the other. White has offered the example of how wind velocity influences airspeed and, hence, the vertical flight path angle. The converse is also true. Any change made by the pilot in the power setting will affect airspeed, which in turn will alter the crab angle necessary to maintain lateral alignment with the runway in a crosswind. In a similar fashion, heading (bank angle) changes made to correct for ground track error will produce momentary changes in angle of attack and, consequently, flight path angle.

Horizontal and vertical control must be considered as interrelated and simultaneous tasks for the pilot. However, in passing it should be noted that, while pilots do attend to both control tasks continually, they tend to assign them different priorities at successive points along the approach path. During the initial part of the approach pilots usually concentrate on obtaining a satisfactory lateral alignment with the runway first. They then attempt to hold this alignment while shifting their primary attention to control in the vertical plane. This is sometimes referred to as "getting lined up and then starting down the glide slope". Vertical control remains the dominant concern until the threshold is neared and flare is initiated. Attention then reverts to the horizontal control task for decrab, touchdown, and rollout. This is not to say that either aspect of control is concentrated upon to the exclusion of the other. It only suggests which receives priority at various times in the approach.

The reasons for this tendency are not definitely known. It may have something to do with the relative difficulty of the horizontal and vertical control tasks. Unless wind conditions are extremely adverse, control in the horizontal plane is, on the whole, easier than vertical control. Pilots, therefore, may attend to lateral alignment with the runway first in order to get this element of the approach under satisfactory control before tackling the more demanding task of vertical flight path control. That is, they may prefer to solve the elements of the control problem sequentially by stabilizing the aircraft in one dimension and then holding this solution while coping with the problem of control in the other. Studies of tracking behavior in general suggest this is the strategy employed by most persons in performing a multiple-axis tracking task.

But why the horizontal dimension first? The relatively greater stability of the aircraft in the horizontal plane and consequent ease of control may be only part of the answer. Another reason may be the shape of the spatial envelope into which the pilot is trying to fit the aircraft. In the case of the ILS beam, at least, the lateral dimension of the flight path envelope is about 6 times greater than the vertical dimension. A similar ratio may exist for the conceptual model used by the pilot in the VFR approach, although this is hard to say because it is a mental construct which cannot be measured. Because the lateral dimension is greater, it is logically and technically sound to solve the approach problem by ordering the tasks in terms of descending magnitudes and tolerances.

A third reason for the initial priority of horizontal over vertical control may lie in the nature of the visual cues available to the pilot at the beginning of the approach. The length of the runway (the height of the trapezoid as it appears to the pilot) is a fairly large angular dimension even at the beginning of the approach. It is about 1° at a distance of 5 miles. The visible or estimated centerline of the runway (the height of the trapezoid) is used as the major index of lateral track error. That is, if the runway centerline is perpendicular to the horizon, the pilot knows he is correctly aligned with the runway. By contrast, the visual cues related to control in the vertical plane subtend much smaller angles at the beginning of the approach, and they are much less easily discernable. The tendency to give first attention to horizontal control tasks, therefore, may be the result of the superiority of the visual cues relating to this task at the beginning of the approach.*

---

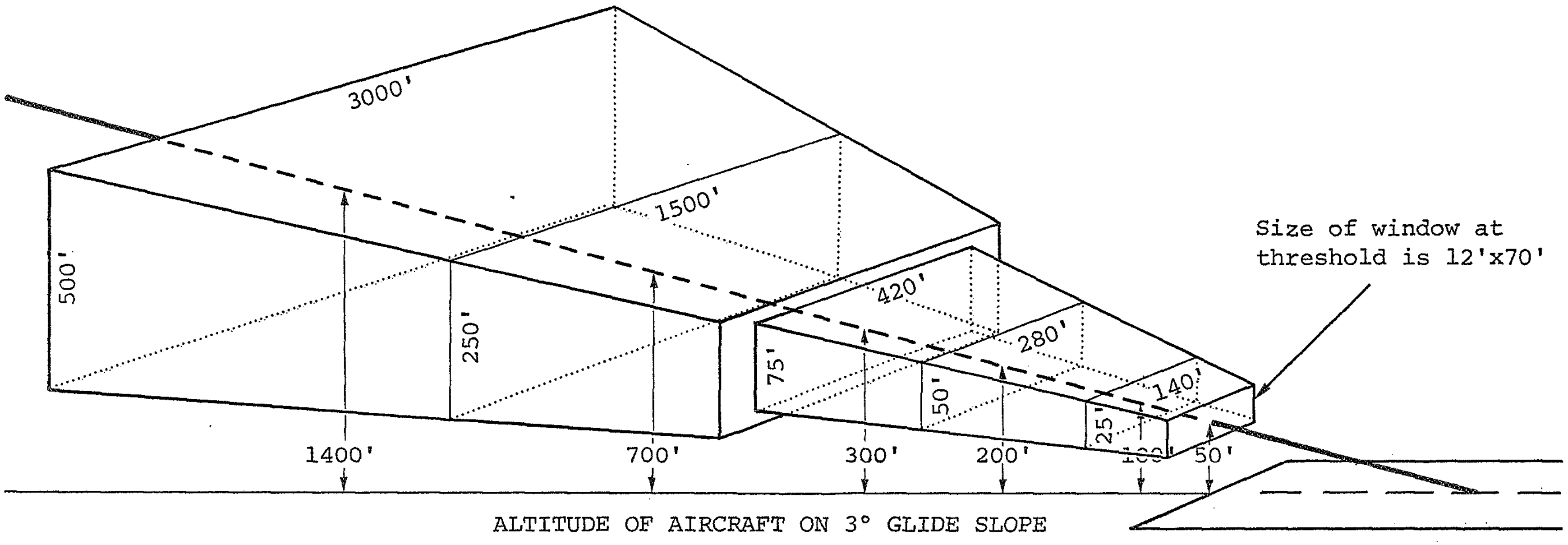
* A more detailed discussion of visual cues and how the pilot uses them is contained in Chapter IV.

Basically, the pilot's control tasks during the approach reduce to keeping the aircraft in a spatial envelope of constantly decreasing size. The shape of this envelope is that of a flattened, elongated funnel whose smaller opening is situated at, or just short of, the runway threshold. The dimensions of the envelope, based on ILS accuracy requirements, are shown in Figure 6. To stay within these limits the pilot must control the horizontal and vertical components of the flight path with increasing linear, but constant angular, precision as he nears the threshold. In general terms, the conditions to be met as the aircraft reaches the threshold are:

1. A vertical flight path angle of about 3°,
2. An aircraft ground track aligned with the extended runway centerline,
3. An aiming point about 1000 feet beyond the threshold,
4. An over-threshold altitude of about 50 feet,
5. A stabilized (or at least not increasing) rate of descent,
6. A sufficient reserve of speed for maneuver, but not too much to be bled off during touchdown and rollout.

Landing

There is no clean-cut division between approach and landing. The process is essentially continuous between the time the aircraft begins the approach at a distance of 5 miles or so from the airport and the time it taxies off the runway. For the purpose of analysis, however, approach shall be considered to end and landing to begin at the time the aircraft crosses the threshold. The threshold has been chosen as the demarcation line because it is about here that a certain sequence of actions associated with bringing the aircraft to rest on the airport surface begins to occur. These actions are flare, decrab, touchdown and rollout.



Size of window at threshold is 12'x70'

Based on accuracy requirements for typical ILS glide slope and localizer. Values for 100 ft and threshold altitudes are extrapolations.

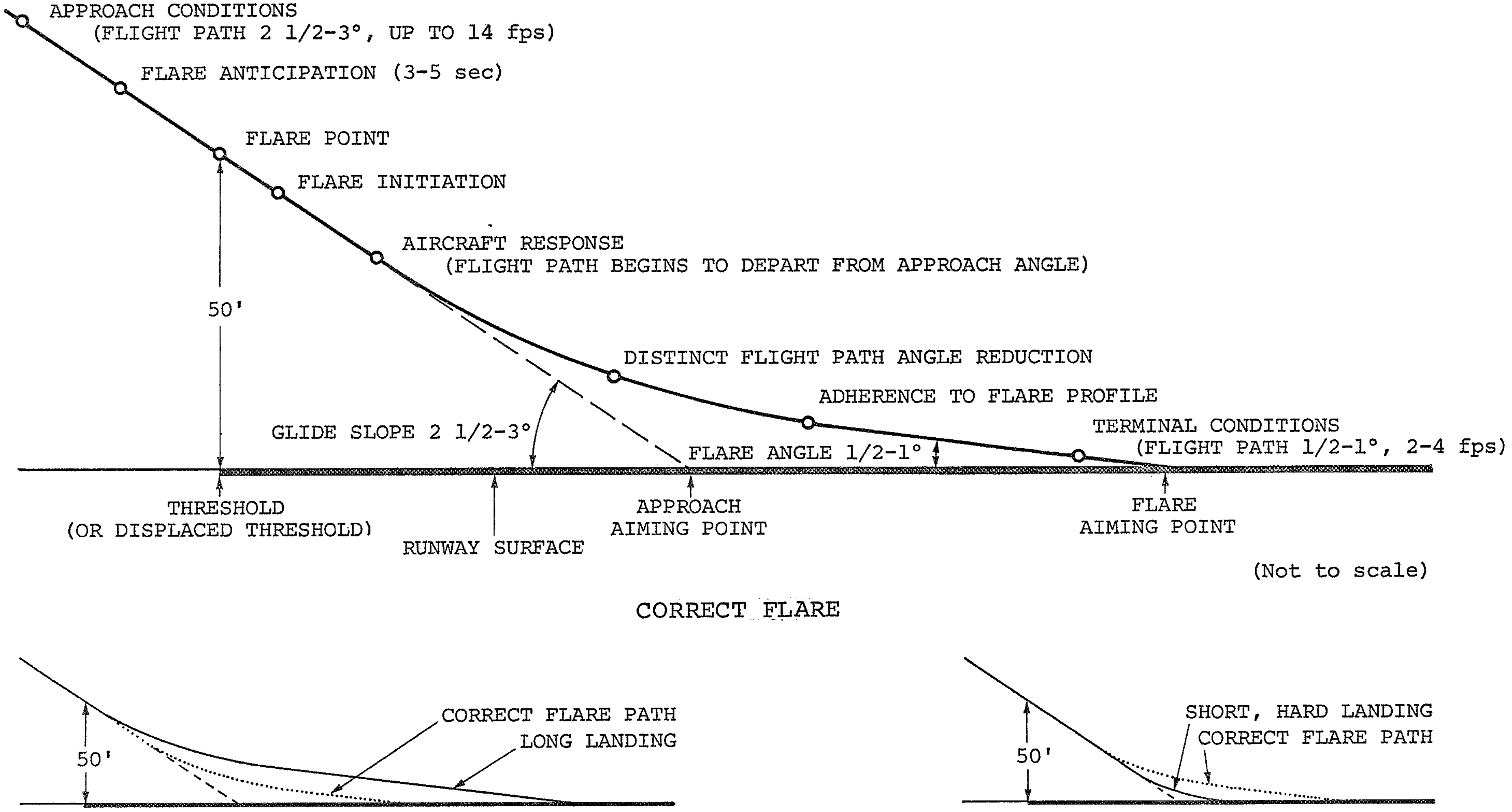
(Not to scale)

Figure 6

Flare is a maneuver in the vertical plane, the purpose of which is to round out the flight path so as to make an asymptotic approach to the runway surface. Flare is especially important in large jet transports because of their higher approach speeds and consequently greater rates of descent. In an ideal flare the flight path would be parallel to the runway surface at the moment the wheels touched down. In practice, pilots usually try to convert the flight path from an approach angle of 3° or so to about 1° to 1-1/2°, which will give a rate of descent of 4 to 6 feet per second at touchdown. A small rate of descent at the completion of the flare is desirable to ensure that the aircraft touches down promptly and does not "float" along above the runway, thereby decreasing the available runway length for deceleration after touchdown.

Flare is customarily initiated at an altitude of about 50 feet. Nominally, this is the altitude at which the aircraft crosses the threshold on a 3° glide slope, aiming for a point 1000 feet beyond the threshold. In typical jet approaches with a rate of descent of 12 feet per second, the aircraft crosses the threshold about 4 seconds before the wheels make contact with the runway if the 3° approach angle were maintained. The effect of the flare, however, is to make the flight path shallower, with the result that the time until touchdown is prolonged to about 10 seconds. Figure 7 is a schematic diagram of the flare maneuver.

A perceptive and informative analysis of the flare maneuver has been offered by Litchford. (Ref. 5) The main points of his analysis are as follows. The pilot employs a dual-angle homing and guidance concept in conducting the flare. He first



(Not to scale)

CORRECT FLARE

FLARE TOO SOON

FLARE TOO LATE

(Adapted from Litchford, Ref. 5)

Figure 7

aims his flight path toward a point about 1000 feet beyond the runway threshold ("approach aiming point"). To start the flare he uses visual cues for guidance to rotate the aircraft in pitch, seeking a new "flare aiming point" some 1000-1500 feet further down the runway. He holds this aiming point and flies to touchdown on the main-landing-gear wheels after arriving at a stable and quite shallow flight path relative to the runway surface. Then, about 3-1/2 seconds later, or about 600 feet further down the runway, the nose wheel touches down.

Litchford further observes that some sort of flare anticipation is needed by the pilot. An anticipatory period of about 3-5 seconds is necessary so that when the flare altitude of 50 feet is reached, the proper flight control action can take place safely and without delay. Delay in obtaining the anticipatory cues, or in responding to them, plus the inertia of a large aircraft will delay the departure of the aircraft from the straight trajectory of the approach path. Timing is therefore critical for a successful flare. If initiated too early, the aircraft will touchdown late, i.e., too far down the runway. If flare is initiated too late, there will not be sufficient time for the aircraft to overcome its inertia and decrease the flight path angle. As a result, the rate of descent will be excessive. To avoid the danger of landing long on one hand and the danger of landing short and hard on the other, the pilot has -- at most -- a 2-3 second time interval in which to estimate his altitude correctly and execute the flare maneuver.

The next major step in the landing sequence is decrab. This is a maneuver in the horizontal plane to bring the longitudinal axis of the aircraft parallel to, and directly over, the runway centerline. It is executed when there is a crosswind which has necessitated crabbing into the wind to correct for drift, i.e., to keep the ground track aligned with the runway heading. Decrab (which is technically a forward slip maneuver) customarily occurs just after flare, i.e., when the aircraft is committed to a touchdown. The exact timing depends upon the magnitude of the crosswind component and the weight and handling characteristics of the aircraft.

Like flare, decrab is a time-critical maneuver. If executed too soon, the aircraft will be blown off the runway centerline by the wind, creating the danger of going off the runway shoulder at touchdown or during rollout. Of equal concern is that lateral velocity at touchdown due to crosswind can produce undesirably high, even dangerous, side loads on the landing gear. If decrab is carried out too late, similar hazards will be present. If the longitudinal axis of the aircraft is not in line with the rollout path along the runway at touchdown, undesirably high cornering angles and sideload factors are created in the landing gear. Also landing in a crabbed condition will produce a rollout which is not parallel to the runway centerline, with the resultant danger of going off the runway during rollout. Assuming that the left main gear is 50 feet from the edge of the runway at touchdown and that there is an error of 2° to the left in alignment with the runway centerline, the aircraft would run off the paved surface within a distance of about 1400 feet after touchdown if no corrective action were taken.

Thus, flare and decrab are last-second, time-critical maneuvers which call for fine angular discriminations by the pilot and precise altitude judgments. In conditions of good visibility neither causes the pilot undue concern. In low visibility, or even at night, flare and decrab become much more difficult to execute safely and correctly because of the impoverishment of the pilot's visual cues. A closer examination of the required visual cues and the effects of darkness and weather will be made in Chapter IV.

Touchdown, the next step in the landing sequence, marks the point of transition for the airplane from an airborne to a ground vehicle. At touchdown and during the initial part of the landing roll, the aircraft is still an aerodynamically controlled vehicle. Through the use of spoilers to kill lift and thrust-reversers to decelerate below flying speed, the aircraft is converted to the equivalent of a high-speed, three-wheeled ground vehicle. The basic tasks from touchdown through rollout are the same -- controlling direction and speed through estimates of heading, centerline displacement, runway remaining, and rate of closure with the end of the runway. However, the means of control change. Initially, flight controls are employed. As the aircraft slows, directional control is accomplished by nose wheel steering and differential braking; and speed is controlled by a combination of brakes and throttles. The landing is completed when the aircraft turns off the runway onto a taxiway.

An Approach and Landing Model

In the preceeding discussion, approach and landing have been treated largely as a model exercise, i.e., in terms of nominal or average values for key parameters. Table VI is a summary of the major requirements of the approach and landing model. It is based on characteristic performance values for large jet transport aircraft (Boeing 707, 707B, 720, 720B and 727, Douglas DC-8 and DC-9, and Convair 880) and corresponds to Approach

TABLE VI

APPROACH		LANDING	
FLIGHT PATH ANGLE	2 3/4 ±1/4°	FLARE ANGLE	1 ±1/2°
RATE OF DESCENT	12 ±2 fps	RATE OF DESCENT AT TOUCHDOWN	3 ±1 fps
SPEED	140 ±5 kts	SPEED AT TOUCHDOWN	125 ±5 kts
ANGLE OF ATTACK	5 ±1°	ALTITUDE OVER THRESHOLD	50 ±20 ft
LATERAL TRACK ERROR		LATERAL TRACK ERROR	
Angular from Runway Centerline	±1°	Decrab	±1°
Displacement from Centerline		Displacement from Centerline	
At 5 miles	±1500 ft	At threshold	±35 ft
At 1 mile	±210 ft	At touchdown	±25 ft
AIMPOINT DISTANCE FROM THRESHOLD	1000 ±500 ft	TOUCHDOWN DISTANCE FROM THRESHOLD	1500 ±500 ft

Categories C and D of FAR 97.3(b). For smaller aircraft of either the commercial or general aviation types some of these requirements may be extreme. For example, the values for speed and rate of descent on the approach are too high for smaller aircraft; 100 knots and 10 feet per second would be more representative. Likewise, the accuracy tolerances for touchdown distances laterally and along the runway should be relaxed for smaller aircraft. Piston-engine pilots, for instance, generally try for a touchdown within the first third of the runway -- which on a 10,000 foot runway would mean a touchdown at 2000 ± 1500 feet from the threshold.

It is impossible to lay down a single set of requirements for all aircraft. The purpose in basing the model on the larger jet aircraft is to provide a realistic but somewhat severe picture of the problems faced by pilots and of the operational context in which the head-up display might be used.

It is also intended that the model apply to operations in both VFR and IFR conditions. This, too, may cast some doubt on the validity of the model. Some of the requirements may be too severe for approach and landing on a dry runway in good clear weather. On the other hand, they are probably not severe enough for Category III operations. Compromises have been made, generally in the direction of making the requirement applicable for conditions down to and including Category II. Here, again, the purpose is to present a veiw of operating problems in their more difficult forms.

Alongside this list of aircraft performance requirements, it is possible to set down a preliminary list of the information needed by the pilot to carry out his tasks satisfactorily.

The basic information needed for flight in the approach zone is:

1. Identification of the landing site
2. Flight path and attitude reference
3. Altitude reference
4. Speed reference
5. Distance to runway
6. Positive threshold and aiming point definition

For the present it is not important which, if any, of the items of information are supplied by instruments. It is important though that they be available in a simple form, requiring no interpretation, and that they be obtainable immediately when needed.

After crossing the threshold, the information needed for flare, decrab, touchdown, and rollout is:

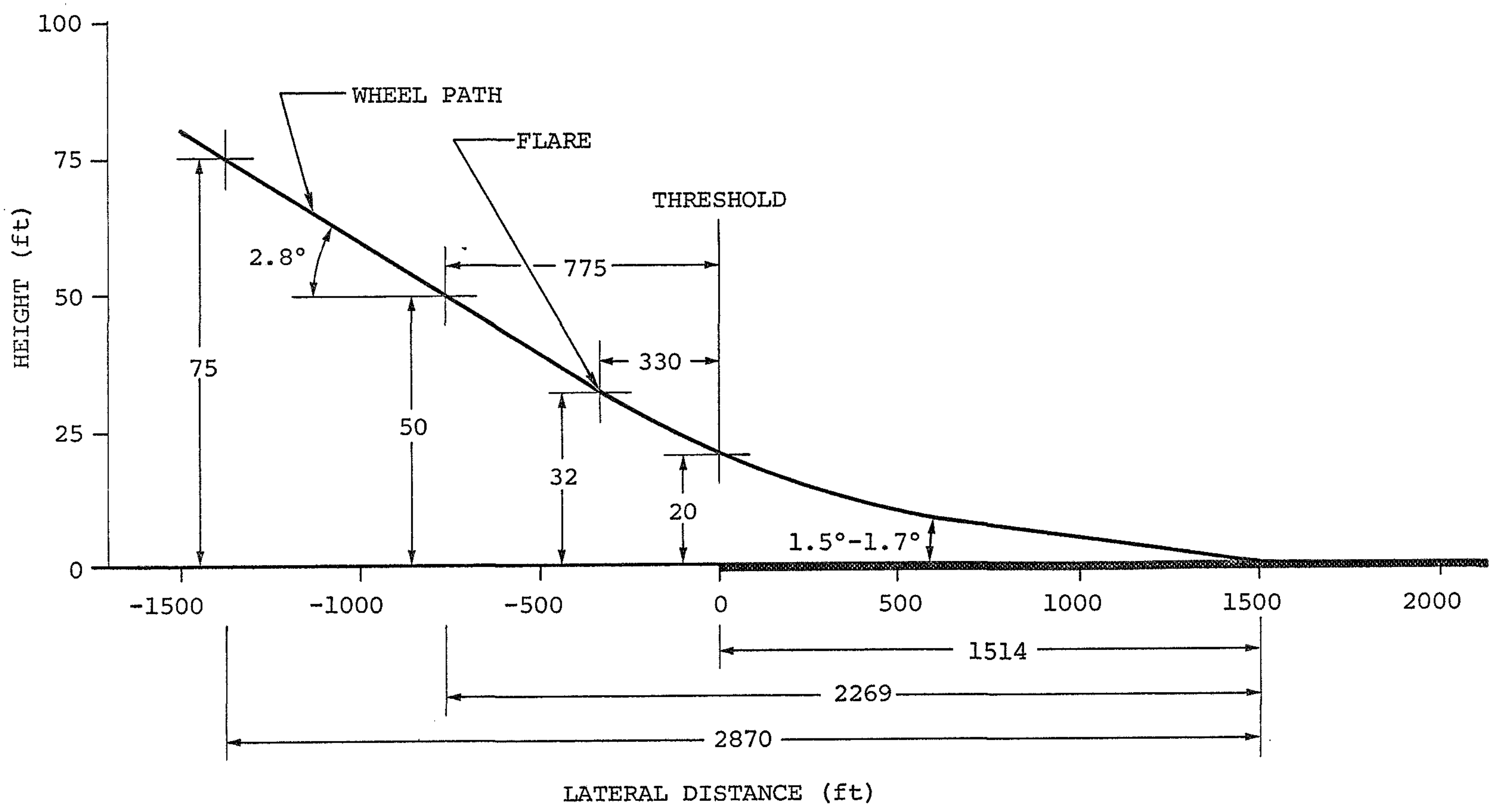
1. Identification of the landing site
2. Flight path and attitude reference
3. Definition of the runway surface plane
4. Runway alignment reference (and rollout guidance)
5. Runway distance remaining

The information needed for landing is, thus, similar to that needed for approach, although priorities and degree of need differ between the two flight phases. It should also be noted that, as visibility decreases and instrument systems bear more of the burden of supplying information, the form in which the information is needed and the degree of precision may be changed. (Ref. 6)

The foregoing lists of information requirements is only preliminary, and certain points will need amplification. Further discussion, however, will be reserved until Chapter IV, where they will be taken up in connection with the pilot's visual task.

Before leaving the subject, it is in order to ask how actual pilot performance compares with the requirements postulated in the model. Several statistical studies have been made of approach and landing parameters under operating conditions. One of the most comprehensive was that published by the Federal Aviation Agency Bureau of Flight Standards in 1962. (Ref. 7) This was based on measurements made at Chicago (O'Hare), San Francisco International, Denver (Stapleton), and Dallas (Love) airports. Data were taken for 183 landings by large jet aircraft (Boeing 707, 707B, 720, 720B, Convair 880, and Douglas DC-8). A summary of that mean values found for the vertical flight path profile is given in Figure 8.

Other studies, conducted at the London, Los Angeles, and John F. Kennedy (New York) airports, have produced results which are in substantial agreement with the FAA findings. The London Airport study (Ref. 8) was made by the UK Air Registry Board (ARB), which measured 100 landings by two types of large jet aircraft. NASA (Ref. 9) collected data in two samples, taken eight months apart, at Los Angeles International Airport in 1960. Touchdown conditions were measured for approximately 300 landings by two types of large jet transports and one type of turboprop aircraft. Litchford (Ref. 10) reports a study made at John F. Kennedy Airport, where data were taken for 97 landings by large jet aircraft. All studies, including the FAA study, were made under daylight VFR conditions and comprise a total sample of about 700 landings.



(Adapted from FAA data, Ref. 7)

Figure 8

The FAA study showed, in agreement with the earlier ARB and NASA findings, that the angle of the approach slope (flight path angle) averaged about 2.8°. Jenks (Ref. 6) reported in 1956 that random observations of visual approaches indicated that 2.8° was also the preferred approach slope angle for pilots of six types of propeller and turboprop transports. Further, a study by the Air Line Pilots Association (Ref. 11) concluded that 2.8° was typical of line flying in VFR weather and would remain essentially unchanged as an average for IFR weather regardless of minima. The value of 2/34 ± 1/4° given in Table VI has been selected with these studies in mind. The figure of 3°, which is used in several examples for the sake of simplicity, is slightly high but still may be taken as representative.

Table VI indicates that wheel height when crossing the threshold should be on the order of 50 ± 20 feet. This figure, which is in accord with FAA regulations, is derived from calculation of the altitude which would result from flying a 2.8° approach slope toward a touchdown point 1000 feet beyond the threshold. The FAA, ARB, and JFK studies revealed that the actual wheel height over the threshold (runway edge) was considerably lower -- only about 22 feet. Figure 9 shows the composite of the wheel height data obtained in these three studies.

A factor which may account for the low threshold heights observed is the wheel-to-eye distance. The pilot's eye level for the type of aircraft involved is roughly 15-20 feet above the wheel height. Since these landings were made by visual reference, the pilots' estimates of altitude would be correspondingly higher, i.e., between 37 and 42 feet.

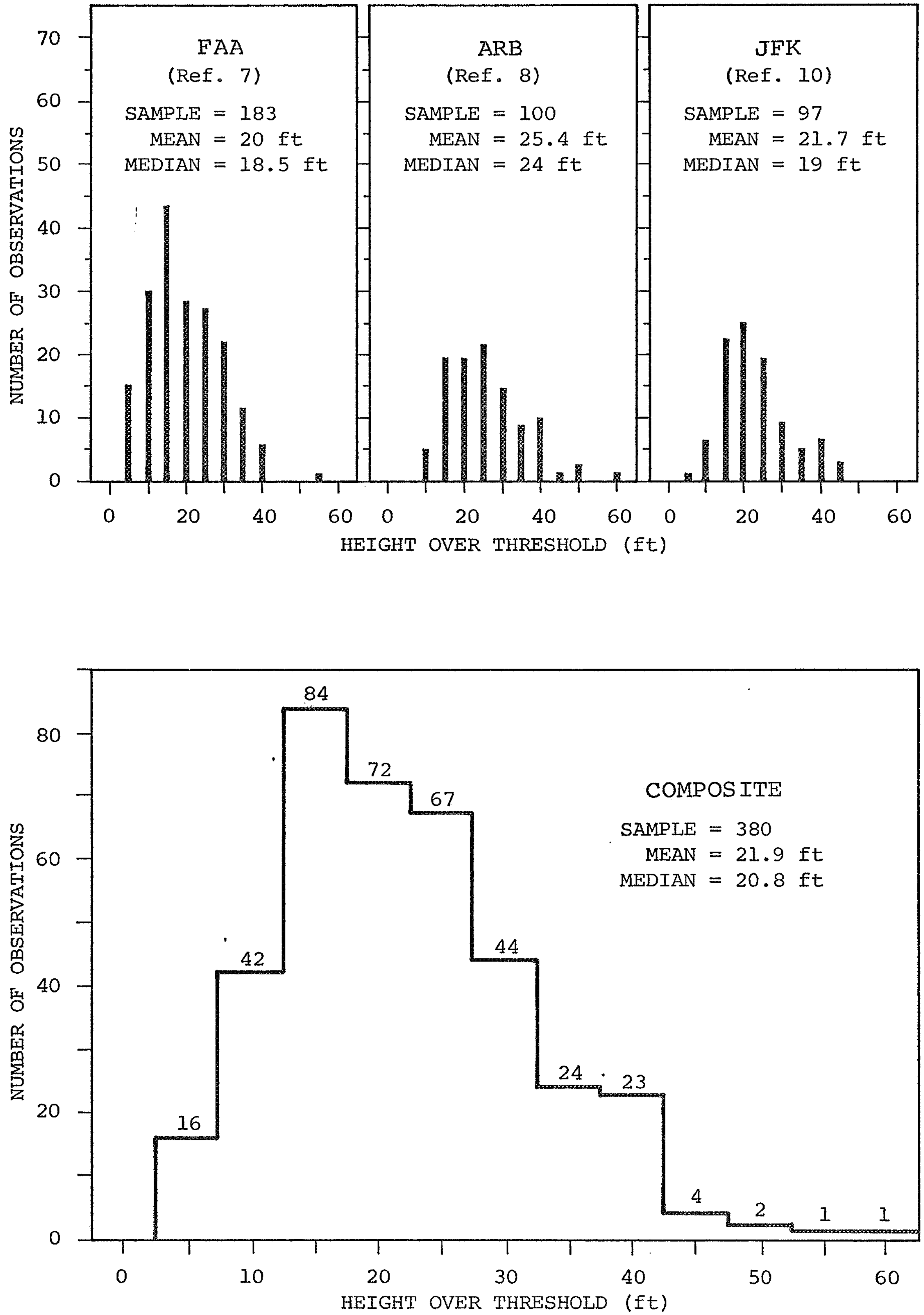

FAA
(Ref. 7)
SAMPLE = 183
MEAN = 20 ft
MEDIAN = 18.5 ft
ARB
(Ref. 8)
SAMPLE = 100
MEAN = 25.4 ft
MEDIAN = 24 ft
JFK
(Ref. 10)
SAMPLE = 97
MEAN = 21.7 ft
MEDIAN = 19 ft
NUMBER OF OBSERVATIONS
0
10
20
30
40
50
60
70
0
20
40
60
0
20
40
60
0
20
40
60
HEIGHT OVER THRESHOLD (ft)
COMPOSITE
SAMPLE = 380
MEAN = 21.9 ft
MEDIAN = 20.8 ft
NUMBER OF OBSERVATIONS
0
20
40
60
80
16
42
84
72
67
44
24
23
4
2
1
1
0
10
20
30
40
50
60
HEIGHT OVER THRESHOLD (ft)

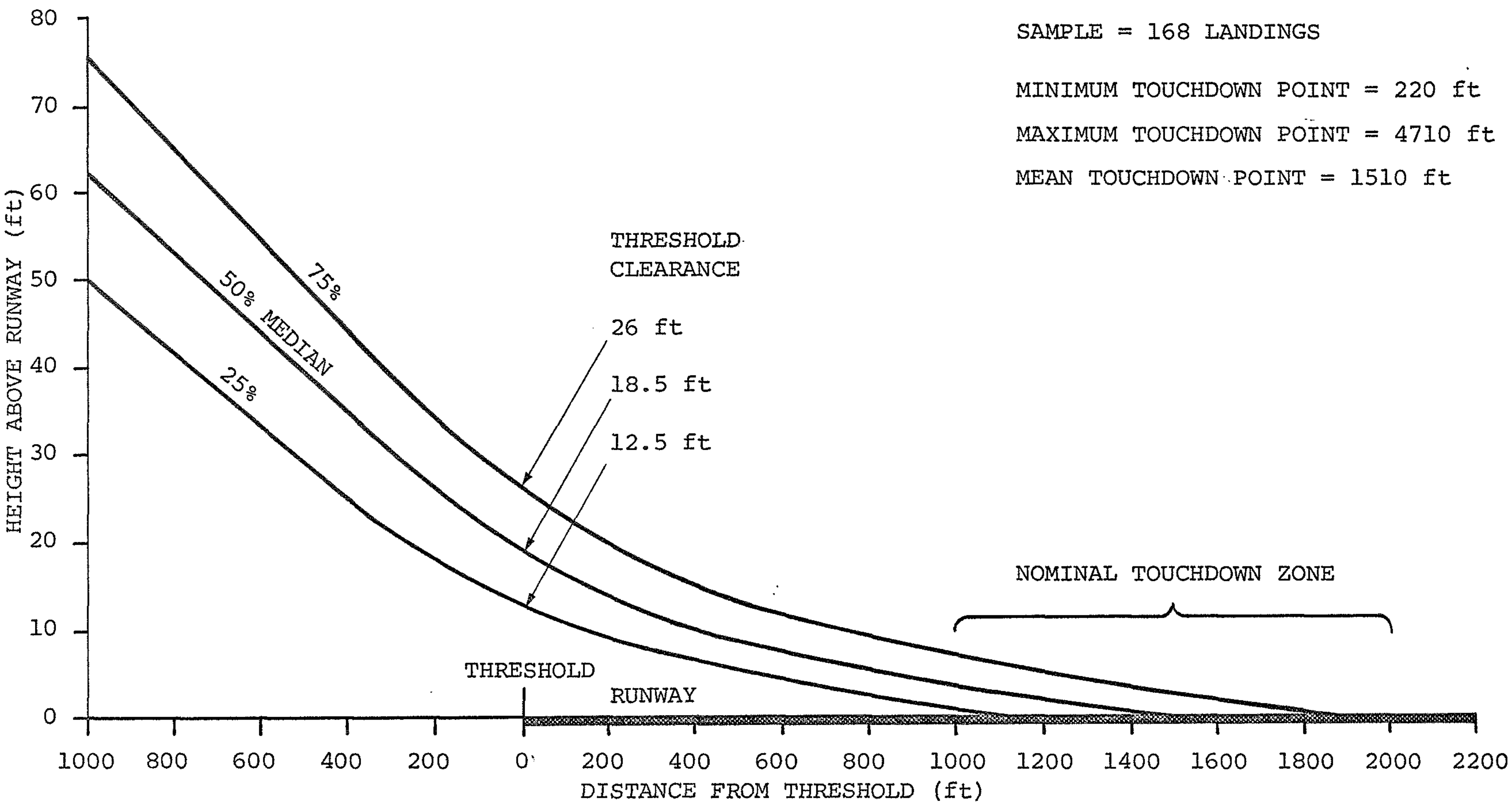
Figure 9

Nevertheless, the fact remains that wheel heights when crossing the approach end of the runway are dangerously low in actual line flying. This is even graver when one considers that 22 feet is an average figure. The maximum height in the FAA study was 65 feet and the minimum was 3-1/2 feet. In the JFK study the range of threshold crossing heights was 4 to 45 feet. The ALPA study (Ref. 11), which reviewed the FAA findings, commented that while the low threshold crossing heights were undoubtedly typical of line flying, they must be considered marginally safe. The ALPA study also suggested that low heights over the threshold may be the result of a conscious or unconscious compromise between a safe wheel-to-runway clearance and a desire to minimize the touchdown distance from the threshold. That is, a higher altitude at the threshold would increase the touchdown distance and thereby the overall landing distance and the danger of overrun. It should also be noted that the landings considered in all of these studies were made in VFR conditions. In reduced visibility the threshold clearance altitude would probably be greater.

A further examination of the FAA, ARB, and NASA studies shows that, except for altitude over the threshold, actual pilot performance is substantially in accord with the requirements of Table VI. For example, speeds average about 135 knots at the threshold (when the aircraft was already partially flared) and 125 knots at touchdown. Table VI gives 140 ± 5 knots and 125 ± 5 knots, respectively, for approach and landing speeds. Rates of descent on the approach and at touchdown were not specifically measured in the FAA and ARB studies, but they can be calculated from the approach slope and speed. The average rate of descent was about 11 feet per second on the final stages of the approach and about 5 feet per second at touchdown. The rate of descent at touchdown was slightly in excess of the 2-4 feet per second given in Table VI. The difference results from the somewhat steeper flight path angle at touchdown (1.6°as compared to 0.5° to 1.5° in Table VI).

Figure 10 shows the distribution of altitude vs. distance for landings observed in the FAA study. Over half of the touchdowns were within the range of 100 to 2000 feet from threshold specified in Table VI. The combined average touchdown distance from threshold for the FAA, ARB, and NASA studies was 1370 feet, which is also in line with the requirements in Table VI.

From this brief examination of landing statistics it is possible to conclude that there is a remarkably high degree of consistency in pilot performance under actual operating conditions, at least in VFR. Through years of experience qualified pilots have established firm operational patterns and practices which are not likely to change. As a result, pilots have developed a nearly uniform mental model which they apply, almost instinctively, to each landing. While there may be variability in executing the landing (the alarming range of threshold clearance altitudes is a case in point), the model as shown by measures of central tendency remains very much the same from landing to landing and from pilot to pilot to pilot. More importantly, this model has been developed under VFR conditions. In good visibility the pilot checks performance against the model by using the available visual cues. In poor visibility he envisions his performance in relation to the model by observing his instruments until such time as he makes visual contact with the landing site. The model remains, however, basically a VFR model since this is the predominant experience. It follows,



(Based on FAA data, Ref. 7)

Figure 10

then, that any system intended to aid the pilot in IFR conditions must foster performance which is consistent with that to be expected in VFR conditions.

The aircraft landing statistics also provide a reasonably exact indication of the physical dimensions of the approach and landing model. Earlier, the initial part of the approach was likened to flying down a flat, elongated funnel whose narrow end points at the approach end of the runway. With increasing precision, the pilot is trying to bring the flight path of the aircraft in line with the runway and the desired approach slope. That is, he is controlling the trajectory of the aircraft so it will pass through a narrow, imaginary spatial aperature near or at the approach end of the runway. The size of this aperature at an altitude of 100 feet, when the aircraft is nominally 1000 feet from the threshold, is roughly 140 feet horizontally and 25 feet vertically. Considering the dimensions of present day jet transports, this is literally like threading a needle at 235 feet per second.

From an altitude of 100 feet until touchdown, the path of the aircraft is roughly 3500 feet long. At typical jet approach speeds the time to traverse this distance is about 15 seconds. During this time the flight path angle is reduced to about half the original approach angle by means of the flare maneuver. When the aircraft crosses the threshold, it is already in flare flying at a slope of 1.9° to 1.5° to the runway and descending at about 6 to 8 feet per second. At touchdown the speed is roughly 125 knots and the rate of descent is on the order of 2-4 feet per second. The other dimensions of the landing model have been presented in Table VI. The comparison with the measurements made under routine operational conditions has shown that the requirements of Table VI are consistent with, and representative of, actual pilot performance. The model will, therefore, be used as the test case for evaluating both present approach and landing aids and the potential contribution of the head-up display.

OTHER FLIGHT PHASES

This section contains a brief examination of three other flight phases in which the head-up display may be of assistance to the pilot. They are takeoff, missed approach, and taxi. Here, as in the preceeding section on approach and landing, no attempt will be made to offer a complete analysis of aircraft operations during these flight phases. Rather, the intent is to identify specific performance problems and to describe the nature of the pilot's tasks in preparation for Chapter VI which will discuss the potential role of the head-up display.

To place takeoff, missed approach, and taxi in proper perspective, it should be noted that the industry tends to regard the problems of these flight phases as secondary in comparison with approach and landing. Except for a few isolated examples in the research literature, almost no attention has been devoted to any phase of flight other than approach and landing. Most of the effort to provide improved instrumentation and aids has been directed toward the approach and landing problem, and any application of the new equipment to other phases of flight has been largely serendipitous.

It may well be, as industry opinion seems to hold, that takeoff, missed approach, and taxi are relatively less difficult and demanding of pilot skill and aircraft capability. A second, and more probable, reason is that they do not pose problems except in conditions of severely reduced visibility, i.e., in Categories II and III of IFR. Visibility of one-half mile, the Category I minimum, is generally considered adequate for taxiing an aircraft or even for takeoff, both of which are carried out almost wholly by visual reference. Executing a missed approach (go-around) from an altitude of 200 feet (the Category I decision height) is not an excessively demanding maneuver, even with a large jet aircraft. However, as the industry seeks to penetrate into the lower reaches of Category II and eventually into Category III (blind landing), the visual cues available on the ground for taxiing and takeoff will be sharply reduced, and the altitudes at which a go-around may be initiated will be 100 feet or lower. For this reason it is reasonable to assume that problems will begin to emerge and the need for supplemental instruments and aids will begin to be felt. Therefore, the following discussion of takeoff, missed approach, and taxi will pay particular attention to those elements of guidance and control which may be affected by reduced visibility.

Takeoff

Takeoff is in many ways simpler than landing. During the takeoff roll the aircraft is a ground vehicle with fewer degrees of freedom than later on when it becomes airborne. Control is therefore a somewhat simpler problem. Even after liftoff, control is not a highly demanding exercise because there is no need to hold a flight path as precisely as in landing. Moreover, as the takeoff progresses and climbout is established, the control tolerances become more relaxed, instead of the reverse which is true of landing.

At the same time, however, takeoff also poses some unique problems which are not present in landing, at least to the same degree. Takeoff is carried out entirely under manual control. The present state of autopilot technology is such that the pilot cannot turn a portion of the control task over to the autopilot as he can in the approach and landing. Moreover, manual control must be accomplished almost solely by visual reference. Radio aids, such as the ILS localizer, are situated so as to be in an optimum position for landing, with the result that they are of little or no use for holding runway heading during takeoff. Thus, in terms of the available support and assistance to the pilot, takeoff is one of the most primitive phases of modern civil aviation operations.

Takeoff consists of three major elements: holding runway alignment during takeoff roll, monitoring the increase of airspeed in relation to selected points along the runway, and rotating the aircraft to takeoff and climbout attitudes when the proper speeds are reached. To these can be added a fourth task which is assuming greater and greater importance for takeoff from airports in congested urban areas. This is the execution of noise abatement procedures, which involve adjustments in speed and climbout angle and adherence to specific climbout corridors (including perhaps procedural turns).

Lami (Ref. 12) has presented a more detailed analysis of the pilot's control task during takeoff. The following is an adaptation of his exposition.

1. Establish initial position and alignment with respect to the runway centerline.
2. Run up power, release brakes, and begin takeoff roll.
3. Maintain runway alignment, using nose-wheel steering and guiding on the runway centerline (frequently imaginary or obscured by tire marks).

4. Relinquish nose-wheel steering at 60-80 knots (depending on the aircraft) and maintain runway alignment by rudder action and visual guidance.
5. In case of crosswind, use ailerons to keep upwind from lifting prematurely.
6. Monitor speed and acceleration in relation to runway checkpoints. The speeds to be monitored are:
    a. Minimum control speed (Vmc), above which the movable aircraft surfaces become fully effective for controlling the aircraft;*
    b. V_1, above which the takeoff should be continued in case of engine failure;
    c. V_r, the speed at which the aircraft should be rotated to a takeoff attitude (nose-wheel liftoff);
    d. V_2, takeoff speed -- also the speed which will give the best initial rate of climb (main gear liftoff).
7. At liftoff, maintain climbout path along runway heading, correcting for crosswind as necessary.
8. Retract landing gear and adjust flaps as required.
9. Execute noise abatement procedures, which include:
    a. Reduction of power;
    b. Maintaining climbout corridor, sometimes involving procedural turns;
    c. Observance of climb angle, bank angle, and altitude restrictions.

For jet aircraft the entire operation, from brake release to throttling back for noise abatement, consumes about 60 seconds, during which time the aircraft has accelerated from 0 to a speed in excess of 150 knots.

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* Technically, this is Vmc_g, minimum control speed on the ground. There is a higher speed, Vmc_a, which is minimum control speed in the air.

Two major problems emerge from Lami's analysis. How does the pilot receive guidance for the takeoff roll and for controlling attitude and flight path after liftoff? How does the pilot monitor airspeed and take appropriate action?

The initial guidance for the takeoff is visual, both in VFR and in present Category I IFR operations. It is anticipated that visual reference will also be the only means of reference in projected Category II operations. In Category III (zero-zero), obviously, some other means will have to be found. On ill-lighted runways at night and even on the best lighted runways in reduced visibility (down to 1200 feet) visual cues may be marginal. At the speeds attained during the latter part of the takeoff roll and in visibility of 1200 feet, the pilot's forward view will be the equivalent of only about 6-7 seconds of his progress down the runway. This is probably adequate, but only just so, and for lesser visibility ranges (such as those associated with Category III) reliance on unaided visual guidance will not be practical or safe. Hence, the extent and quality of the pilot's visual reference is a problem which will increase in severity as operations are extended closer and closer to full zero-zero conditions.

Of equal concern is that, at rotation, the pilot's view of the runway is obscured by the nose of the aircraft, which also covers his forward view of the horizon. The pilot thus loses visual attitude reference (except peripherally) and must refer to the attitude indicator on the instrument panel for guidance in controlling pitch for rotation and climbout. Adjustment to this new instrument preference is a process which involves adaptation to a different illumination level, accomodation to the shorter viewing distance, and time for reorientation and interpretation. Under adverse conditions this process may consume up to 3 to 4 seconds, which come at a critical point in the takeoff. This problem is further complicated by the fact that the attitude reference system is gyro-stabilized and therefore tends to process during takeoff acceleration. This means that the attitude indicator will give a false pitch reading which the pilot must be aware of and make appropriate compensation for.

Because the pilot's view is outside the cockpit until very late in the takeoff (i.e., until rotation), the monitoring of airspeed -- which is a critical takeoff parameter -- also becomes a problem. The common solution is to have the co-pilot read off airspeed during takeoff and call out the critical values. During typical jet takeoffs these speeds are reached in such rapid succession that the co-pilot frequently calls them out in a single burst ("V_1, V_r, V_2"). The pilot, as long as he is looking out of the cockpit for visual guidance to hold runway alignment, has no way of monitoring speed directly or of anticipating when critical speeds will be reached. Mostly pilots rely on experience and the "feel" of the takeoff. This is a rough and ready method at best. Because of the variations in acceleration due to takeoff weight, temperature, and runway surface conditions, this is a rather complicated estimate which must be made at a time when much of the pilot's attention is focussed on guiding the takeoff roll. Furthermore, this is entirely a memory process. Even though the flight crew has looked up the critical speeds in tables prior to starting the takeoff, the responsible crew member must remember and call them out correctly as the speeds are reached.

Noise abatement introduces an additional complication in speed control. Typical noise abatement procedures call for maintaining a speed only 10-20 knots above V_2, which necessitates a precise power reduction almost immediately after takeoff. Since turning maneuvers are frequently a part of noise abatement the aircraft can come comfortably close to an unstable flight condition. The following, drawn from Clark (Ref. 13) are typical instructions to flight crews concerning noise abatement procedures.

TURNS

> "With V_2 + 10 kts. and at least 300 feet above the airport, initiate 15° bank in the desired direction.
>
> Warning: Do not allow bank angle to exceed 20°."

POWER REDUCTIONS

> "Climbout at V_2 + 10 to 400 ft.
>
> At 400 ft. select flap 20, but do not allow speed to increase. (The change in stall speed is only 3 kts.)
>
> Should it become apparent after throttling that the aircraft is not maintaining V_2 + 10 kts. without loss of height, then the RPM should be increased.
>
> Warning: Thrust reduction should not be started before reaching 600 ft."

The implication of the warnings is self-evident.

A further example, also drawn from Clark, will illustrate how close to the margin conditions may come.

> "Studies of a current jet transport indicate that if a pilot had to utilize a 34° bank angle to avoid collision he would only be 4 knots above the 1G stall speed at V_2. For those who question the probability of these load factors occurring we refer them to the NASA study on operational experiences which show that quite frequently jet aircraft have exceed these load factors..."

Noise abatement is a thorny and somewhat emotionally charged subject which need not be pursued further since it is not central to the present discussion. The only point in raising it was to bring out an additional indication of the criticality of the pilot's speed control task.

To sum up, the pilot has two principal concerns in takeoff. The first is to monitor airspeed, but this cannot be done directly until late in the takeoff when he has redirected his vision from the external world to the instrument panel. The second concern is guidance for the takeoff roll and initial climbout flight path, and this can be obtained only by referring to the external world. The pilot is thus confronted with conflicting demands for his attention. In conditions of poor visibility interpreting the available visual cues to assure he is on the correct path can consume much of the pilot's attention. Poor visibility also reduces the pilot's ability to judge the runway remaining and the progress of the takeoff in relation to it. At liftoff the pilot loses visual reference and must convert to (and adjust to) an instrument frame of reference for part of the takeoff and instruments for the remainder. In the case of airspeed he has no way of reading it directly unless he looks down at the instrument panel, with the consequent loss of outside reference. To avoid glancing back and forth from the runway to the instrument panel, the pilot must rely on indirect, verbal reports of airspeed from another crew member.

Missed Approach

A missed approach (go-around) is conducted whenever the pilot is not certain that the approach can be carried through to a successful landing. Excluding failure of aircraft or ground equipment and similar in-flight emergencies, the decision to initiate the missed approach procedure is made for one of two basic reasons:

1. The aircraft is so far off the required horizontal or vertical flight path that it cannot, in the pilot's estimation, be brought back in line safely before reaching the runway.
2. The aircraft has reached a specified altitude along the approach path, and the pilot has not established the required visual reference to continue the approach to land.

In either case the pilot has the sole responsibility for the decision to continue or go around. To make this decision he must have information about the flight path of the aircraft with respect to the landing site. If this information leads the pilot to believe the flight path is out of acceptable tolerances, he must make a go-around. More importantly, the pilot also must make a go-around if he does not have visual contact with the landing site by the time he has reached a minimum altitude, i.e., if he is not certain <u>from visual reference alone</u> that he can bring the aircraft down safely on the runway.

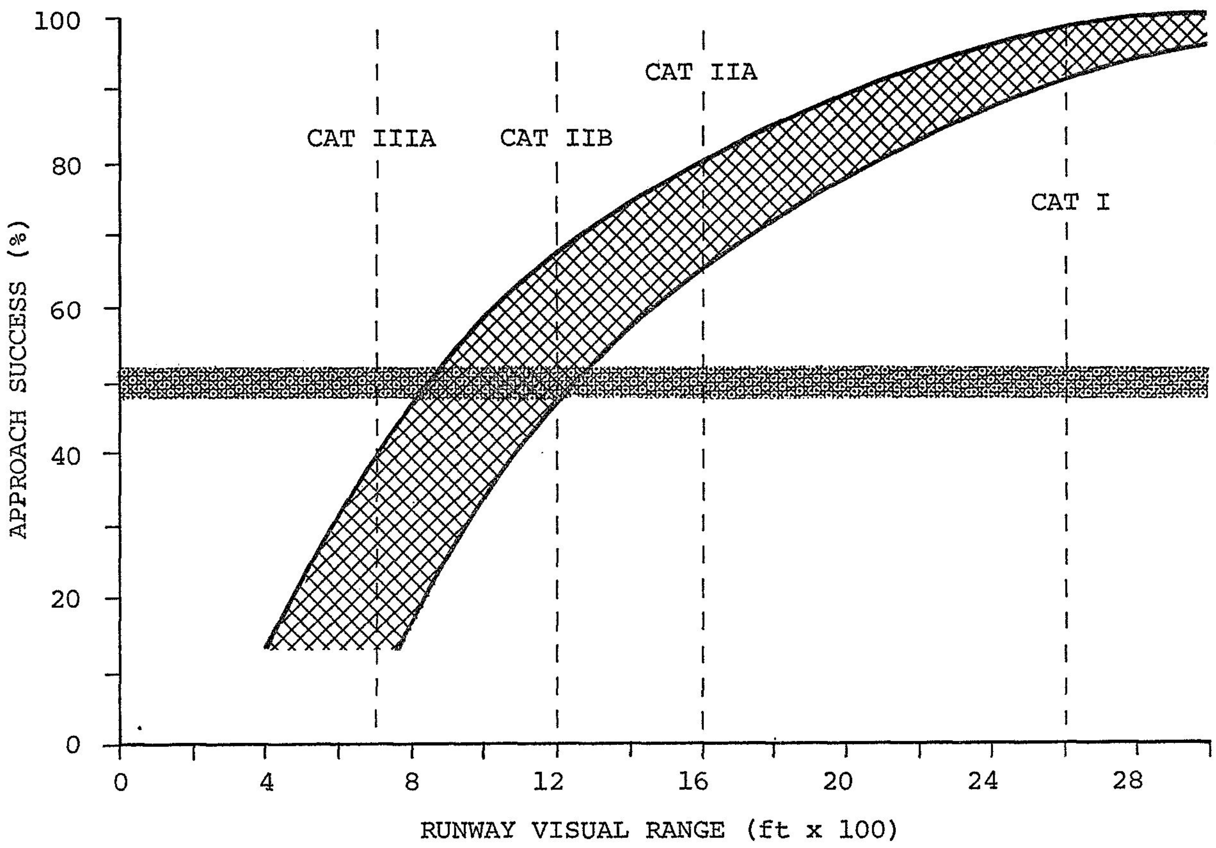
The see-to-land concept is therefore basic to aircraft operation in either VFR or IFR conditions. In VFR, visual contact with the runway is established at the beginning of the approach by instrument reference alone down to a minimum altitude (Decision Height). Beyond this minimum altitude, however, the pilot can continue only if he has visual contact with known ground references, which may be the runway itself or a portion of the approach and threshold marking clearly identifiable with the runway. Visual reference is required in the final stage of an IFR approach both to confirm the accuracy of the instrument guidance system and to serve as primary guidance for completing the landing.

As might be expected, visibility has a direct and dominant influence upon completing the approach to land. Statistics on the landing success rate (the ratio of completed landings to those attempted) shows a dramatic increase in the number of missed approaches as visibility worsens. The following, drawn from Beck (Ref. 14), is a tabulation of missed approaches at Heathrow Airport, London by all aircraft during 1963, 1964, and 1965.

RUNWAY VISUAL RANGE	PERCENTAGE MISSED APPROACHES
700-600 meters (2300-1970 ft.)	22.2%
600-500 meters (1970-1640 ft.)	30.6%
500-450 meters (1640-1475 ft.)	40.5%
450-400 meters (1475-1312 ft.)	45.5%

Figure 11, which is based on data presented to the International Civil Aviation Organization All-Weather Operations Panel (Ref. 15), further illustrates the effect of low visibility. In Category I (2600 feet Runway Visual Range and 200 feet Decision Height) over 90% of the approaches are successfully completed to landing. In Category IIB (1200 feet RVR and 100 feet DH) it is forecast that the success rate will drop to about 50%. With 700 feet RVR the forecast is that only about 20% of the approaches will be successful.

Reduced visibility, therefore, has several important consequences for missed approaches. As visibility decreases, the incidence of missed approaches can be expected to go up sharply. The altitude at which the missed approach decision must be made



(Based on ICAO AWOP III data,
adapted from Litchford, Ref. 16)

Figure 11

is lowered as visibility decreases. The extent and quality of the pilot's external visual cues, the information upon which he must base the decision, are progessively degraded. The net effects of reduced visibility are to diminish the information the pilot has to work with, to shorten the time he has to make a decision before reaching the ground, to weaken the certainty of his judgment, and to postpone the start of the go-around. An examination of the nature of the missed approach maneuver will further clarify the impact of reduced visibility upon the pilot's guidance and control problem.

In carrying out a missed approach the pilot has three major concerns. First, through application of power and rotation of the aircraft in pitch, the descent of the aircraft must be checked and a climbing flight path established. Second, since the missed approach is usually conducted at altitudes of 200 feet or lower, altitude loss must be kept to a minimum between the time the pilot makes the go-around decision and the time the aircraft actually responds and starts to climb. Third, precise control of pitch in relation to airspeed is required to avoid overrotation of the aircraft, which would introduce the danger of stall. Clearly, the missed approach is a critical maneuver which is as demanding of the pilot's skill and sense of timing as landing.

In low visibility the pilot has a two-fold problem. First, he must decide whether he has the required visibility to land. To do this he must look out of the cockpit for approach and runway markings. As pointed out above, the promptness and correctness of his decision are entirely a function of the external cues available to him and his ability to interpret them. The more obscured the external scene, the longer he will take to reach a decision and the greater the possibility of error. Once he has decided that he does not have adequate visual reference or that he is not on the correct approach path, the pilot must then effect the go-around. To do this he needs information on the pitch attitude, speed, and altitude (or vertical velocity) of the aircraft. To obtain the information he must redirect his vision from the external world to the instrument panel. The pilot is, thus, placed in a situation where he must divide his attention between two different information sources, which implies not only different viewing distances and levels of illumination but also different frames of reference.

Initiating the go-around from an altitude of 200 feet (the Category I minimum), although a demanding exercise, does not appear to cause pilots great concern. The altitude cushion is sufficient, even for large jets, providing the decision is reached promptly and appropriate control action is taken with minimal delay. Starting the go-around at the Category II Decision Height of 100 feet is another matter, as the following analysis shows.

The customary approach procedures in Category II call for the pilot to fly the approach path on instruments down to the Decision Height. At this point, the pilot shifts his attention outside the cockpit to determine whether he has the necessary visual reference to proceed and to assess the position and movement of the aircraft with respect to the desired approach path. This entails a complex visual process which includes adaptation to a different illumination level, accommodation for distance, and interpretation of the external visual scene. Assuming that the pilot decides a go-around must be made, he must then revert to the instruments for information to guide the maneuver. That is, he must repeat the visual process just described.

The research literature contains clear evidence as to the time required for the transition from head-down to head-up and back to head-down again. Beck (Ref. 16) refers to studies conducted by the Royal Air Force Institute of Aviation Medicine which showed that the time lapse averaged 2.39 seconds*. Corroboration of this figure can be found in Wuifeck (Ref. 17) To the time of 2.39 seconds a further time lapse must be added to account for decision making. The time will vary according to the situation and the individual; 2 seconds shall be assumed as a minimum value. (Ref. 17) This means that the total elapsed time to raise the eyes from the instrument panel, to adjust to and interpret the external scene, to make a decision, and to return the eyes to the instrument panel is on the order of 4.4 seconds. Since the aircraft on the approach is descending at about 12 feet per second, the time lapse can be equated with an altitude loss of about 50 feet.

After reaching the go-around decision, an additional time lag will occur before the flight path rounds out and the aircraft starts to climb. Cleary (Ref. 18) reports a study of two forms of instrument guidance for go-around, one the conventional flight director and the other a pitch command go-around system based on angle of attack inputs. Pilots were not told in advance whether to continue to land or to conduct a missed approach. The decision was made at a selected altitude by the check pilot. Altitude loss between announcing the go-around

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* The parameters used in this study were muscle movement, eye movement, foveal perception, distance accommodation, recognition, and re-accommodation for distance. The largest time components were those involving changes in accommodation.

decision and establishing a climbing flight path averaged a little over 40 feet for each guidance system. The standard deviation was about 13 feet for either method of guidance. The aircraft was a DC-7, which is prop-driven and has an approach speed of about 125 knots and a gross landing weight only about two-thirds that of a typical large jet. The altitude loss in a large jet aircraft, which is both heavier and faster, would probably be somewhat larger and certainly no less. 40 feet will be used, however, as a nominal figure. Confirmation of the appropriateness of this figure can be found in Warren (Ref. 19), who indicates that altitude losses of 35-50 feet were observed in simulator trials of go-around in a supersonic transport. Warren also suggests this compares roughly with figures for current large jet transport aircraft.

Combining the results of these two calculations, the altitude lost between reaching the Decision Height and the establishment of a positive vertical velocity in the go-around would be about 90 feet. Since the process was started at 100 feet, this would leave an average remaining altitude of only about 10 feet. This is, however, an average figure. Cleary's results indicate that the altitude lost in carrying out the go-around may be as much as 66 feet on a two-sigma basis, i.e., about one time in 40. Further, this analysis does not take into account altimeter errors, which in a barometric system can amount to approximately 35 feet, also on a two-sigma basis. It is apparent that the missed approach is fraught with risk when the aircraft is permitted to descent to a Decision Height of 100 feet. A margin on only 10 feet is not adequate, especially since it allows no altitude cushion to compensate for higher than normal sink rates or for displacement of the aircraft below the glide slope.

Since half of the altitude loss in go-around is attributable to the time involved in the transition from head-down to head-up and back again, elimination of this time lag would do much to improve the safety of the missed approach maneuver at low altitudes. The nature and severity of the transition problem is eloquently illustrated by the accident investigation report issued after the crash of a DC-7B in November 1962 during an attempted approach to runway 4R at New York International Airport. The Civil Aeronautics Board report stated:

> "Execution of the missed approach procedure by the crew necessitated a transition to instrument reference due to the loss of visual reference. This has to be accomplished at an extremely low altitude. There was little time or margin for error if the maneuver was to be successfully accomplished.
>
> "The Board concludes that additional aircraft rotation was not effected due to a lack of immediate instrument orientation, and that additional power was either not requested or delayed because of other duties."
>
> (Ref. 20)

A further example of the problems and dangers of the missed approach is offered by Beck. (Refs. 21 and 22) A British European Airways Vangard aircraft crashed at Heathrow Airport, London in October 1965 while attempting to land in a heavy ground fog. BEA's minima at that time were 1200 feet RVR and a Decision Height of 150 feet. The reported RVR at the time of the accident was 1200 feet. Three approach attempts were made, and the Vangard's flight recorder showed that each time an altitude of 150 feet was reached a missed approach was executed. On the third go-around that aircraft crashed, killing all on board. Among the conclusions reached by the accident investigation board was that during rotation and pull-up in a missed approach the lag in pressure instruments (such as the rate of climb indicator, the airspeed indicator, and the altimeter) was of such a magnitude that they gave an erroneous picture of the performance of the aircraft. The pilot thought he was climbing too rapidly, apparently pushed forward on the control column, and crashed. Other pertinent points from the investigation are summarized by Beck as follows:

> "1. Pilots may experience some difficulty in the transition from flying on the full flight director instrument during a precise ILS approach to flying on the same instrument as a simple artificial horizon on a go-around.
>
> "2. The range of movement on the pitch scale is so small that a large change in the actual pitch of the aircraft will be shown as a relatively small movement of the pitch indicator.
>
> "3. The airspeed, altimeter, and vertical speed indicator, being pressure operated instruments, are subject to lag and error caused by rapid changes of pitch attitude of the aircraft, and may be as long as 2-3 seconds.
>
> "4. A go-around is much more hazardous than was previously realized."
>
> (Ref. 21)

In view of the importance of the missed approach maneuver and the need for precise control and timing which it imposes, it is understandable that the airlines and the FAA stress the missed approach in pilot training and qualification. The FAA qualification procedure, as outlined in Advisory Circular 120-20 for Category II operations, gives missed approach the same emphasis as landing under reduced visibility. The FAA requires that two approaches be made "under the hood" to the Decision Height of 100 feet. In one of these approaches the hood is removed and the pilot continues to land by visual performance. In the other the hood remains in place, and the pilot must execute a missed approach on instruments with a simulated loss of power in one critical engine.

The realism and appropriateness of this qualification procedure has been subject to criticism. Beck (Ref. 23) points out that check flights are almost always conducted under VFR conditions, which means that the pilot will have unrestricted visual reference from the time the hood is removed. Thus, the amount and quality of what the pilot sees at the Decision Height will differ vastly from the visual cues he would have in true Category II conditions with fog or swirling snow. In the case of the missed approach, the pilot conducts the maneuver by reference to the same instruments he has used to reach the Decision Height, without ever taking his eyes off them to assess the external visual situation. Again, this lacks realism because the pilot is not obliged to revert from visual reference to instruments at the moment of the go-around, as he would have to do in actual Category II operations. Beck concludes:

> "In neither of these two widely practiced maneuvers has the Pilot in Command been given an appreciation of the problems with which he will be faced in low visibilities, nor has he been trained or checked in his judgment regarding a decision. The decision has already been made for him -- by the Check Pilot. Certainly this is not realistic training."

Cane (Ref. 24) has expressed similar criticisms of the method of training and qualifying pilots for the problems of approaches and missed approaches under conditions of low visibility.

> "There is no doubt that when the decision has to be made at a height of 30 metres (100 feet) as to whether a landing is possible, it is the sole responsibility of one pilot to make this decision. In carrying out this task he must assess the value of the visual cues available,

decide whether the aircraft is correctly positioned to continue the approach and whether the cues available are sufficient to enable him to make a successful flare and landing. If he decides for any reason that a landing cannot be made, then an immediate instrument overshoot* is required. It is not a feasible proposition for the same pilot to transfer his attention from the outside world back inside the aircraft in order to commence flying on instruments. He cannot carry out this task safely in marginal conditions himself, unless full head-up overshoot guidance is proved or automatic overshoot is available -- neither of these facilities are provided in the majority of the present proposals for a Category II system.

"The particular problems associated with the transition phase from an instrument approach to a visual landing at very low decision heights and from an instrument approach to an instrument overshoot are normally obscured by the present generally accepted methods of training pilots in this type of operation. Such training is usually carried out with the use of screens either completely obscuring the pilot's sight of the real world, or permitting him normal vision from the cockpit. His ability to operate to this 30 metre (100 feet) decision height is assessed by his performance in landing the aircraft or overshooting, if not correctly positioned, when the screens are removed, or alternatively in overshooting on instruments at 30 metres if the screens are not removed. In the former case, when the screens are removed, he usually has all the normal cues available to him in true visual conditions and therefore gets no appreciation of the problems of decisions that he will be faced with should he actually become visual at this height with the minimum available visibility of 400 metres (1200 feet). In fact, the decision he has to make is governed by the same conditions as those in which he carries out his normal visual landings. In the latter case, the screens remain in place

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* Overshoot, in British parlance, means missed approach.

> and he demonstrates his ability to overshoot on instruments from his decision height with one engine out -- here he has no decision to make. From this it is often assumed by the individual that he is capable of performing both tasks in the real world of restricted visibility. Until a successful system is evolved of simulating low breakouts in low visibilities it is not really possible to give a pilot adequate training in this phase of operations, nor to give him a proper appreciation of the problems with which he will be faced."

Missed approach may be summarized as a maneuver of some inherent risk -- the degree of risk rising in inverse proportion to the altitude at which it is initiated. The risk is compounded by present instruments and procedures which require the pilot to shift his attention from the cockpit to the outside world, and then back again if the missed approach must be executed. Further, the instruments now used for guidance of the missed approach are difficult to interpret and may exhibit dangerous lags in providing information on the flight path of the aircraft. In low visibility operations, where the decision heights are low and the available visual cues difficult to discern, the decision as whether to make a missed approach may be delayed while the pilot tries to assess the adequacy of his visual reference and the correctness of his flight path. An additional factor which contributes to the danger of the missed approach is the deficiency of present training methods which fail to give the pilot adequate familiarity with the problems of low visibility and with the demands of the missed approach under actual operating conditions.

Taxi

In present civil aviation operations the taxiing of aircraft is guided entirely by visual means with supplemental surface movement direction and traffic advice from the ground controller. Visual guidance is likely to remain the primary (and probably the sole) method of guidance in projected Category II operations, in which the Runway Visual Range may be as low as 1200 feet. With the present system of airport lighting, taxiing is not considered to be a major problem, although there are some vexing aspects to trying to find one's way around in darkness and fog, especially at crowded airports. Several airline captains interviewed during this study commented on the risks of making wrong turns on taxiways, taxiing onto the active runway by mistake, and running off the taxiway altogether. There have even been some instances of competent pilots becoming lost on the complex taxiways of unfamiliar major airports. On the whole, however, it would appear that the present system is adequate, though not entirely satisfactory, and that no major effort is forthcoming by the government or the airline industry to effect improvements in the present methods of taxi guidance for Category I and II operations.

On the other hand, there is serious concern and a recognized need for improvement in the methods of taxi guidance in conditions of very low visibility. The following discussion, therefore, will examine the problems which can be expected to arise when civil aviation enters the realm of Category III, where it is contemplated to conduct operations in visual ranges of 700 feet, 150 feet, and eventually 0.

The problem of taxiing aircraft in very low visibility is really three problems. The first is how to guide the aircraft along any given path on the airport surface. The second problem is how to determine which path is the correct one. That is, how does the pilot find his way from the active runway to the terminal and back again? The final element of the taxi problem is avoiding physical contact with structures, ground vehicles and equipment, and other aircraft while moving about to and from the terminal. For convenience of reference these three problems shall be designated guidance, direction, and obstacle avoidance.

The present system of taxi guidance for night and reduced visibility consists of lights of various colors and intensities, either flush-mounted within the taxi surface or raised and placed alongside the path of movement. As the aircraft completes the rollout after landing, the first lights available for taxi guidance are the runway centerline lights themselves. These are flush with the runway surface. The lights are spaced 25-50 feet apart and have a maximum intensity of 2000 candela. The color is white until a point 3000 feet from the far end of the runway, when red and white lights are used alternately. The lights are all read in the last 1000 feet from the end of the runway. Turnoff points along the runway are marked by flush-mounted lights spaced at 12.5-foot intervals, defining the curved path of aircraft travel from the runway centerline to the entry onto the taxiway. These lights are white and have an intensity on the order of 200 candela. The taxiway itself is marked with blue lights spaced 12.5 to 25 feet apart and situated along both edges of the paved surface. The typical intensity of the taxiway lights is 100 candela. (Ref. 25)

It must be emphasized that the above lighting system is employed only on a precision approach runway (the so-called all-weather runway). Turnoff and taxiway lighting at many airports falls considerably short of this standard both in spacing and intensity. However, since the concern here is with Cagetory III operations, this lighting system may be taken as representative of that which will be available to the pilot for taxi guidance in very low visibilities. It should also be noted that, while this system is standard in the United States, it is not used universally in other parts of the world. Generally, however, the all-weather lighting system used by countries which contemplate entering into Category III operations is at least of this quality.

Generally, the adequacy of the taxiway marking system is a function of the intensity and spacing of the lights. That is, the lights must be bright enough to be seen, and a sufficient number must be in view at any time to give an indication of the path to be followed. Bressey (Ref. 26) has pointed out that at some European airports aircraft are now cleared for takeoff in visibility as low as 150 meters (about 500 feet), which is an RVR somewhat less than the Category IIIA minimum of 700 feet. In visibility of 500 feet the range at which taxiway lights can be discerned ("Taxiway Visual Range" is Bressey's term) is only about 165 feet because of the lower intensity of these lights in comparison with runway lights. This amounts to reduction of visual range on the taxiway in comparison with that on the runway by a factor of about three to one, a relationship which holds substantially true throughout the range of Category III conditions.

In modern jet aircraft the downward visibility from the pilot's eye position (cockpit cutoff angle) is limited to about 15% by the nose of the aircraft. In the new jumbo jets this angle has been increased to 18°. The nearest point on the ground which the pilot can see ahead of the aircraft is somewhere between 35 and 90 feet, depending upon the cockpit cutoff angle and how far above the ground the pilot is sitting. Thus, in Category IIIA the pilot will be able to see a segment of lights about 200 to 150 feet in length starting at a distance of 35 to 90 feet from the aircraft. In Category IIIB he will be able to see no, or at most one, taxiway light. (See Figure 12)

The Blind Landing Experimental Unit (BLEU) of the Royal Aircraft Establishment, Bedford, has conducted preliminary studies of the pilot's ability to taxi in severly limited visibilities. Coldwell (Ref. 27) reports a simulator study conducted at BLEU in which airline pilots were required to taxi aircraft in conditions of visibility ranging from 70 to 220 feet. With a cockpit cutoff of 50 feet this meant that for some of the runs the pilots were working with a visual segment of only 20 feet. Two results of interest emerged from this study. First, pilots tend to adjust their taxi speed in low visibility so that they can see a distance ahead equivalent to a constant interval of time. This time varied between 6 and 12 seconds for the pilots taking part in the study. At very low visual ranges where the cockpit cutoff was a large proportion of the visual segment this rule obviously broke down, and taxi speeds seldom exceeded 5 miles per hour. The second important result of the study was that pilots preferred to see at least three taxi lights at all times but could taxi effectively with only two. Since light spacing is dependent upon visual range, which is a function of light intensity, there can be some trade-off between light intensity and the interval between lights. Coldwell also concluded that for some time to come the lower limit of RVR achievable in Cagegory III will probably be determined by the taxi guidance problem. An examination of Figure 12 would suggest that this limit is in the neighborhood of Category IIIB.

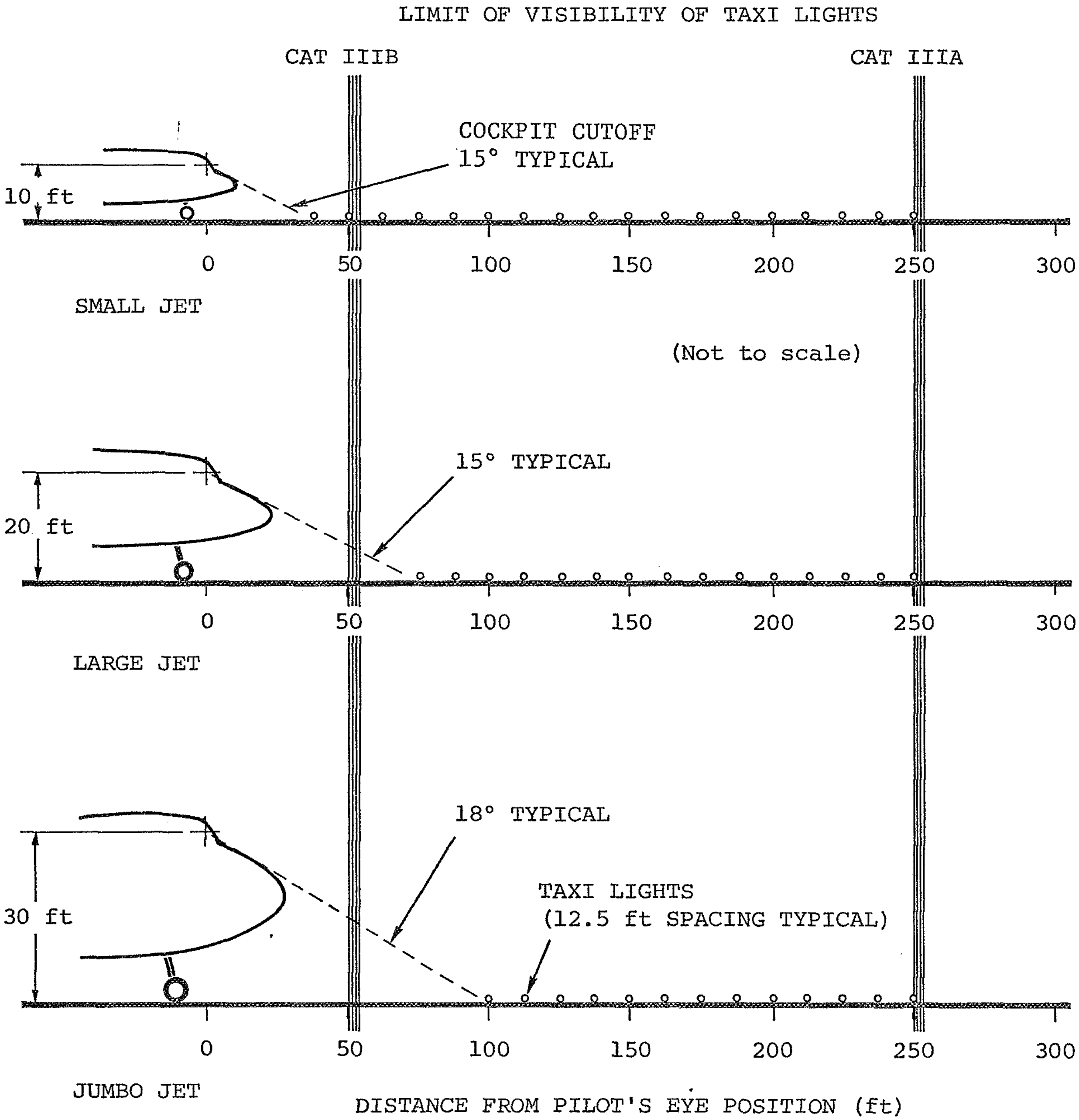

LIMIT OF VISIBILITY OF TAXI LIGHTS
CAT IIIB
CAT IIIA
COCKPIT CUTOFF
15° TYPICAL
10 ft
0
50
100
150
200
250
300
SMALL JET
(Not to scale)
15° TYPICAL
20 ft
0
50
100
150
200
250
300
LARGE JET
18° TYPICAL
TAXI LIGHTS
(12.5 ft SPACING TYPICAL)
30 ft
0
50
100
150
200
250
300
JUMBO JET
DISTANCE FROM PILOT'S EYE POSITION (ft)

Figure 12

The most significant consequence of the BLEU study is that taxi speed decreases as visibility lessens. The effect of low speed taxiing will be a general reduction of the rate at which aircraft can be processed by the terminal facility, which in turn will have an effect on the acceptance rate at which aircraft can be handled in Category III. It may well be that the determinant of the lowest attainable limit of Category III operations will be not the RVR at which aircraft can land but the visual range required for safe and efficient movement of an aircraft and crash and rescue equipment on the airport surface.

Guidance, however, is only one part of the problem. Another part is direction, i.e., ascertaining that the aircraft is on the correct path to or from the terminal. At present the pilot relies on what he can see of the taxiway plus his own knowledge of the airport and voice direction from the ground controller in the tower. The ground controller, in turn, bases his direction on what he can see of the aircraft and the taxiways or -- in reduced visibility -- on radar information from Airport Surface Detection Equipment (ASDE). Even under Category I and II conditions today this system does not always prove satisfactory. Taxiway lighting may cause confusion, especially when weather and darkness obscure or disguise airport landmarks. The need for steady voice communication with the ground controller burdens the voice radio channels and may compound the confusion when several aircraft are being directed at the same time. One writer (Ref. 28) has characterized the standard U.S. taxiway lighting system as a "blueberry-pie maze of lights". While this may be a somewhat facetious description, it does underscore the shortcomings of the present system of guidance and direction which relies almost exclusively on visual means.

London(Heathrow) Airport, which has a high proportion of bad weather, uses a very advanced lighting system for direction and ground traffic control. The system consists of green lights in the center of the taxiways to indicate the route for individual aircraft. The pilot has only to follow the green lights to his destination. A bar of red lights is displayed across the taxiway, with the green lights discontinued beyond, whenever the aircraft is to hold at a given point. In recent years this system has been supplemented with strobe lights in the taxiway surface to give another and more prominent indication of direction and routing. (Ref. 29)

In Category III even a system as advanced as that of the London Airport will probably not be adequate because it relies on what the pilot can see at one end and the quality of present ASDE at the other. Litchford (Ref. 30) has stated that direction is one of the major problems to be solved before Category II operations, much less Category III, can be conducted routinely and safely. The control of as many as 100 aircraft moving about a multi-runway airport at moderate speeds, without visual contact with each other and with the tower, is a formidable undertaking. Litchford summarizes the problem of direction and control as follows:

> "The current requirements for electronic facilties for safe CAT-II-B landing operations disregard ASDE (Airport Surface Detection Equipment). But under low-visibility conditions we must have this short-range but very-high-resolution radar (jet outlines, runway details, taxiway occupancy, etc. are pictured) to replace the visual cues the tower normally uses to control the surface traffic.
>
> ASDE facilities should be mandatory for anything with less visibility than CAT I, yet ASDE's limitations must also be recognized.

> Even though a hundred aircraft presumably under surface control may be "seen" by the radar, it is far from evident just how they should be controlled. Semi-automated sections of runways, taxiways, gates, etc. -- much like the "block signaling" used for control of railroad traffic -- have been tested and currently look like the best approach to this problem. Just what electronic element should sense the presence and location of the aircraft and signals the information to the controller, and what form instructions to the pilot should take, are still open to question. However, providing direct guidance to each aircraft may also prove mandatory, since the interaction of all the routings and conflicts possible on a massive super jetport of the future are beyond comprehension.
>
> Thus a "Micro" surveillance, detection, navigational, and control system must be evolved for airport surface control. ASDE or its modernized version should be one of the three elements, the other two being surface navigation and semi-automated surface control of aircraft.
>
> Semi-automated decisions of efficient routings, crossings of active runways, and optimization of traffic flow of perhaps 100 aircraft to and from two, three, or even four parallel runways spell out a big electronic engineering challenge for a small piece of real estate. And we are learning airport real estate is probably the most difficult thing to obtain in our modern society. What we have and what we gain in airport real estate must be used to the utmost efficiency and with complete safety.

Directing the pattern of movement of large number of aircraft at a busy airport is more than just a problem of electronic detection and routing. There is also the problem of how to convey the necessary information to the pilot. Experiments have been conducted with low visibility guidance and display systems, primarily in England where there is a more immediate concern because of the prevalence of bad weather. One such system makes use of a cockpit indicator to provide right, left, stop and go signals derived from a cable buried in the taxiway. Trials have also been conducted of specially equipped ground vehicles which can pick up signals from a buried cable and relay them to the pilot by visual means. (Refs. 31 and 32) while initial results with both methods are promising, the expense of furnishing an airport with the cables and associated equipment and of providing the aircraft or ground vehicles with the required sensors and displays is of enormous proportions. At present there is no solution which is fully satisfactory on technical and economic grounds.

Avoiding contact with ground obstacles and other aircraft is the third major element of the problem of taxiing in reduced visibility. The present system of "see-and-be-seen" for aircraft and of warning markers and lights for surface structures relies entirely upon the pilot's vision. In conditions where the pilot can see only a few feet, or at most a few yards, from the cockpit the present system is plainly inadequate. Since it will not be possible to assume that the pilot can see and avoid obstacles, any system for taxi guidance and control in Category III must include some other, non-visual method of guaranteeing an invoilable envelope about the aircraft and of directing movement so that collisions do not occur.

AIRCRAFT-PECULIAR REQUIREMENTS

Each type of aircraft has peculair flight characteristics which impose special requirements for proper handling and control.

The consequences of these differences are unhappily illustrated by the airline safety record, which shows a "spike" in the accident rate curve whenever a major new class of aircraft is introduced into service. One of the largest and most difficult of these adjustment periods accompanied the changeover from piston and turboprop aircraft to jet aircraft. A second such period coincided with the advent of the short haul jets such as the Boeing 727, Douglas DC-9, BAC 111, and Caravelle. At the present time, with the jumbo jets coming into service and the SST expected within a few years, it is reasonable to assume the unfamiliar performance characteristics of these aircraft will produce new problems in the areas of guidance and control.

It would be impractical and unnecessary to catalog all the performance differences among aircraft types. The purpose of this section is merely to sketch some of the major differences and to trace their consequences in terms of the pilot's control tasks. Emphasis will be placed upon the problems presented by the newer types such as the jumbo jets and supersonic transports. However, the differences between jets and propeller aircraft will also be touched upon because, as jets come into wider use in general aviation and feeder airline operations, the historical problems of propeller-jet transition can be expected to recur.

One of the major and most obvious differences between propeller and jet aircraft is the latter's higher approach and landing speeds. Not only is the whole exercise of approach and landing more compressed in time, the control of critical parameters such as rate of descent, flight path angle, and angle of attack is more demanding in jet aircraft. This aspect of jet aircraft performance was examined in some detail earlier in this chapter in connection with the general problem of approach and landing. There is no need for elaboration here except to indicate that the lower values of speed and rate of descent given in Table Vc and Vd (pp III-10) are representative of propeller aircraft while the higher values are characteristic of jets. Thus, propeller and jet aircraft present a performance spectrum in which maximum values are over 50% greater than minimum values.

The differences between propeller and jet aircraft are also reflected in applied practical aerodynamics. The flight characteristics of swept-wing jet aircraft differ markedly from propeller aircraft in such areas as speed stability, stall onset and control, dutch roll tendency, response to turbulence upset, effect of asymetrical power operation, thrust required vs. thrust available curves, and engine response ("spool-up") times. Thus, the problems imposed by higher approach and landing speeds in jets are complicated further by the adverse effects of certain handling qualities. The net result is to tighten the pilot's performance requirements and at the same time to introduce new and more critical elements in his control task.

The importance of these differences was emphasized by a pilot in charge of training for a major airline. During an interview in connection with this study, he stated that the major training problem faced in teaching pilots whose previous experience was confined to propeller aircraft was how to manage approaches in jets with their longer bodies, greater inertia, steeper angles of attack, and back-side-of-the-power-curve operation. The need, as he phrased it, is for a display which permits a more prompt and accurate assessment of flight path angle and speed (angle of attack) in approach and landing.

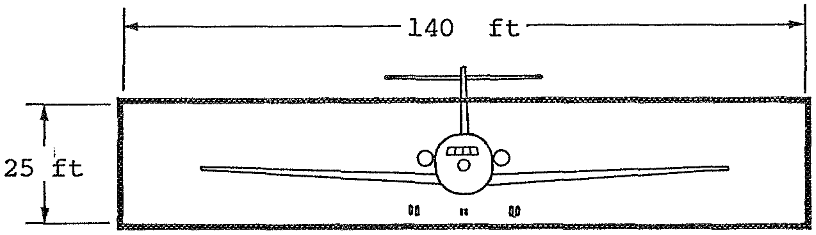
Another senior airline pilot (Ref. 33) has remarked that the four most critical maneuvers to be considered in training pilots to operate new types of aircraft are 1) engine failure at takeoff at V_1, 2) low altitude maneuvers or circling approaches, 3) 50% power loss landings, and 4) missed approaches. He based his conclusions on industry experience with new aircraft in the past and speculated that the very same problems were likely to accompany the introduction of the jumbo jets. It is hardly coincidental that for all these maneuvers precise control of flight path angle and speed are crucial elements of the pilot's task. Moreover, all of these maneuvers are conducted at present by visual reference, either wholly or in part.

Additional commentary on the differences between propeller and jet aircraft is offered by Beck (Ref. 34) and Litchford (Ref. 35). Both writers stress the relationship between approach and landing accuracy and the slower response time of larger jet aircraft. Generally, the larger the aircraft the more tightly controlled and precise must be the approach. For example, the time needed to correct for lateral displacement from the desired approach path (the side-step maneuver) varies directly with the weight (inertia) of the aircraft. Litchford reports that studies conducted by the UK Ministry of Aviation in 1961 showed that about 10 seconds was required for a 50-foot side-step in propeller aircraft. For jet aircraft, with a more "sluggish" response, a lateral correction of this magnitude might take as much as 15 seconds. Since the side-step must be completed before flaring the aircraft and committing it to a touchdown, the pilot must carry out the side-step further in advance in jet than in propeller aircraft. This leaves the jet pilot one of two courses of action. Either he must start the side-step at a higher altitude (which may be impossible if he is operating in low visibility and cannot see that he needs to make a correction) or he must hold off touching down until the side-step is completed. The consequences of the latter are a touchdown much further down the runway than normal and a reduced distance available for rollout and deceleration. Beck, in a similar analysis, concluded that a side-step to correct for a 10-foot lateral effort in a jet aircraft would result in a touchdown over 900 feet beyond the normal distance from the threshold.

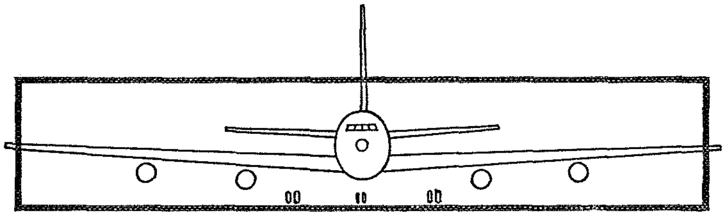
Control in the vertical dimension is likewise affected by the differences between propeller and jet aircraft, and even more so by differences in aircraft size. Jets are generally larger and heavier than propeller aircraft. Since increased weight also involves increased speed (rate of descent) and since downward inertia increases with the square of velocity, the net effect for jets is a slower response for vertical maneuvers such as flare and missed approach. Thus, not only is there a greater rate of descent to be overcome, but also the time to overcome it is prolonged by the aerodynamics of large aircraft with jet propulsion. Concern with the problems of mass interia and the slower response of jet engines to power changes has led to extensive experimentation with faster and more effecitve methods of controlling lift and large jet aircraft. All of the new jumbo jets employ spoiler mechanisms to provide direct lift control at constant airspeed and pitch angle so that vertical maneuver can be accomplished through translation rather than rotation. The presence of these devices reflects an awareness of the more demanding vertical control tasks which come along with increased size and weight. There is equal awareness, but much less certainty about the solution, of the problem of how to provide the pilot with the flight path guidance needed to make best use of direct lift control.

The size of the aircraft has another important effect upon the pilot's guidance and control tasks. The aircraft grow larger, but the dimensions of the spatial envelope into which the aircraft must be fitted remain nearly constant. Tolerances for lateral and vertical displacement from the approach slope do not change appreciably for jumbo jets in comparison with large or medium jets. The dimensions of the runway remain the same. However, in relative terms these tolerances grow tighter as aircraft size increases.

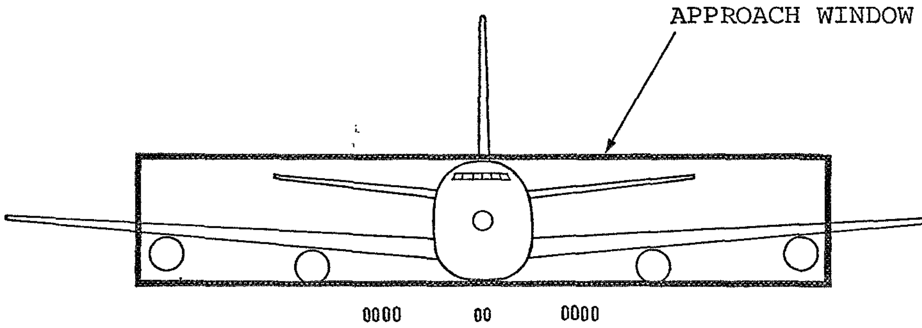
For example, the size of the approach "window" at an altitude of 100 feet (the Category II decision height) is approximately 140 feet horizontally and 25 feet vertically, but these are absolute terms. If the tolerances are expressed as proportions of basic aircraft dimensions, the envelope shrinks as the aircraft grows larger. (See Figure 13) The lateral approach path error tolerance at an altitude of 100 feet, expressed as a percentage of wing span, is ± 65-70% for current medium jets. That is, the aircraft can be displaced laterally from the ideal approach path by as much as 70 feet (70% of its wing span), and the longitudinal axis of the aircraft will still be within the approach window. For large jet aircraft this same 70-foot linear displacement implies a tolerance of ± 50% of wing span. For jumbo jets and supersonic transports the tolerance is ± 35-40%. Vertical tolerances, expressed as a percentage of wheel-to-eye distance, are ± 100% for medium jets, ± 65-70%



MEDIUM JET



LARGE JET



JUMBO JET

(Adapted from Stout & Naish, Ref. 36)

Figure 13

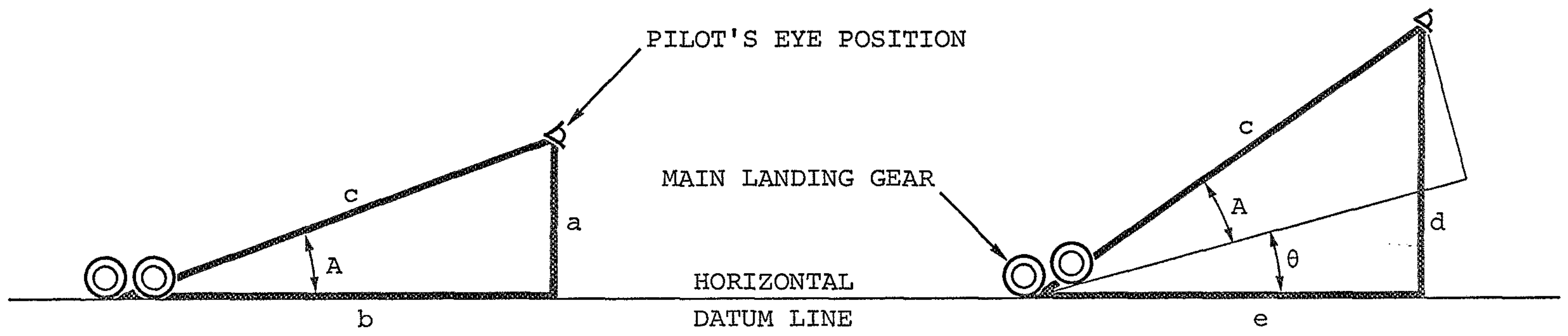
for large jets, and ± 25% for the SST. Thus, there is less margin for either horizontal or vertical error with larger aircraft. Since guidance of the aircraft at an altitude of 100 feet is accomplished by visual reference in both VFR and Categories I and II of IFR, the pilot's visual task becomes more and more exacting with the increase in aircraft size.

The demand for greater accuracy of guidance and control with larger aircraft carries through to touchdown and rollout. The tolerance for lateral displacement from the runway centerline at touchdown is a function of the overall width of the landing gear. With present medium and large jets, whose landing gear width is on the order of 20-30 feet, the pilot has some latitude in where he touches down on a 150-foot wide runway. With jumbo jets, where the landing gear width is 60-75 feet, this margin is sharply reduced. That is, the pilot of a jumbo jet must put the aircraft down within 30 feet or so of the centerline to assure a safe rollout. The distance of 30 feet represents only about half of the total width of the landing gear.

Probably the most important effect of aircraft size is the influence which it has upon the pilot's visual reference for controlling the approach path. In small aircraft the vertical distance between the pilot's eye position and the landing gear is only a few feet. With larger aircraft the wheel-to-eye distance becomes a significant factor which must be compensated for in selecting a visual aiming point for the approach. That is, in lining up for the approach the pilot selects an aiming point on the runway and flies the aircraft so that the point remains in constant angular relation with the horizon. Assuming a steady approach path, the pilot's eye will follow a line which is depressed below the horizontal by an angle equal to the desired approach slope and which terminates at the aiming point. The landing gear, however, follow a lower but parallel path and will make contact with the runway short of the visual aiming point. The distance between the eye path and the wheel path is a function of the position of the landing gear in relation to the cockpit and the pitch of the aircraft in the approach attitude. Figure 14 shows the derivation of wheel-to-eye distances in the approach for typical large jets, a jumbo jet, and a supersonic transport.

If the pilot flies a 3° visual approach to an aiming point 1000 feet beyond the threshold, the height of his eye above the ground will be about 50 feet when the aircraft crosses the threshold (assuming that the aircraft has not yet been flared). The landing gear will cross the threshold at a lower height, which is equal to 50 feet less the wheel-to-eye distance. (See Figure 15a) In case of the jumbo jet and the SST, where the wheel-to-eye distances are 35 and 47 feet respectively, flying a standard visual approach to a visual aiming point 1000 feet beyond the threshold will result in a dangerous erosion of the landing gear clearance height at the threshold. To maintain the prescribed 50-foot clearance between the landing gear and the threshold, as shown in Figure 15b, the pilot must choose a visual aiming point correspondingly further down the runway. In the extreme case of the SST this requires picking an approach aiming point over 2000 feet from the threshold.

Thus, the size of the aircraft (specifically the wheel-to-eye distance) plays a major role in selecting the aiming point and in determining the overall safety of the approach. For visual approaches in the jumbo jet or the SST the pilot must



BASIC AIRCRAFT DIMENSIONS

a = vertical distance, pilot's eye position to ground

b = horizontal distance, pilot's eye position to main landing gear

$A = \arctan \frac{a}{b}$

$c = a \cdot \csc A$

ROTATED TO APPROACH ATTITUDE (θ)

θ = pitch attitude in the approach

d = vertical wheel-to-eye distance, in approach

$= c \cdot \sin (A + \theta)$

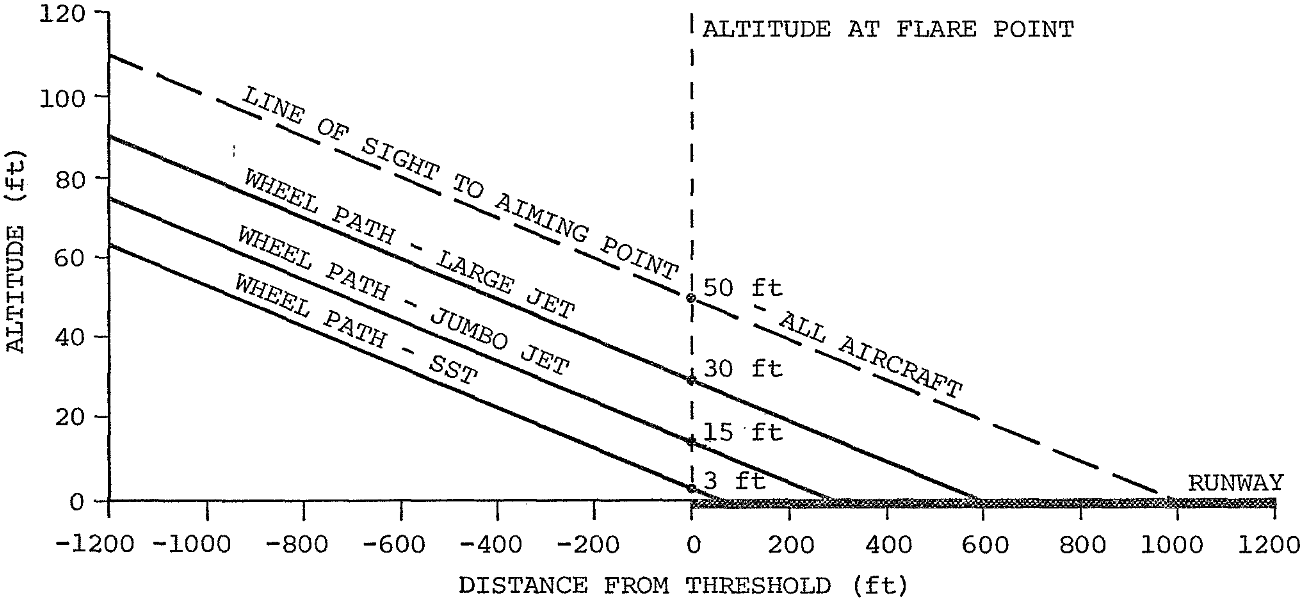
e = horizontal wheel-to-eye distance, in approach

$= c \cdot \cos (A + \theta)$

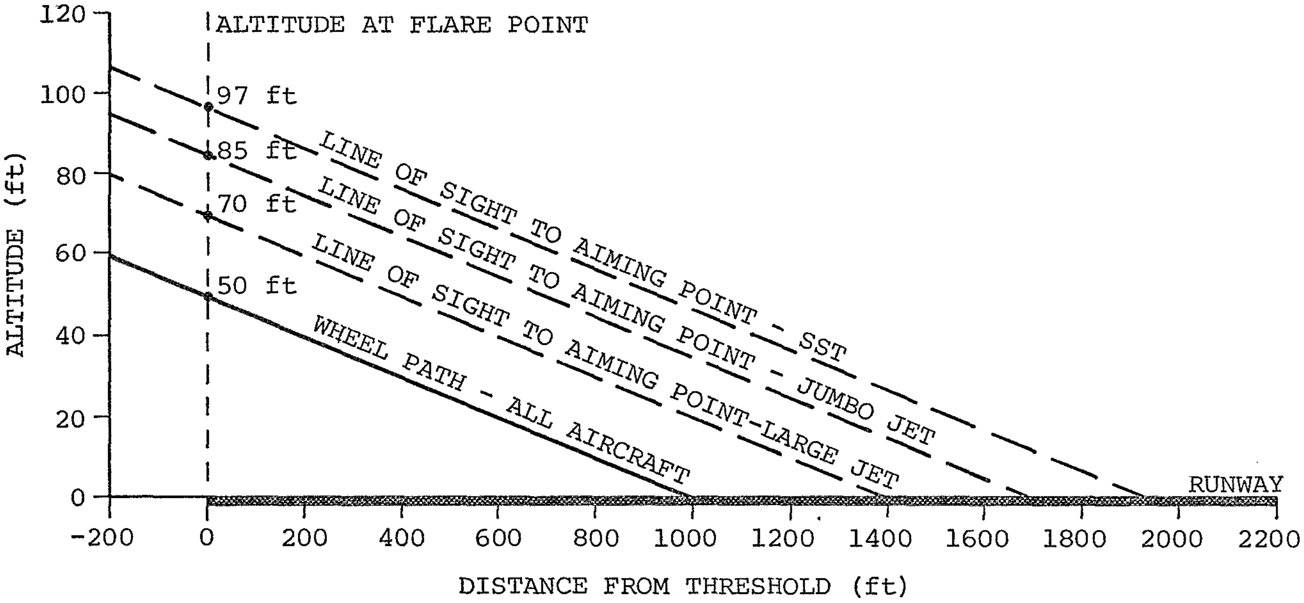
	EYE POSITION IN RELATION TO GROUND (a)	MAIN GEAR (b)	PITCH (θ)	WHEEL-TO-EYE DISTANCE IN APPROACH VERTICAL (d)	HORIZONTAL (e)
LARGE JET	17 ft	65 ft	3°	20 ft	64 ft
JUMBO JET	30 ft	100 ft	3°	35 ft	98 ft
SST	27 ft	100 ft	12°	47 ft	92 ft

(Based on data from Sleight, Ref. 37)

Figure 14



A. EFFECT ON THRESHOLD CLEARANCE IF AIMING POINT IS CONSTANT



B. EFFECT ON AIMING POINT IF 50-FOOT WHEEL CLEARANCE HEIGHT AT THRESHOLD IS MAINTAINED

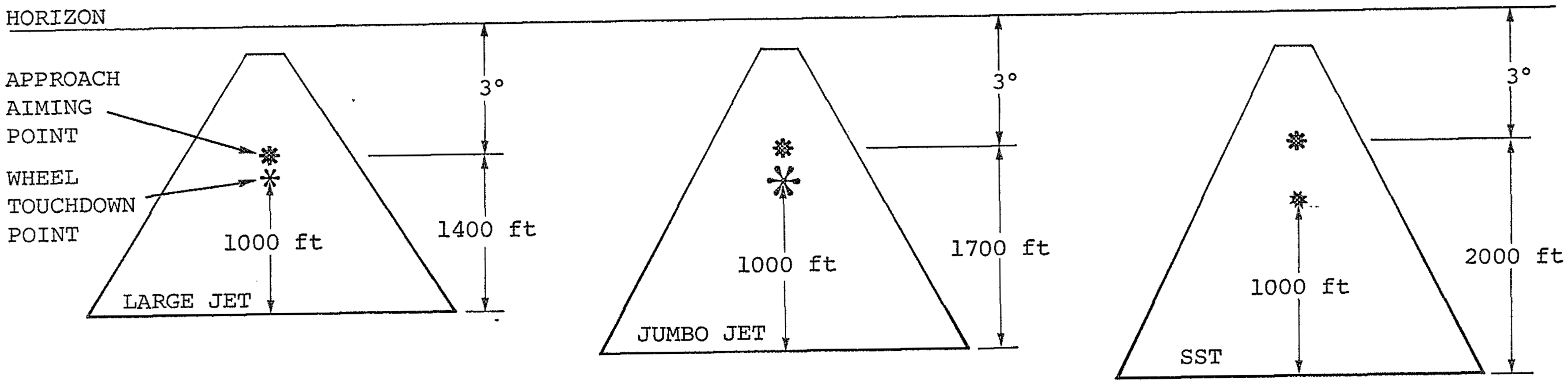
Figure 15

shift his aiming point much further beyond the threshold, with the result that the overall landing distance is increased. Failure to change the aiming point will create the danger of a short landing. For ILS and VASI approaches the situation is even more complicated. As will be shown in Chapter V, the instrument and visual approach aids now in use are predicated upon an aiming point about 1000 feet from the threshold, which is much too close for the jumbo jet and the SST. If the pilot flies the approach using ILS or VASI in their present locations he will either have to use some sort of "Kentucky windage"or he will have to shift his aiming point in that last few seconds of the approach, neither of which would be an acceptable practice. Alternatively, if the ILS and VASI locations are moved further down the runway to accommodate the jumbo jet and the SST, they will no longer be appropriate for the majority of the other aircraft using the airport. The solution of installing two sets of approach aids, one for normal users and the other for very large aircraft, is probably not practical on both economic and technical grounds. There is a need, therefore, for an approach and landing aid which is flexible enough to serve aircraft of all sizes.

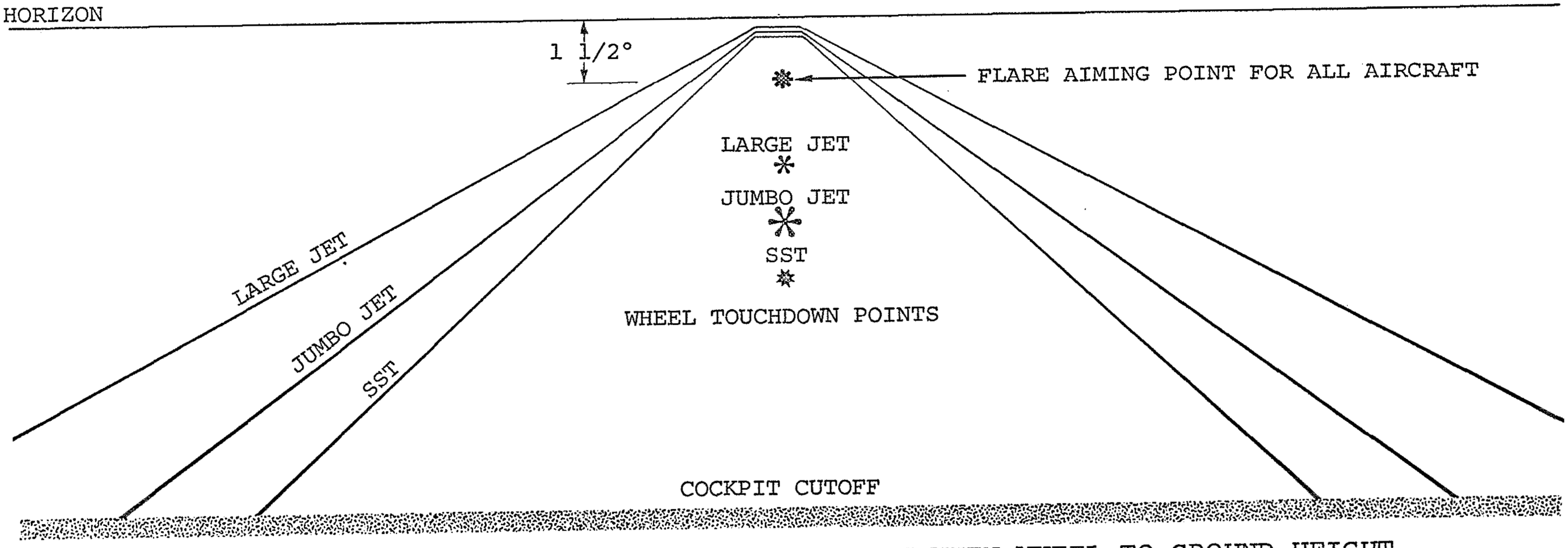
Wheel-to-eye distance also has a great influence upon the decision as to whether to continue the approach or abort at the moment of breakout in low visibility approach. In Category II operations, for example, this decision must be made at an altitude of 100 feet. This means that in a jumbo jet the pilot's eye position (the only point from which he can make a judgment by external visual reference) will be about 135 feet above the ground plane. If the pilot makes a decision at this point, he will not be taking full advantage of the authorized visibility minimum. If he elects to wait until his eye position reaches a height of 100 feet (an interval of about 3 seconds), the landing gear will be only 65 feet above the ground -- a dangerously low altitude at which to initiate a missed approach in a 235-ton aircraft. In the SST, where the wheel-to-eye distance is nearly 50 feet, the situation will be worse.

The increased wheel-to-eye distance of the jumbo jets and the SST has another effect which grows in significance as the aircraft nears the runway. At the start of a visual approach the difference between the eye path and the wheel path will have a negligible effect on runway perspective. However, by the time the aircraft reaches an altitude of 100 feet or lower, the wheel-to-eye distance will produce a marked change in the pilot's perspective view of the runway. Since the pilot uses the shape and relative position of runway elements as primary visual cues for flight path and flare control and for altitude estimation, the success of the flare and touchdown will be profoundly affected. Figure 16 is an illustration of the perspective differences at altitudes of 100 feet and 20 feet in a large jet, a jumbo jet, and an SST. For pilots not fully accustomed to the visual angles of the approach in the jumbo jet and the SST, the elongation of the runway shape will create the impression that the approach angle is too steep. As a result, there will be a tendency to make the flight path shallower and thereby to land long, which in turn will introduce the danger of overrun.

Likewise, there will be some confusion in estimating the point of contact with the runway in very large aircraft. In each of the upper illustrations in Figure 16 the touchdown point is 1000 feet past the threshold. In the lower illustration the touchdown point has been shifted to 1500 feet from the threshold



A. RUNWAY AS SEEN FROM PILOT'S EYE POSITION WHEN WHEEL-TO-GROUND HEIGHT IS 100 ft ON 3° APPROACH APPROXIMATELY 1000 ft FROM THRESHOLD



B. RUNWAY AS SEEN FROM PILOT'S EYE POSITION WHEN WHEEL-TO-GROUND HEIGHT IS 20 ft AND AIRCRAFT IS FLARED TO 1 1/2°

Figure 16

as a result of flare. However, the angular relation between the touchdown point and the visual aiming point does not remain constant for all aircraft. This variation will make it extremely difficult for the pilot to judge by unaided visual means whether the approach and flare are proper and how to correct them if they are not. His visual task will be even further complicated if there is a large and unexpected perturbation of the flight path, such as occurs with atmospheric turbulence, wind shear, or trailing vortex from preceeding aircraft.

Although the previous discussion has dealt largely with approach and landing, a similar set of problems are engendered in other flight phases by the advent of the jumbo jet and the SST. For example, rotation of the aircraft at takeoff must be controlled to a much more precise degree in the jumbo jet and the SST in order to avoid tail scrapes in the event of over-rotation and inadequate climb performance and obstacle clearance in the event of underrotation. (Ref. 38) The problem of taxiing in reduced visibility with the larger aircraft was discussed in an earlier section. Missed approach, because of the increased weight and length of the jumbo jet and the SST, also becomes a more demanding and inherently risky maneuver, especially at the lower decision heights called for in projected Category II operations.

Gerber (Ref. 39) has expressed the understandable concern which pilots feel about operations in the new jumbo jet aircraft. He has suggested that the problems of becoming properly adjusted to the new visual cues and the different handling qualities are such that in-flight training should be conducted only in restricted circumstances. Among the limitations he suggests are:

1. Only in daylight.
2. Only in ideal weather conditions (no turbulence, crosswind, visibility restrictions, etc.)
3. Only after extended simulation practice.

He also recommends that emergency procedures and missed approaches be practiced only after the trainee pilot has had a substantial background of normal flight experience. Finally, Gerber advises that more training time in the aircraft be spent on taxiing (especially on narrow taxiways), parking and maneuvering in confined areas, VFR takeoffs, and flying visual approaches with the aid of VASI to get the proper angles and sink rates established. It is significant that all of Gerber's recommendations deal with tasks in which visual reference is the sole or major source of guidance and with assuring that external visual cues are optimum during training. If adequate visual reference is this important for training, how much more so will it be in regular operations where these restrictions cannot be observed?

Thus, the increased size of the next generation of commercial transports will pose a number of problems both in the area of control and in the area of the pilot's visual tasks. The mastery of the new visual angles will take some time to accomplish since it is basically a process of accumulating experience and becoming adjusted to new visual patterns. The pilot must not only learn how to interpret the changed visual cues, he must also learn to adjust his control responses to account for differences in aircraft characteristics and handling qualities. In aircraft such as the jumbo jet and the SST, where the pilot's vantage point is so far above and forward of the center of gravity, the general concern will be not so much the trajectory of the pilot's eyes through space but instead the path described by the center of gravity. There is an urgent need for an instrument or aid which will assist the pilot in making estimates of the correct visual angles and which will provide a more direct indication of the actual flight path of the aircraft.

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CHAPTER IV

THE PILOT'S VISUAL TASK

During final approach the aircraft flies a straight line flight path to the runway over a distance of 4 to 7 miles and over altitudes ranging from 1,000 to 2,000 feet above runway elevation down to the runway. As described in Chapter III, the pilot tasks during final approach are to control the aircraft in the vertical plane and the horizontal plane. Control in the vertical plane comprises control over airspeed, angle of attack, altitude, rate of descent, and flight path angle. Parameters of horizontal control include roll control and lateral alignment of the flight path with the runway centerline. These control variables are monitored and corrected by the pilot during the entire final approach, whether in an automatic or manual landing mode. The final approach includes these significant milestones or events: initiation of final approach, arrival at decision height, and, given the go decision, flare, de-crab, landing and roll-out. For the pilot to control the variables affecting alignment with the runway, vertical and horizontal displacement from the runway and runway centerline, vertical and horizontal velocities and accelerations, he needs certain information. This chapter will discuss the information required which is primarily acquired through the pilot's visual sense.

VISIBILITY

Before defining what the pilot needs to see to achieve each milestone in the final approach, it must first be determined what he can see under different conditions of visibility. It is obvious that the visual scene presented to the pilot is a direct function of environmental conditions as well as patterns of objects and markings. Environmental conditions include amount of available light (day vs. night) and factors which degrade visability to some extent (fog, rain, ice, etc.) Beck (Ref. 1) described five different types of visibility usually discussed for the approach and landing operation. These include:

- Meteorological visibility - based on human judgment and included in the teletype weather sequence report.
- Tower visibility - what the airport control tower operator sees.
- Pilot visibility - what the pilot sees.
- Runway visibility - the distance along an identified runway that an observer can see a 25 foot-candle light at night or perceive dark objects against the sky background during the day.
- Runway visual range (RVR) - the horizontal distance a pilot may expect to see down the runway. The range is computed by having a projector emit a beam of light, usually along a 500 foot path, which is received by a photo-electric detector which measures amount of light received as a percentage of the amount received through a clear atmosphere.

The runway visual range is currently used as the estimate of what the pilot can expect to see during his approach. One problem with this procedure is that the RVR is measured close to the ground while the aircraft is somewhat more removed from the ground. It is not uncommon that fog conditions can exist between the pilot's eye and the ground which are not accounted for by the RVR. Beck estimates that RVR is not representative of what the pilot sees at least 20 percent of the time. Therefore, once in five landings a pilot could be misled in his visual judgments due to information received from the ground.

The RVR is also important in determining the minimum visual segments which must be available to the pilot under different categories of IFR landing. For each category a minimum decision height and corresponding RVR is specified. The decision height is described as a specified height above the highest elevation in the touchdown zone at which a missed approach must be initiated if the required visual reference has not been established. The limits on decision height and RVR are as follows:

Category	Decision Height (ft.)	RVR (ft.)
I	200	2600-1800
II A	150	1600
II B	100	1200
III A	0	700
III B	0	150
III C	0	0

At the present time airline operations below Category IIB are not authorized. The rules for Categories I and II prescribe that the pilot may proceed below the appropriate minimum altitude only if he has "adequate visual reference."

INFORMATION REQUIREMENTS AND VISUAL CUES

These categories are prescribed for IFR conditions. During VFR the pilot has visual contact with the runway throughout the final approach. During the final approach the fixed wing pilot flying IFR views the external situation 56 percent of the time and, after the decision height and go decision, the pilot views the outside world almost continually. Given this demand, what are the information requirements and visual cues which enable the pilot to use visual information to control horizontal and vertical displacements, velocities, and acceleration? As stated in Chapter III the requirements prior to flare include:

- Identification of the landing site
- Alttitude reference
- Speed reference

- Distance to the runway
- Positive threshold and aim point definition

The visual cues associated with each of these information requirements are presented below.

Identification of the Landing Site

In his report on vision in military aircraft, Wulfeck, et al (Ref. 2) enumerated the visual cues which help a pilot discriminate a runway from surrounding terrain. These cues include brightness contrast, color contrast, and texture differences. At greater distances the brightness contrast cue is dominant. As the runway is approached, color contrast and texture increase in importance. Measurements of brightness contrast between runway surface and surrounding terrain led to the conclusions that a white concrete runway viewed against an earth background will not be detected until the aircraft is about 2400 feet from the runway (.4 nautical miles).

Flight Path and Attitude Reference

The aspects of the visual world which enable the pilot to effectively control his flight path and attitude are identical with those which are used in the control of horizontal and vertical displacements, velocities, and accelerations. These include the horizon, the impact point on the runway or point X, the relationships between point X and the horizon, the runway centerline extended, and runway markings or landing lights.

The horizon gives the pilot the primary attitude reference in the vertical plane, i.e., pitch and roll. Changes in aircraft attitude in the pitch and roll axes are reflected in displacements and rotations of the horizon. The relationship between the horizon and the impact point or point X (the point at which the tangent of the aircraft track intercepts the ground, Ref. 3) gives the pilot information concerning glide slope. An increase in the distance between impact point and the horizon indicates a projected overshoot (provided that the impact point and the aim point coincide) while a decrease in the angular distance incidates an undershoot (Behan and Siciliani, Ref. 4).

The runway centerline extended, and its spatial relationship with the horizon, provides the pilot with information whereby he establishes the adequacy of his alignment during the approach. Errors in alignment are attributed to offsets in bank angle and lateral displacement. Given that the pilot sees the horizon, the presence of an undesired bank angle is readily discernible. Without the horizon and seeing only the runway centerline, the pilot is unable, based on visual cues alone, to attribute a misalignment of the centerline to a bank angle or to lateral displacement. Thus while the horizon is essential for visual judgments of vertical displacement, the relationships of the horizon and runway centerline extended provides the necessary visual information for judgments of lateral displacement.

On a clear night, when the horizon and runway centerline markings are obscured, the pilot makes visual judgments of his vertical and horizontal displacement based on information recevied from the approach and runway lights. Beck (Ref. 5) presented an illustration of the present U.S. Category A approach and runway light configuration which is reproduced here as Figure 17. The approach lights effectively extend the runway centerline 3,000 feet out from the threshold. The approach light configuration consists of 27 groups of lights spaced 100 feet apart. In place of the 28th group is a set of three red terminating bar lights aligned perpendicular to the approach centerline and extending 50 feet to the right and left. There is no 29th group of lights which results in the black hole immediately before threshold. At a distance of 100 feet from the threshold, two red wing lights are emplaced left and right of centerline.

The 1,000 foot decision bar (white) extends 50 feet right and left of the centerline.

The approach light system is controllable in five stages of brightness. Condenser discharge sequenced flasher lights or strobe lights have no intensity control and in stages 1 through 3 they terminate at the 1,000 foot bar. In stages 4 and 5 they run the full length of the approach light system up to 300 feet from threshold.

Green threshold lights, spaced no greater than 10 feet apart, extend over the end of the runway. The runway centerline lights extend from runway threshold to threshold. The spacing of these lights is not standardized but is usually 25 feet. The intensity of the centerline lights is 20,000 foot candles on-center peak.

Touchdown zone lights of 7,500 foot candles maximum intensity, extend 3,000 feet down the runway from threshold. Each group of lights is placed 30 feet to the left and right of the centerline lights and are spaced 100 feet apart. The centerline and touchdown zone lights are of variable intensity. High intensity runway edge lights, spaced 200 feet apart, are located off the edge of the runway. These lights are variable intensity in five discrete steps with a 10,000 foot candle maximum (Ref. 5).

It is assumed that when flying at night the pilot uses the information from the light system to mentally construct what he would see in the daylight. Thus the lateral light arrangements, the 1,000 foot bar, the red terminating bar, and the runway threshold lights provide the pilot with the same alignment cues derived from the horizon since they too are perpendicular to the centerline.

As reported by Wulfeck, et al (Ref. 2), the visual cues provided by runway lights alone have been demonstrated to be inadequate for landing where visibility is poor. Hence the approach light system was implemented. An approach light system must be able to satisfy two classes of visual requirements. First, it must supply all visual cues needed to align the aircraft with the runway, to achieve and maintain proper glidepath, and to aid in maintaining or adjusting aircraft attitude and make the rapid critical adjustments required for a safe landing. These requirements are not met by the spatial pattern of the lights. Second, the pilot must be able to see the approach light system far enough away to enable his shift from instruments to visual flight before reaching the point where he can no longer perform precisely on instruments. This requirement is not met by using intense monochromatic lights.

One problem with the use of approach lights is to clearly define where the runway begins. This can be done by using radically different runway and approach lights or by using special boundary lights between the two, or both (Ref. 2).

A gross cue to flight path and attitude reference is the orientation and perceived size and shape of the runway, either as perceived directly or as outlined by the runway edge lights. Behan and Siciliani (Ref. 4) make a point of the pilot's use of runway perspective as a cue to flight path adequacy. On a given approach, if a runway appears long and narrow, the pilot judges that the aircraft will overshoot. Problems with this cue were discussed in Chapter III of this report where it was determined that the variability which exists in length and width of different runways is a source of ambiguity in the pilot's visual reference. Without knowledge of the dimensions, the pilot cannot determine, based on visual cues alone, whether the perceived shape of the runway is due to runway variables or flight variables (altitude, distance, and glide slope). Figures 2 and 3 illustrate this ambiguity. This criterion was supported by Wulfeck, et al (Ref. 2) who asserted that a pilot approaching an unfamiliar airport may have trouble judging position by the shape of the rectangle outlined by runway lights. After a few landings at one airport the pilot learns the length-to-width ratio for that runway which are used to visually determine glide slope. Going to a strange airport where the runway is shorter or wider, if he attempts to use the same perspective cues as before, the pilot will end up high and come in at too steep an angle. If the unfamiliar runway is longer or narrower, the pilot will come in low.

Altitude Reference

Bell (Ref. 6) reported that for any runway width the perspective angle that the runway edges make with the horizon at the vanishing point is a function of altitude alone. This implies that a pilot could estimate altitude by this apparent angle if he is familiar with the runway dimensions. It is concluded that this angle may serve as a cue for altitude judgments (Ref. 6).

The cues used by the pilot in judging altitude are the same as those used in judging distance. These include relative size of objects, aerial perspective and motion perspective. The relative size cue refers to the situation in which objects of known size appear smaller as the eye-object viewing distance is increased. Aerial perspective refers to the change in color of distant objects coupled with the loss of sharp outline and detail. Motion perspective or parallax refers to the relative apparent motion of viewed objects as the observer moves (Ref. 4).

Speed Reference

In controlling the aircraft in the vertical and horizontal planes the pilot must control vehicle displacement, velocity, and acceleration in these two planes. The result of this control is the determination that the impact point or X (the point where the tangent of the aircraft track intercepts the ground) lies within acceptable limits for the point in the approach which is reached at that moment (Ref. 3).

As defined by Calvert the angular distance of X below the horizon indicates rate of closure with the ground. The angular distance of X from the vanishing point of the runway edges (at the horizon) gives the rate of closure in the vertical plane through the runway centerline. The movement of X perpendicular to and along the horizon gives acceleration information in the vertical and horizontal planes respectively. Thus it is apparent that the point X is essential in making visual determination of velocities and accelerations.

As the pilot proceeds along his flight path, he more or less fixates the point X where he will land given a constant path for the remainder of the approach. While watching the X point the pilot perceives all objects in the field of view as moving along paths which Calvert and Gibson termed streamers. Thus the X point does not move while all other points in the field do move away from the point and toward the periphery of the field. Due to the inability of the pilot to perceive small movements, the pilot sees not only the X point as not moving but also some finite area around it (Havron, Ref. 7). With an aircraft on a 3 degree glide slope flying at 105 mph and 4,000 feet from touchdown and the pilot using an X spot 1,000 feet from threshold, the area of no apparent movement is described as a large cigar shaped figure symmetrical to the runway centerline 150 feet in width and 1,100 feet long (Ref. 7).

The streamers which are perceived from the X point are similar to those projected on the pilot's retina only as long as he looks along the center line in a fixed direction in space. This is why pilots stare straight ahead during the final portion of the approach. Distraction of any kind results in head and eye movements lending to degraded accuracy of rate judgments.

The velocity of the streamers in the visual field at any given angular distance below the horizon is inversely proportional to the height, assuming the velocity of the aircraft is constant. Without definite objects in the field the pilot will then have poor height guidance as well as poor rate guidance.

Distance to Runway

In judging the distance from the runway to determine when to initiate the final approach, Behan and Siciliani (Ref. 4) state that the pilot needs these visual cues: the angular distance between horizon and aim point; relative size cues; and aerial perspective. The latter two cues were discussed under altitude reference. The angular distance cue refers to the displacement between the aim point and horizon and requires the pilot to determine the aim point and bring it into coincidence with the threshold.

Positive Threshold and Aim Point Definition

Behan and Siciliani (Ref. 4) reported that the pilot uses four visual cues to project the impact point of the aircraft with respect to the selected runway aiming point. These include the stationary aim point, the runway perspective, motion parallax, and the angular distance from the horizon to the aim point. The difference between the intended aim point and the projected impact point is taken as an indication of error of the approach path. The pilot attempts to fly the approach path such that the aiming point and impact point coincide (Ref. 4).

In determining the point at which to initiate the flare maneuver the pilot must consider the aircraft height above the runway. The visual cues used in judging this distance include the following:

- Head movement parallax or motion parallax, based on different views of the runway while continually scanning.
- Motion perspective on the gradient in motion as the aircraft approaches the runway. During this approach objects are perceived to pass beneath the aircraft at progressively greater speeds.
- Density gradient or the texture of the runway and the surrounding terrain. An increase in density usually runs upward in the visual field (Ref. 4).

According to Beck (Ref. 8) the pilot has used a single aim area during visual approach. Just before reaching threshold the pilot executes the flare. This maneuver is accomplished primarily through judgment derived from information concerning cockpit height, cockpit cutoff angle, speed, body angle, and the fact that the aim area is continually progressing down the runway until the wheels touch down. The pilot is also aided in his flare judgments by the rate of apparent movement of the lights in his peripheral vision as well as pitch and roll guidance of the lights ahead of him on the runway (Ref. 8).

DEGRADATION OF VISUAL CUES - EFFECTS OF REDUCED VISIBILITY

In conditions of reduced visibility the pilot cannot see the horizon and thereby loses an essential cue for attitude control judgments. In Category II B conditions at a critical height of 100 feet and with an RVR of 1,200 feet, just what can the pilot see?

According to Beck (Ref. 1) with an RVR of 1,200 feet at night the slant visual range at the 100 foot critical height will be less than 1,200 feet almost 70 percent of the time.

From a height of 50 feet prior to the go-no-go decision at a critical height at 100 feet, the pilot takes 2 to 3 seconds to view the surface (Ref. 9). Actually when the pilot makes the transition from instrument viewing to viewing of the external scene, 2:39 seconds will elapse due to the inability of the eye to instantly change from short distance vision to long distance viewing. This time lag comprises time for focusiing of the lens of the eye and time to fixate and does not take into account problems due to the adoptive state of the eye, pilot fatigue, individual difference, turbulence, etc. (Ref. 8)

What the pilot sees at 100 feet and 1,200 feet RVR is a visual segment extending only 350 feet due to the cutoff angle of the cockpit and the reduced visibility. Surface cues extend from 500 feet to 850 feet in front of him. The relative velocity of the few objects within this segment is high and he does not have ample variation in the velocity to adequately judge closure rates and rate of descent. At the 100 foot point the aiming point is not visible, therefore, the pilot has no reference to fixate while continuing the approach (Ref. 9). With 1,200 RVR the pilot will be 70 to 80 feet above the ground before he acquires the aiming point, given that slant visual range is as long as RVR. Since the actual aim point is not visible until some 8 seconds after the critical height, the pilot sees the visual surface segment depressed well below the flight path angle and well below the impact point of the flight path vector.

The pilot will find pitch attitude difficult to judge from visual cues removed several degrees from the horizon and flight path vector. The patch of ground actually visible to the pilot will be positioned in the windscreen where his normal visual aim point would be if he were flying with an increased angle of attack. Therefore, he may be confused into lowering the nose to put the ground where he thinks it should be. (Ref. 9)

As the aircraft descends, the surface segment becomes larger and more distant and more distant objects move vertically in the windscreen. This vertical rising comprises a false visual pitch reference and may induce the pilot to erroneously conclude that he is pitched down excessively.

Since the pilot cannot see the runway during the first three seconds after the 100 feet altitude, he can misjudge his altitude by using local terrain cues rather than the runway itself. This can lead to problems since the terrain adjacent to and before the runway may well be at an elevation well below that of the runway. Litchford sums up the low visibility problem by asserting that in Category I operations, which comprise the greatest proportion of landings, the pilot cannot build up the experience needed for Category IIA and IIB conditions, nor can he develop the alertness to possible illusioning cues which could be misleading at a critical moment. (Ref. 9) Pilot experience, using visual cues under good visibility to form a perspective of runways and lights, has provided him with a set of assumptions or mental models which are instinctively applied to each landing. In poor visibility the pilot envisions these cues by observing his instrument panel display of flight path, attitude, speed, etc. before establishing visual contact. (Ref. 10)

As indicated by Beck (Ref. 8) there is a general lack of realistic knowledge concerning visual capabilities in fog and its effect on slant visual range available to the pilot. This investigator identified the types of fog which appear to adversely affect aircraft as radiation, advection and warm front fogs. Radiation fog is a shallow fog formed at night at flat inland airports under stable conditions. Advection fog comprises air which has been cooled by a colder surface into fog which is then transported by wind. This type of fog is most prevelant along coastal areas and near large inland bodies of water.

With the shallow (50 to 80 foot thick) radiation fog the pilot will, prior to the 100 foot critical height, have a visual segment which is constant or is slowly decreasing. The slant visual range will not be low enough to require a missed approach. At about 100 feet the slant visual range decreases and the rate of decrease becomes greater as he approaches the top of the fog. On penetration of the fog the SVR goes to minimum and then increases to the value of the RVR. In this situation the pilot is in the beginning of his flare and suddenly the world goes blank. (Ref. 1)

Advection fogs occur when moist air moves over colder water or ground. Along coastal areas it is termed "sea fog". Such fogs are non-homogenous or are in a state of flux 90 percent of the time. If the RVR is reported at 1,200 feet, 95 percent of the time the SVR from 100 feet will be less. When the

RVR is less than 1,200 feet, about 50 percent of the time the SVR will be less than 700 feet.

Warm front fogs are caused by the addition of moisture to the air through evaporation of rain. This fog forms rapidly and can cover a widespread area. Visibilities can be patch as well as very low, especially at night. (Ref. 1)

One visual illusion usually associated with fog conditions is the pitch-up illusion where the pilot suddenly loses his visual field of view due to the rapid onset of fog. The pilot's past experience lends him to conclude that such a rapid loss of the visual segment means that he has inadvertently pitched the aircraft up. To correct this he then pitches down.

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CHAPTER V

PRESENT AIDS AND SOLUTIONS

Chapters III and IV have delineated several problem areas in current and projected civil aviation operations. The history of aviation has been one of research and experimentation to develop solutions to these problems. Much has been accomplished, but much remains to be done in order to attain the near-perfect regularity and safety which are the goals of aviation research. The persistence of certain problems is in no way a reflection on the quality of the work which has been done nor on the amount of effort which has been expended. Rather, the problems remain because they are inherently some of the most difficult in all of human factors and systems research and because solutions developed for one level of operating conditions no longer prove adequate as aviation pushes into new areas more demanding of men and machines.

The purpose of this chapter is to review quickly the aircraft instrumentation and ground aids now used to help the pilot in his guidance and control tasks. While the discussion will emphasize the shortcomings of present aids and solutions, this is not an attempt to belittle their value. The intent is to shed further light on the general guidance and control problem and to identify specific ways in which the head-up display could contribute to the solution. That is, the head-up display is not conceived as a replacement for any of the aircraft and ground equipment now in use but as a supplement to make the whole system safer and more efficient. To play a useful role in civil aviation the head-up display must do more than fill in the gaps in existing equipment and aids. It must also harmonize them. To accomplish these ends it is necessary first to take a critical look at how major parts of the present system work.

VISUAL AIDS

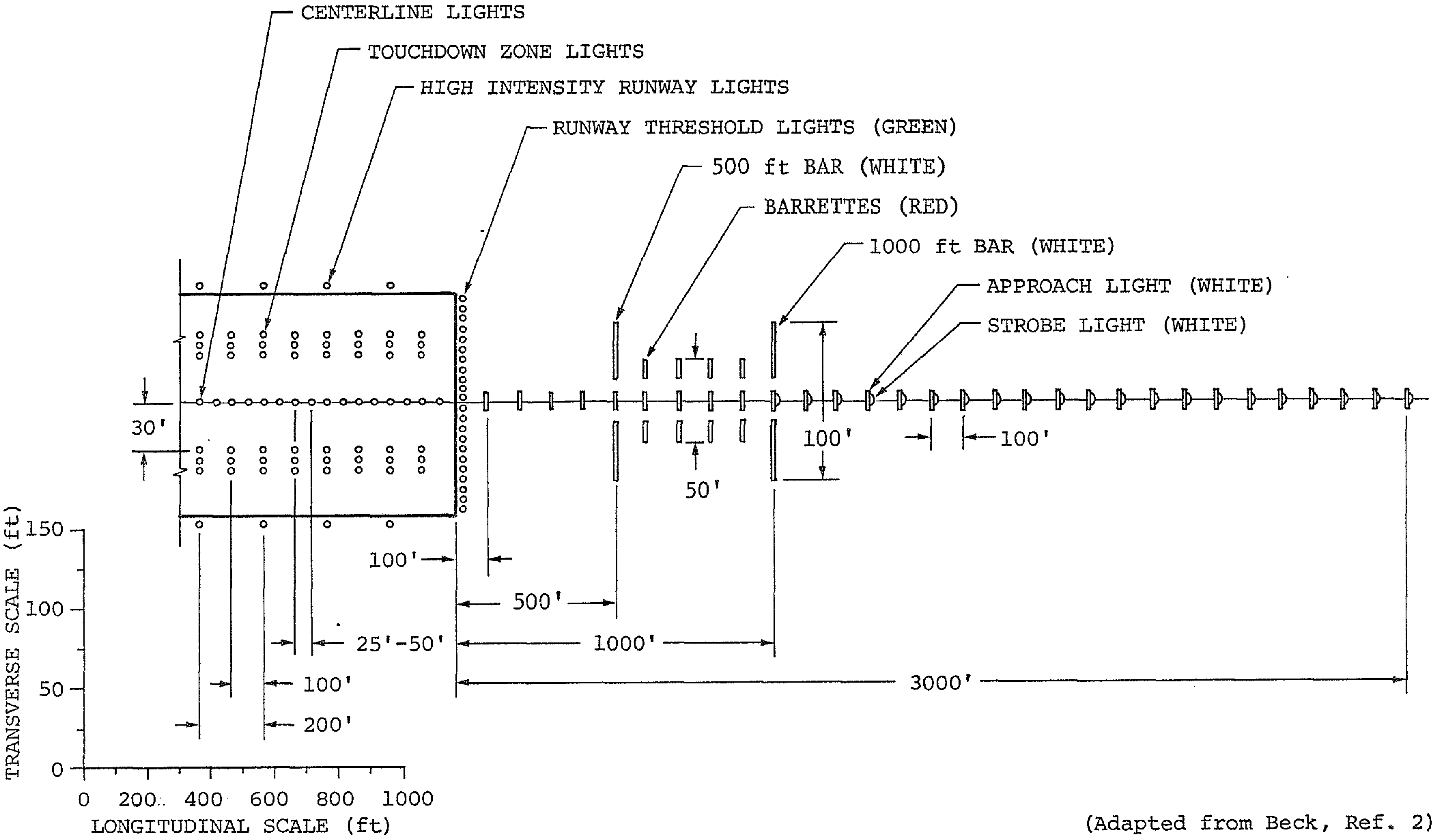
The pilot has three major types of visual ground aids available for guidance to and on the runway. The first is the painted markings on the runway surface and its surroundings. These were described in Chapter III and illustrated in Figures 1 and 4 (pages III-3 and III-7). In conditions of darkness or low visibility the pilot also has available a second major aid, the approach and runway lighting system. The third and latest addition to the family of visual aids is the Visual Approach Slope Indicator (VASI). The approach and runway lights and the VASI are discussed below.

Approach and Runway Lighting

The approach and runway lighting system is designed to provide guidance for three purposes:

1. Night visual approach and landing.
2. Transition from instrument approach to visual approach and landing in conditions of reduced visibility due to weather.
3. Night and low-visibility operations on the runway surface, such as taxiing and takeoff.

A variety of lighting systems are in use at U.S. and foreign airports. One of the best is the U.S. Standard Configuration "A" Centerline Approach Lighting System, which is shown in Figure 17. Nearly 200 of these systems are now in use, and another 220 are programmed for installation at U.S. Airports in the 1970s. (Ref. 1)



(Adapted from Beck, Ref. 2)

Figure 17

The system consists of a row of high intensity white lights which mark the extended runway centerline for a distance of 3000 feet outward from the threshold. The lights are arranged in 27 groups, spaced 100 feet apart, which end 300 feet short of the threshold. At 200 feet from the threshold is a red terminating bar placed at a right angle across the approach lights. The terminating bar is 14 feet in width. The threshold itself is marked by a row of green lights, not more than 10 feet apart, which extend the width of the runway. At distances of 1000 and 500 feet short of the threshold are transverse bars of white lights, 100 feet long and centered on the approach lights. (Ref. 2)

An additional feature of the Standard Configuration "A" system is the condenser-discharge sequenced flashing lights (the strobe lights or the "rabbit"). These lights are located at each of the approach lights up to the 1000 foot bar and are discharged twice per second along the line of approach to the runway. The result is a series of brilliant blue-white bursts which give the effect of a ball of light or tracer shells travelling through space to indicate the path of approach. The strobe lights are designed to penetrate severe atmospheric conditions and to attract the pilot's vision to the location of the approach lighting system. (Ref. 3) The value of the strobe lights is somewhat controversial, however, because they seem to do their job too well. Many pilots complain that the brilliance and apparent movement of the strobe lights are distracting and tend to obscure the approach lights. In very low visibility, where the range at which the strobe lights can be seen is short, they come into view quite suddenly. The result is that instead of appearing to flash in sequence they seem to explode all at once like a flash bulb. This pulsating of light in the cockpit can be distracting and potentially dangerous to a pilot trying to interpret marginal visual cues. (Ref. 4)

The intensity of the approach lighting system is controllable in five steps, each giving a decrease in intensity of 80% of the previous step. The standard step intensities are:

V.	10,000	candela
IV.	2,000	candela
III.	400	candela
II.	80	candela
I.	16	candela

Strobe lights have no intensity control.

Beyond the threshold the lighting system of the runway itself consists of centerline lights, touchdown zone lights, and runway edge lights. The centerline lights, spaced 25-50 feet apart, extend the length of the runway. They are adjustable to a maximum intensity of 2000 candela. The centerline lights are white until a distance of 3000 feet from the far end of the runway, where they are alternately red and white. Starting at 1000 feet from the far end of the runway, the centerline lights are all red. The touchdown zone lights are arranged in two rows straddling the centerline at a distance of 30-35 feet. They extend 3000 feet down the runway from a point 75-125 feet beyond the threshold. The touchdown zone lights are white, with a maximum intensity of 7500 candela. Runway edge lights are located on either side of the runway and are spaced at intervals of 200 feet along the length of the runway. They are white and -- like the approach lights -- are adjustable in five steps from a maximum intensity of 10,000 candela. (Ref. 6)

The U.S. Standard Configuration "A" Centerline Approach Lighting System is in use on all runways in the United States served by precision approach aids for Categories I and II of IFR.

It constitutes a vital and integral part of the low-visibility approach and landing system. However, Configuration "A" is by no means the only lighting system in use, nor is it the most common. The Neon Ladder and Left Single Row configurations are still used on some ILS-equipped runways. For non-instrumented runways there is no one standard system. A cursory examination of FAA Approach and Landing Charts for airports served by commercial carriers shows over a dozen different configurations in use. While it is true that such systems are not intended for low-visibility operations, they do constitute a substantial proportion of what is available for air transport service at night. For the general aviation pilot, whose use of precision approach runways is somewhat infrequent and whose general level of skill and experience is lower than the commercial pilots', the lack of standard night approach and runway lighting constitutes a major problem.

The situation worldwide is even more diverse. A pilot on an international carrier may encounter a different lighting system at each foreign airport, all of which are intended for some category of low-visibility operation. The situation is particularly bad at airports in underdeveloped countries, where the lack of economic resources or a lower level of technical sophistication prohibits installation and proper upkeep of a high-quality approach and landing system. The problem posed by the "have" and the "have not" countries was the subject of a recent article by Captain R. J. Ritchie, General Manager of Qantas Airlines. (Ref. 7) The lack of a standard international low-visibiilty approach and runway lighting system and the small likelihood that lesser nations would be able or willing to conform to it if there were one led Ritchie to conclude it is mandatory to adopt a self-contained visual approach guidance system which is independent of any ground-based installation. Ritchie goes on to state his opinion that the head-up display is the preferred solution.

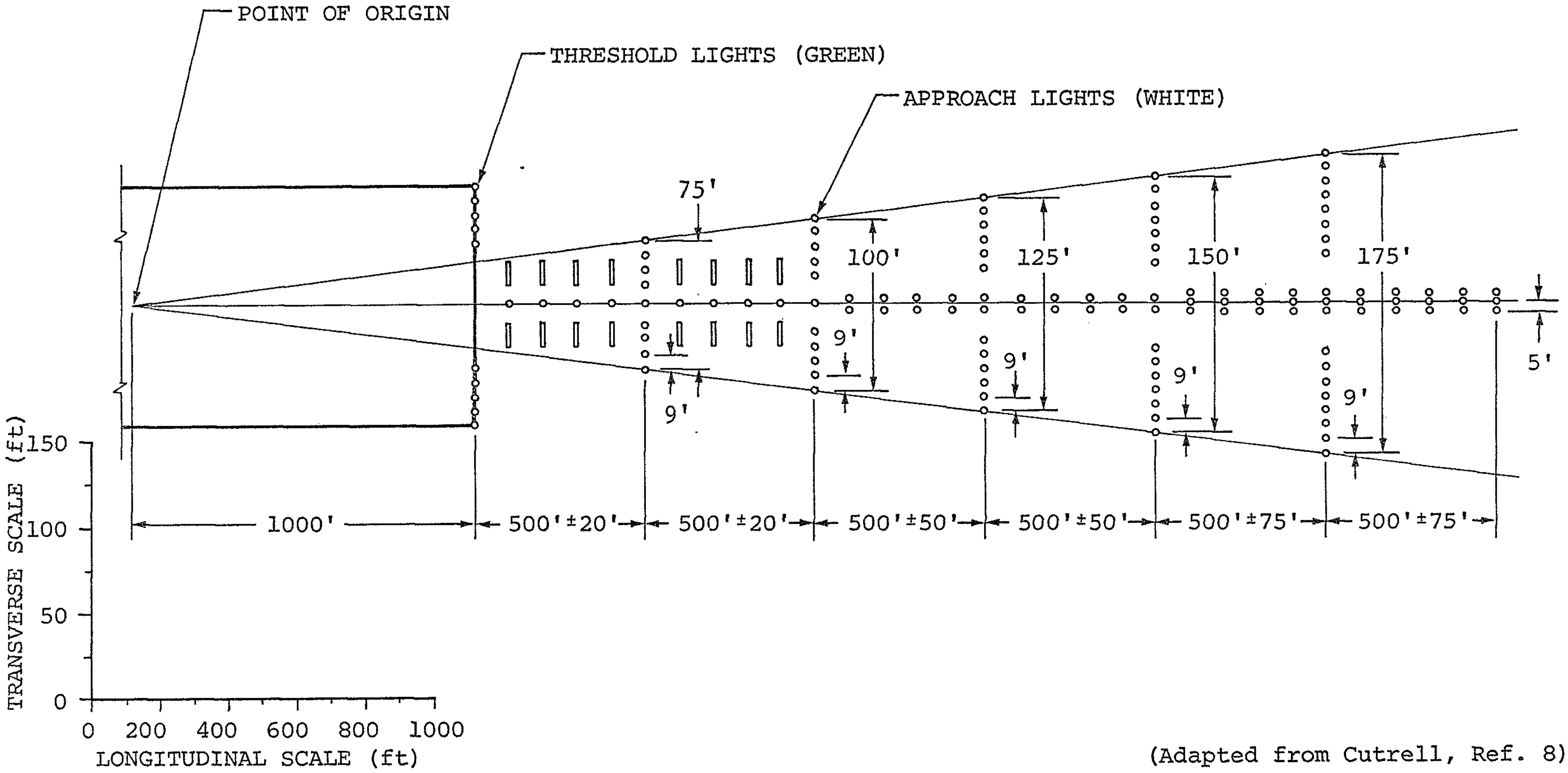
In fairness it must be added that the diversity of lighting systems, both in type and quality, is not a problem which is confined to underdeveloped nations. Orly International Airport (Paris) has three different approach light systems. The Canarsie approach to Kennedy International Airport (New York) is not ILS-equipped, and the lighting system is of a different type and lesser quality than those on other JFK approaches.

The lack of uniformly high quality approach and runway lighting is only one aspect of the problem however. Even the best lighting systems now available (of which Configuration "A" is certainly one) are not wholly adequate in the Category I and II situation. In effect, the approach lighting system amounts only to a visual extension of the runway centerline. In a Category IIB approach the pilot will have a forward visual range of 1200 feet. However, at the decision height of 100 feet approximately the first 500 feet of his view of the approach lights will be cut off by the nose of the aircraft, leaving a visual segment of about 700 feet. With the U.S. Standard Configuration "A", this means the pilot will have seven, or at most eight, of the individual approach lights in view. At typical jet approach speeds this amounts to the equivalent of 3 seconds of visual guidance. There is some debate as to whether 3 seconds of visual guidance is adequate, but even the most optimistic opinion regards it to be only marginally sufficient.

More importantly, the visual cues offered by the approach lights constitute only partial guidance. As shown in the previous chapter, the pilot in flying an approach needs information to make continuous judgments with respect to six variables: displacement, rate of closure, and acceleration relative to the runway centerline and relative to the glide slope. The visible line of approach lights provides cues relating primarily to the three variables of horizontal control. And even here the approach lights are not totally sufficient since the meaning of the cues is ambiguous without some horizon reference. The 1000-foot bar, threshold lights, and touchdown zone lights offer some additional assistance, but they appear very late in the approach sequence in Category II operations and at very low altitudes. As to vertical control, which is probably the more critical concern in low-visibility approaches, the Configuration "A" approach lights offer little or no guidance since they neither show the location of the aiming point nor give information for pitch and altitude estimation. Touchdown zone lighting does provide cues for vertical control, but these lights will not be seen in Category II until after the decision height has been passed and the aircraft has been flared.

A system which is superior in some ways to the U.S. Standard Configuration "A" is the Calvert Approach Lighting System which is widely used in Europe. (See Figure 18) The prominent feature of the Calvert system is a series of transverse bars placed at 150-meter (500-foot) intervals along the extended runway centerline. At least one of these bars will always be in sight, even during the Category II approach. They offer valuable assistance in making judgments relating to the three variables of horizontal control since they provide a series of reference lines parallel to the horizon. As such, they also offer cues for controlling the roll attitude of the aircraft.

However, even the Calvert approach lighting system is



(Adapted from Cutrell, Ref. 8)

Figure 18

deficient in terms of the information it offers for vertical flight path control since it does not indicate the aiming point and the location of the horizon. Several studies of pilot performance using visual guidance and manual control in low visibility have been conducted by BLEU at the Royal Aircraft Establishment, Bedford. Morrall (Ref. 9) summarized the results of these studies as follows:

> "The main safety problem in bad weather landing using present-day techniques is considered to be the shortcomings of the visual control in pitch during the final phase of the approach and landing especially in low visibilities. Mr. Calvert of the R.A.E.* has given this problem intensive study and the argument can be summarised as follows. In making his decision whether to continue with the landing or not after becoming visual the pilot must assess not only his position relative to the ideal flight path, but also his velocition, both cross track and vertical, to determine where the aircraft is going.
>
> "Whilst it is reasonable to expect a proficient pilot to be able to assess the aircraft's position and velocity in the horizontal plane by looking at a segment of approach lighting which includes only one cross bar, it is more difficult, if not impossible, to make a similar assessment in the pitch plane from the same picture. Even gross errors may be difficult to detect in the time available after visual contact in operations to the lower decision heights of Category II. It is believed that visual control of the aeroplane in pitch begins to become reliable when the pilot can see as far as the point on the ground to which his approach path is heading.

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* The reference is to Mr. Edward S. Calvert, formerly of the Royal Aircraft Establishment/Farnborough and now retired, who was the architect of the approach lighting system which bears his name and a leader in research on the pilot's visual problems.

For a glide slope angle of 3° and a slant range of 400 metres this occurs when the pilot's eye height is as low as 70 ft, and even for a slant range of 800 metres the eye heights is 140 feet. This means, to achieve high standards of safety in these visual conditions, instrument guidance in pitch is required to heights of around 50 to 100 ft. (BLEU studies)...demonstrate effectively the type of pitch performance which takes place when the pilot is completing the approach and landing using visual guidance.

"The results of (studies)...at London Airport when the visibility was about 1,200 metres (Category I) (show)...the deterioration in pitch performance at about 3 to 6,000 ft range (is) quite apparent. The improvement in pitch performance as the aircraft approaches the threshold can also be seen and it is noted that this takes place at the point where the pilot starts to see the runway threshold and beyond at a range of about 3,000 ft.

"B.L.E.U. have recently completed a flight trial where different approach lighting patterns were investigated. A slant range of about 400 metres was simulated with fog screens. The pilots who took part in this trial had made many landings in low visibility both real and simulated and were also well educated in the problems of this type of operation. The results...again show the deterioration in pitch performance when even these experienced pilots assumed manual control using visual guidance. The pitch performance on this occasion does not improve until after threshold, i.e., when at 400 metres slant range the pilot is able to see the aiming point to which he is going. *This flight evidence confirms Mr. Calvert's studies and substantiates the need for instrument guidance in pitch to very low heights even although adequate visual guidance for correcting lateral errors may have been available from higher heights.**"

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* Italics are the author's of this report

It is thus evident that the approach lighting systems now in use do not fully accomplish their avowed purpose of aiding the pilot in making the transition from instrument to visual reference in conditions of reduced visibility. They do provide valuable guidance in the horizontal dimension, but they contribute little to guidance in the vertical dimension. The approach lights extend the runway centerline 3000 feet out toward the aircraft on the approach. However, there still exists the need to extend visual guidance for the glide slope a similar distance.

Visual Approach Slope Indicator (VASI)

It is precisely for the purpose of extending the visual glide slope that the VASI was developed and that it is so highly esteemed. The VASI is designed to provide by artificial means the same information which the pilot obtains with lesser precision from natural visual cues and which the glide slope portion of the ILS provides electronically. The VASI furnishes a path of light, inclined 2-1/2° to 4° from horizontal, which the pilot can use for vertical guidance in the approach zone.

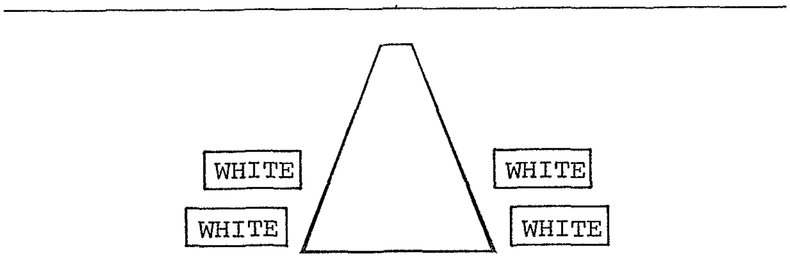
The standard VASI installation is composed of 12 sets of lights arranged in groups of three to form bars on either side of the approach end of the runway opposite the 600-foot and the 1300-foot marks. These are called the downwind and upwind bars respectively. The visual glide slope appears to emanate from a point midway between the upwind and downwind bars, i.e., about 1000 feet from the threshold. The intensity of the VASI is controlled from the ground and is adjusted at pilot request. At maximum intensity the VASI can be seen at approximately the range of the outer marker (4-5 miles) in VFR day conditions and at greater ranges at night. Under bright sunlight or snow conditions the range is decreased to about 3-1/2 miles.

The basic principle of the VASI is that of color differentiation between red and white. Each light unit projects a beam of light having a white color in the upper part and a red color in the lower. The light units are arranged so that during the approach the pilot will see the patterns of red and/or white lights illustrated in Figure 19.

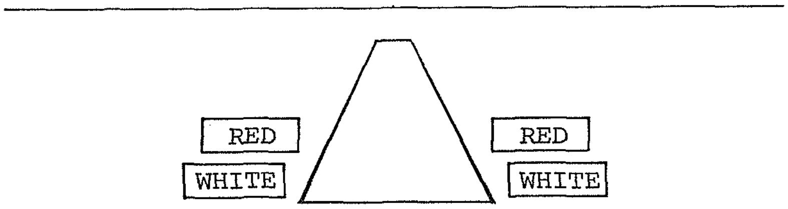
When the aircraft is on the correct glide slope, the pilot is -- in effect -- overshooting the downwind bars causing them to appear as white and undershooting the upwind bars causing them to appear as red. A displacement below the glide slope will cause both sets of bars to be red. If the aircraft is above the glide slope, both sets of bars will be white. Impending departure from the glide slope toward the high side is signaled by a change in color of the upwind bars from red to pink to white. The opposite sequence of color change will occur in the downwind bars if the aircraft is sinking below the glide slope. If the aircraft is extremely low on the glide slope, the two red bars on each side of the runway will tend to merge into one bold red signal.

In haze and dust conditions or when the approach is made into the sun, the white bars may take on a yellowish cast. This is also true when the VASI is operated at low intensity. Certain atmospheric debris may also give the white lights an orange or brown tint. However, since the red lights are not affected by these conditions, adequate color differentiation is preserved at all times. (Ref. 10)

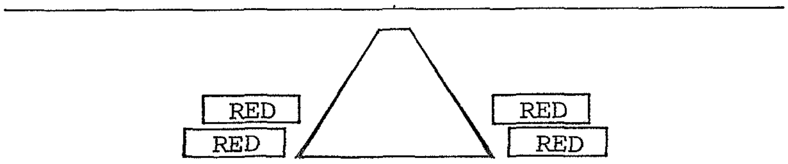
Pilot opinion of the VASI since its inauguration a few years ago has been generally favorable, and often highly laudatory. The criticisms which have been expressed are not concerned so



ABOVE GLIDE SLOPE



ON GLIDE SLOPE



BELOW GLIDE SLOPE

Figure 19

much with the workings of the system itself but with its range of applicability.

The VASI, of course, is intended for use in moderately good visibility, either day or night, and there it serves its purpose well. As visibility degrades to Categories I and II of IFR, the VASI becomes ineffective. Yet the need for a supplement to natural visual guidance becomes greater as the RVR goes down to 2600 feet or to 1200 feet. The dilemma of the VASI is that it works well when the visibility is good; but as the external visual scene grows more impoverished because of weather, the distance at which the VASI can be seen diminishes also. In Category I the upwind and downwind VASI lights cannot both be seen until about 1300 feet from the threshold and at an altitude of 115 feet, which is far below the 200-foot decision height. In Category II the full VASI will come into view only at the threshold, which makes the VASI useless because flare is initiated at this point and the VASI angles are inappropriate for flare guidance. In neither case can the VASI be of any real help in providing vertical guidance or in assessing position with respect to the glide or flare path. The need, therefore, is to find a way to provide visual vertical guidance information (like that supplied by the VASI) over a wider range of atmospheric conditions.

The VASI has a second serious limitation in its use with very large aircraft such as the jumbo jet and the SST. The VASI installation is situated so as to provide a visual glide slope to a point 1000 feet beyond the threshold. This will produce an eye path which crosses the threshold at a height of about 50 feet. In the jumbo jet and the SST, because of their large wheel-to-eye distances, the clearance of the landing gear over the threshold will be dangerously low with such a visual glide path. (The landing gear clearance would be 15 feet for the jumbo jet and only 3 feet for the SST.) To maintain the prescribed landing gear clearance of 50 feet at the threshold, the pilot must select a visual aiming point further down the runway. Thus, the use of the VASI in its present location is thwarted. To shift the VASI to a location which would accommodate the very large aircraft would result in excessively long landings for the majority of smaller aircraft using the runway. To install a second set of VASI lights for the benefit of the jumbo jet and the SST (assuming that one location would be suitable for both), would be prohibitively expensive.

The inflexibility of the VASI also has similar disadvantages for present medium and large jet aircraft. The VASI permits the pilot to aim for only one point on the runway. If he wishes to make any adjustment of the aiming point to compensate for short runway length, slippery surface conditions, or landing weight, he must abandon the VASI as a source of vertical guidance. Here, again, is a case of the VASI being too narrow in its range of use.

These reasons have led many observers to conclude that some more widely useful and flexible substitute for the VASI must be found. Lami (Ref. 11), for example, suggests that the head-up display (which he calls a universal VASI) offers the best solution to the problem of vertical guidance in VFR, quite apart from other value which it may have in IFR conditions. Others share this opinion. (Refs. 12, 13, 14) Captain Ritchie of QANTAS, whose views were mentioned earlier in connection with approach lighting, offers an additional argument against VASI. (Ref. 15) Considering the few airports around the world which are adequately equipped for today's jets and considering the increased demands imposed on airports by third-generation jet standards, Ritchie believes it is unlikely that less affluent nations will spend the necessary funds to install systems like the VASI in the number required. The likelihood would be even lower if dual installations should be needed -- one for present jets and another for jumbo jets. The best recourse, Ritchie concludes, is to adopt an airborne VASI (a head-up display) which is self-contained aboard the aircraft and independent of the vagaries of local financing and technical awareness.

In view of its several limitations, the VASI does not appear to be a viable long-run solution to the vertical guidance problem. It is effective only in VFR conditions. It is too inflexible for use by aircraft of all sizes and in all landing conditions. There are too few VASI installations; and because of their cost and rather narrow range of usefulness, it does not appear probable that the airport funds of individual nations will be expended in this direction. It is both a compliment and a criticism that the head-up display, when it is suggested as a substitute, is referred to by some as an airborne VASI.

GROUND CONTROL

Under prevailing operational concepts the air traffic controller does not play a direct and active part in approach and landing or in takeoff. The air traffic controller acts in a support capacity in which his duties consist of providing information on the weather and the air traffic situation, advising the pilot on procedures and precedence, controlling ground aids, and monitoring the conduct of operations at and near the airport. Historically, this has not always been the case, and until recent years there was a serious competition between the ground controlled approach (GCA) and the instrument landing system (ILS) philosophies.

Litchford (Ref. 16) has traced the evolution of the GCA concept and pointed out some of the factors which led to its abandonment as a solution to the low-visibility approach and landing problem. The deficiencies of GCA included poor closed-loop response, weak signals reflected from the aircraft, obscuration of reflected signals by weather, and ground clutter of the (ground) controller's scope. In addition to these technical shortcomings there was the cost of having a trained GCA team on duty at all times, which acted as a serious economic deterrent.

The choice between GCA and ILS was not clear-cut, however, and considerable effort was expended to develop the GCA during the 1950s and 1960s. In all a total of 22 precision approach radar (PAR) systems were installed at major airports to perform the GCA function. These were finally shut down in an economy move by the FAA in early 1969. Experience showed that pilots seldom made use of GCA facilities and that it cost approximately $100,000 per year to operate and maintain each GCA installation. The FAA concluded this money would be better spent on ILS equipment.

An important factor in the decision to discontinue the GCA was its lack of acceptance by pilots. One of the reasons underlying the coolness toward GCA was the pilots' belief that the GCA operator encroached on traditional pilot responsibilities during approach and landing. Another reason was the nature of the GCA command information which consisted of relatively low-speed, step inputs supplied by voice. Other complaints were that controllers gave too many directions and called for unnecessary changes in attitude or heading at a time when the flight crew was burdened with other duties. In a final effort to overcome the faults arising from verbal communication between the GCA operator and the pilot, an attempt was made in the late 1960s to automate the system. This was abandoned for technical reasons in 1967-68. (Ref. 17)

In the military services, on the other hand, the GCA concept has proven more successful. The Navy An/SPN-41 automatic carrier landing system is a GCA in which aircraft position on the approach path is measured by a K_u band PAR and directional signals are relayed by digital data link to the autopilot and autothrottle systems on board the aircraft and to the pilot's displays. The Army A-scan system for helicopter landing guidance works on similar principles.

Despite the success of GCA in the military field, it seems unlikely that civil aviation will revert to experimentation with control of the aircraft by human or automatic ground monitors as a solution to the problem of low-visibility operations. Civil Aviation has ruled out ground control because of its inherent technical and economic difficulties and because it entails transferring a portion of the overall command and control responsibility out of the cockpit. Guidance for approach, landing and takeoff will continue to come from ground installations such as the present ILS or some future improvement of it, but the closing of the control loop will remain in the cockpit. The pilot will act as the command and control element if the operation is performed manually or as the command and monitoring element if it is performed by automatic systems.

A possible exception is in the area of traffic control on the airport surface. The present system is analogous to GCA in that voice direction to taxiing aircraft is given by ground controllers employing visual observation or high-resolution surface radar. It works moderately well under current operating minima, but it will probably not be adequate in future extreme low-visibility operations. Litchford (Ref. 18) has pointed out that the problem of handling a hundred or so aircraft on the airport surface in Category IIB or in Category III conditions calls for much improved surface detection equipment and for some sort of semi-automatic surface navigation and control system. Even with such an advanced system, the actual maneuvering of the aircraft will still be accomplished by the pilot acting in response to directional signals. The nature of the display which the pilot will use for this purpose has not been determined, but it is a topic which will deserve careful attention.

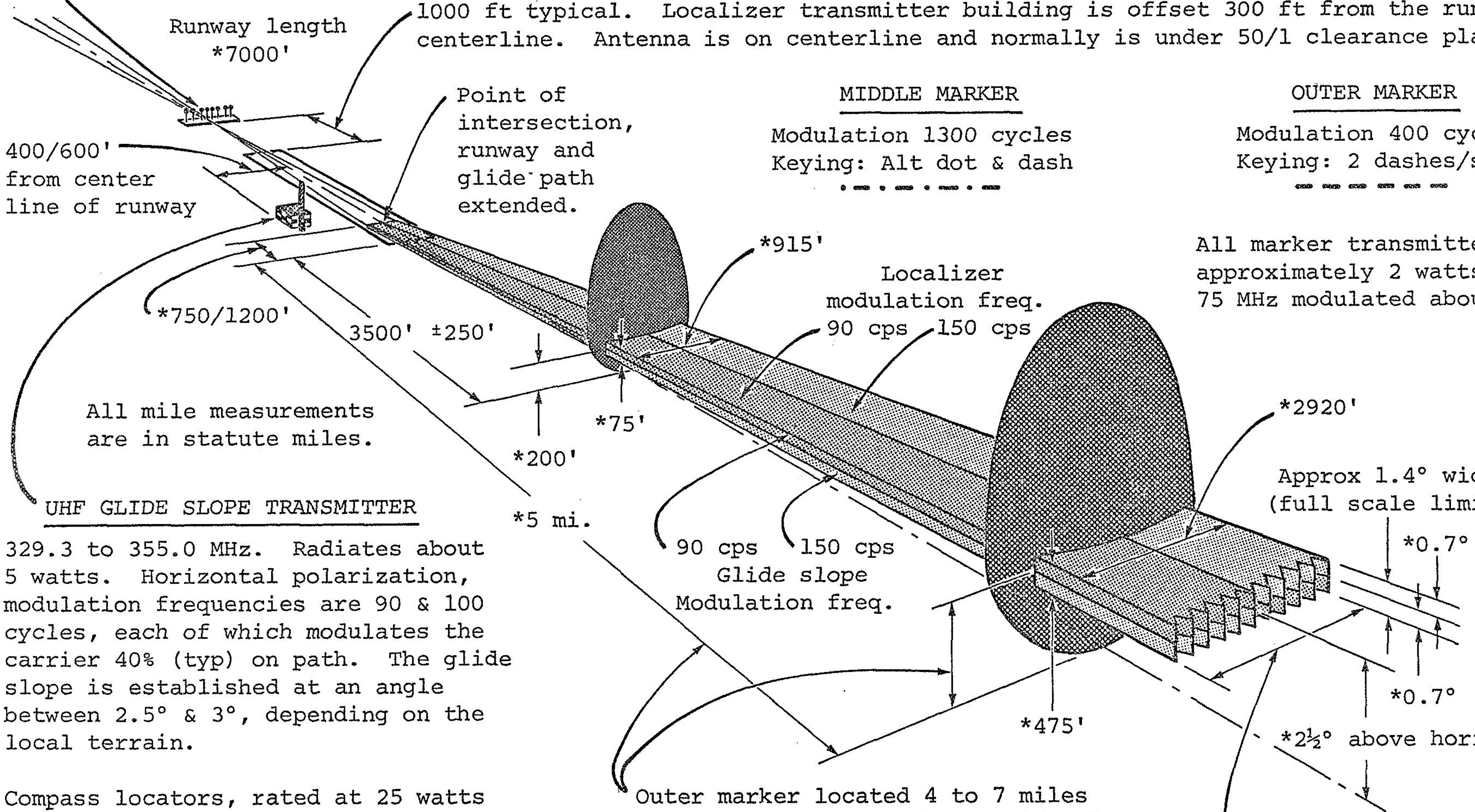
INSTRUMENT LANDING SYSTEM (ILS)

The ILS is the pivotal system in low-visibility operations. Its purpose is to provide by electronic means a horizontal and vertical path for the aircraft on the final approach to the runway. The ILS is comprised of ground and airborne equipment. The ground portion of the system consists of vertically oriented radio beacons (usually two -- the outer and middle markers) situated along the approach path to give range information and two highly directional transmitters located near the runway -- one for the horizontal path (localizer) and the other for the vertical path (glide slope). (Technically, the approach and runway lights are also considered part of the ground system.) The airborne portion of the ILS consists of receivers in the aircraft and a display of guidance signals in azimuth and elevation coordinates. Most modern aircraft also contain equipment which permits the ILS localizer and glide slope signals to be routed directly to the autopilot. Figure 20 shows the

VHF LOCALIZER

108.1 to 111.9 MHz odd tenths only. Radiates about 100 watts. Horizontal polarization. Modulation frequencies 90 and 150 cycles. Modulation depth on course 20% for each frequency. At some localizers, where terrain (siting) difficulties are encountered, an additional antenna (slotted waveguide) provides course straightness.

1000 ft typical. Localizer transmitter building is offset 300 ft from the runway centerline. Antenna is on centerline and normally is under 50/1 clearance plane.



MIDDLE MARKER

Modulation 1300 cycles
Keying: Alt dot & dash
• ▬ • ▬ • ▬ • ▬

OUTER MARKER

Modulation 400 cycles
Keying: 2 dashes/sec
▬ ▬ ▬ ▬ ▬ ▬

All marker transmitters approximately 2 watts at 75 MHz modulated about 95%.

All mile measurements are in statute miles.

UHF GLIDE SLOPE TRANSMITTER

329.3 to 355.0 MHz. Radiates about 5 watts. Horizontal polarization, modulation frequencies are 90 & 100 cycles, each of which modulates the carrier 40% (typ) on path. The glide slope is established at an angle between 2.5° & 3°, depending on the local terrain.

Compass locators, rated at 25 watts output, 200 to 415 KHz, are installed at most outer and middle markers. At some locators, simultaneous voice transmissions are provided from the tower.

Outer marker located 4 to 7 miles from end of runway, where glide slope intersects the procedure turn (minimum holding) altitude, ±50 ft. vertically.

Course width varies: 5° at most locations (full scale limits).

*Figures marked with asterisk are typical. Actual figures vary with deviations in distances to markers, glide angles and localizer widths.

Figure 20

standard ILS characteristics and terminology.

The localizer transmitter is located typically 1000 feet beyond and 300 feet to the side of the non-approach end of the runway. The antenna itself is aligned with the runway centerline. Two different signal patterns are generated -- one on either side of the runway centerline. The localizer course is formed where the signals overlap and are of equal strength. The localizer signal is adjusted to produce a beam whose angular width is between 3° and 6°, as necessary to give a linear width of about 900 feet at the middle marker (3500 feet from the runway).

The glide slope transmitter is located 750 to 1250 feet from the approach end of the runway and offset 400-600 feet from the centerline. Like the localizer, two overlapping signal patterns are emitted -- one above and one below the glide slope, which is set between 2-1/2° and 3° so as to intersect the middle marker at about 200 feet and the outer marker at about 1400 feet above the runway elevation. The glide slope beam is nominally between ± 0.5° and ± 0.7° in width.

Marker beacons are low-power (3 watts or less) transmitters placed along the ILS final approach path to give an indication of distance. As each marker is passed on the approach, visual and aural signals are presented in the cockpit. The outer marker (OM), 4-7 miles from the runway, is normally the final approach fix for an ILS approach. It serves to indicate the position at which an aircraft at the appropriate altitude on the localizer course will intercept the glide slope. The middle marker (MM) indicates that the aircraft is approximately 3500 feet from the runway. If the aircraft is on the correct glide slope, it will be at an altitude of 200 feet above the runway elevation when the middle is reached. The middle marker thus serves as a warning that the decision height for Category I has been reached. Runways used for Category II approaches also have an inner marker (IM) to indicate the point on the approach path at which the decision height (150 feet for IIA and 100 feet for IIB) is reached.

Compass locators (LOM and LMM) are often placed at the outer and middle marker sites. They are low-power radio beacons which provide directional homing signals for a radio compass in the aircraft and thus serve as an aid to navigation. At some sites distance measuring equipment (DME) is also placed at the outer and middle markers. (Refs. 20, 21)

It should be noted that the ILS is not exactly what its name implies. It is not a landing system. The ILS, as it is conceived and presently used, is a low approach system. The general assumption underlying the ILS is that it provides instrument reference to guide the pilot to some specified low altitude (decision height) from which he can complete the approach and landing by visual reference. Implicit in this assumption is the assurance that, if the pilot does not have the required visual reference at the decision height, the ILS guidance will not have placed him in an inextricable situation. The concern of the civil aviation community about the ILS revolves around the adequacy of this implied safeguard at extremely low altitudes, which is ultimately a question of the trustworthiness and accuracy of the ILS guidance.

To make a safe low approach to decision heights of 200, 150, or 100 feet, the ILS must satisfy two general conditions. First, the electronic guidance must deliver the aircraft to a position not too far off the ideal approach path for corrections to be made before touchdown. The magnitude of the tolerable error is a function of both the aircraft response time and time required for the pilot to assess and react to external visual cues. The aggregate of these times is on the order of 5-7 seconds, which means that the error must be no greater than that which can be overcome in this time before committing the aircraft to touchdown. The second general condition is that the ILS must assure an inviolable minimum altitude above the approach terrain at the decision height. This "hard" minimum altitude is that from which a missed approach can be safely executed in the event the pilot does not have the required visual reference to land. This, too, is a function of pilot and aircraft response times, the latter being the dominant factor because of wide variation in aircraft weight and thrust characteristics. Estimates of the time to decide upon and carry out a missed approach differ, but it is certainly no less and probably somewhat more than the 5-7 seconds needed to make adjustments in the flight path before commitment to landing.

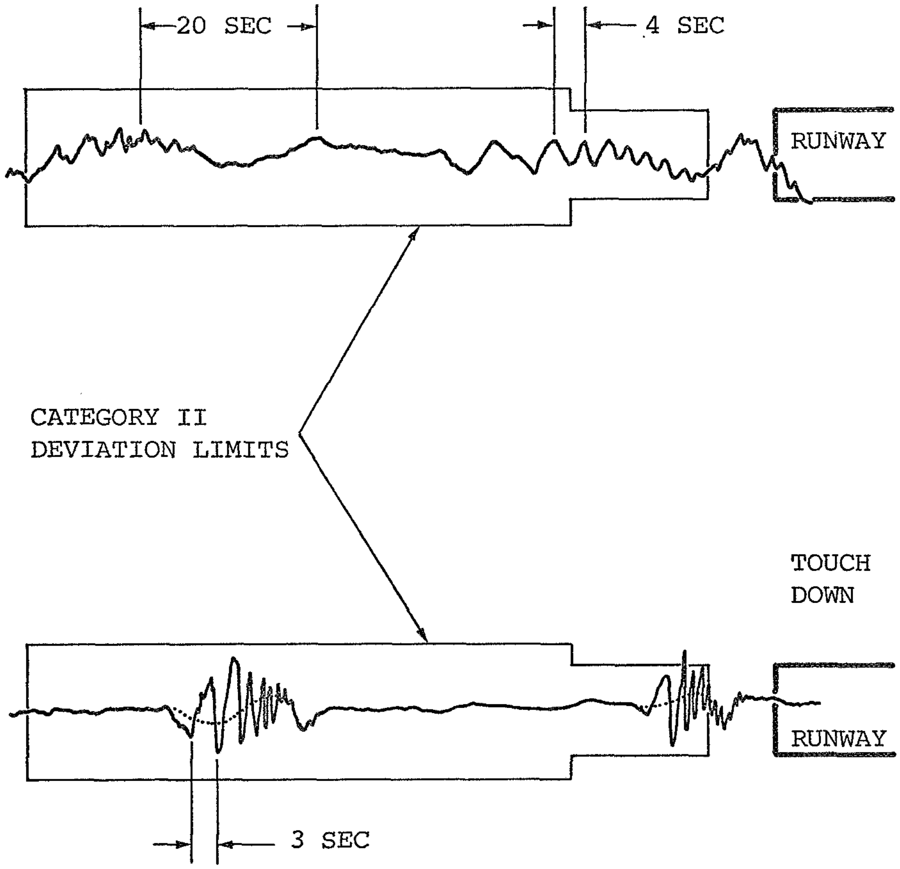
Since the ILS provides both horizontal (localizer) and vertical (glide slope) guidance, probable errors in either of these axes must be considered. Of the two, localizer errors are the most frequent cause of concern and shall be examined first. Glide slope errors, although of lesser magnitude, are also important because of their relation to the generally more critical problems of decision heights and safe missed approach altitudes.

The localizer beam, which is in theory a straight line extension of the runway centerline, is in fact subject to distortions or "bends". There are steady beam distortions due to the transmitter and antenna installation environment. There are also transient distortions of the beam produced by reflections and interference when other aircraft lie between the approach aircraft and the transmitter antenna. Figure 21 is an illustration of typical localizer beam distortions.

Very little engineering data are available as to the quality of localizers actually in use. The data which do exist are scattered through various standardization and advisory documents published by the FAA and ICAO. Moreover, these are statements of maximum allowable errors for certification purposes and not descriptions of what actually exists at various airports. In a recent article Litchford (Ref. 23) has analyzed the implications of the several errors which may be associated with the locations. This analysis is summarized in Table VII.

It does not require detailed study to see that localizer beam distortions of these magnitudes will result in the aircraft being off the lateral approach path by 100 feet or more for one approach in a hundred, even if there are no piloting errors. If one also considers that it takes 10-15 seconds for a modern jet aircraft to effect a side-step of 50 feet (which is only half the 3-sigma localizer error), the inadequacy of lateral approach guidance by ILS is more apparent. In Chapter III it was established that the allowable lateral dispersion of the touchdown point with respect to the runway centerline was on the order of 50 feet for present large jets and 30 feet for jumbo jets. The lateral error of the ILS localizer also falls far outside these requirements.

The localizer errors described in Table VII are all in the class of "steady" beam distortions. The localizer is also subject to transient disturbances caused by other aircraft operating



STEADY BEAM DISTORTIONS DUE TO THE TRANSMITTER AND ITS ANTENNA INSTALLATION ENVIRONMENT

TRANSIENT BEAM DISTORTIONS DUE TO OTHER AIRPLANES FLYING OVER THE TRANSMITTER'S ANTENNA

Figure 21

TABLE VII

Nature of the error	ICAO[1] reference	ICAO CAT II amount	3-sigma value at threshold (ft)	3-sigma value at ICAO Point C (100' DH on glide path)(ft)	3-sigma value at ICAO Point B (3500' from threshold) (ft)
Centerline monitor	3.k.4.5.4	±24 ft (threshold) ±15 ft (recommended)	25	28	33
Course bends	2.1.4	±5 microamp or 0.005 DDM[2] (2-sigma)	20	22	26
Receiver centering (airborne)	2.2.4.1	±5 microamp (1-sigma)	39	43	52
Polarization	3.1.3.2.2.1	0.008 DDM for 20° bank angle	Unknown for specific aircraft		
Linearity	3.1.3.5.5.3	±10%	Applied to above as 3-sigma		
Sector width	3.1.1	0.0004 DDM/ft, 700 ft at threshold			
±10% tolerance; half-sector width; pilot CDI display full-scale deflection	3.1.1	770 ft at threshold; above ±150 microamp = 0.155; DDM = ±350 ft at threshold	770 ±385 Various errors depending upon number of centered galvanometer movements or DC/AC conversion for flight director or autopilot coupling (not considered)	850 ±425	1030 ±515
All flight errors (crab angle, wind-shear, normal track following engine-out, poor heading)	FAA/AC 120-20	FAA: ±25 microamp or 1/6 full scale (less than "one dot" represents the 2-sigma value)	97	104	127

[1] ICAO references are from DOC 8636, COM/OPS (1966), published in 1967.
[2] DDM = Difference in Depth of Modulation.

(Adapted from Litchford, Ref. 23)

in the vicinity. Aircraft parked near the active runway awaiting takeoff act as reflecting surfaces, which are illuminated by signals of high intensity because of their closeness to the localizer source. Considering the number of aircraft which may be in line for takeoff during a peak traffic period at a major airport, large transient beam perturbations can be expected from such an array of aircraft sitting broadside to the localizer. Very little recent data exist on the nature of these distrotions and there is little assurance that current FAA specifications can be met in the presence of more and larger distorting elements (e.g., jumbo jets) as air traffic increases.

Litchford concludes the analysis of "beam-bending" with the following comment:

> "One might logically question why these problems are not more fully identified and understood. In most cases the only party that can complain, since he is the only one in a position at the right time to witness most of these effects, is the pilot himself. Yet, in CAT I, when he breaks out with relatively good visual range, he no longer observes the ILS signals. (As the experience with CAT II-A builds, pilots will be forced to adhere to flying the instruments and ILS path to lower heights, and pilot reports of measurements are then likely to be more meaningful.) Of course, the beam-perturbation phenomena do not occur every time. It is, however, rather unpredictable in magnitude. And, because of such unpredictability, if it occurs but once in a hundred times, because of its critical nature with respect to safety; this may well be once too often."

The inadequacy of the ILS guidance beam in the vertical direction (the glide slope) is also a cause of concern. With many present installations the glide path does not remain straight but starts to show irregularities near the ground, causing vertical guidance to become unreliable at altitudes of 150 to 200 feet (i.e., 2000-3500 feet from the threshold) which correspond to the decision heights for Categories IIA and I respectively. The ILS glide slope is not usable much below the height of 100 feet (the Category IIB decision height). (Ref. 24) The magnitude of this vertical beam-bending may be as much as ± 12 feet on a 3-sigma basis.

The unusability of the ILS glide slope below 100 feet is due only in part to distorted signal characteristics. Even if the beam were perfect, the ILS glide slope has to be abandoned shortly after descending below 100 feet because following it to touchdown would result in a vertical velocity of 9-12 feet per second, instead of the desired 2-4 feet per second. The ILS glide slope, because it is at a fixed 2-1/2° - 3° angle cannot be used for the flare maneuver, which is conducted by visual, not instrument reference.

The glide slope also poses a problem in the 100-200 foot altitude zone because of the placement of the antenna (the glide slope origin). With many present installations the pilot is not led along the same glide path by instruments in bad weather as he would follow by visual reference in good weather. Litchford (Ref. 25) shows that the scatter of glide slope origin from threshold is 700 to 1500 feet. By contrast the approach aiming point under visual conditions is almost always in the vicinity of 1000 feet from the threshold. The flare aiming point, which is about 1200 feet further down the runway, will vary between 1900 and 2700 feet from the threshold for a landing after an IFR approach. This is also inconsistent with the VFR case. Unless the pilot is fully familiar with the location of the glide slope antenna at a particular airport and knows how to estimate the resulting difference between VFR and IFR aiming points, he may find himself in a confusing situation at breakout. He may well decide that a glide slope error exists (when in fact none does) and try to "correct" his flight path to match what his VFR experience tells him is proper. This can lead to a long landing if the ILS glide slope is closer to the threshold than the normal 1000 foot aiming point. If the glide slope origin is beyond the VFR aiming point, the result will be a steepening of the flight path and a short touchdown, possibly before the threshold.

The variation in ILS glide slope antenna placement also contributes to the danger of the "duck-under" maneuver. Litchford (Ref. 26) describes the problem as follows:

> "...The pilot, when flying in poor visibility to an approach aiming point too far down the runway* (taking him too high over the approach lights), will attempt to fly beneath the glide slope when he first attains even limited visual contact with the ground and lights. This so-called "duck-under" maneuver is instinctive and is done to regain desired visual perspective cues and to touch down several hundred feet nearer threshold, thereby gaining maximum roll-out distance for stopping the aircraft. However this maneuver, although prevalent at 200 and 300 foot visual-contact height, cannot be used safely at or below 100 feet because of the high sink rate (up to 20 fps) that results so close to the ground...
>
> "Obviously, the psychological factor of the pilot's training, his confidence in the guidance signals, and his desire to land in poor visibility with the same geometric path and perspective conditions that normally occur when

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* In this context, "too far" means an ILS glide slope installation beyond the normal VFR aiming point.

> visibility is good, but at a higher
> speed -- all these must be considered.
> The day of completely routine, completely
> "blind" landing is still probably far away."

Thus, the adequacy of both vertical and horizontal ILS guidance are subject to question, especially at the 150-foot or 100-foot decision heights prescribed for Category II. Additional doubt is cast upon the wisdom of relying on the present ILS when one considers that the decision height is a point of transition from an imperfect electronic reference system to an even less perfect visual guidance system. Great caution must be shown in assessing how much valid height information the pilot can derive in Category II from even the most sophisticated pattern of lights if he is not certain of his position from instrument reference. Although horizontal guidance from the approach lights is generally regarded as adequate in RVR down to 1200 feet, there may well be problems in assessing the rate of divergence from the desired horizontal path which results from tracking a distorted localizer beam.

A major effort is now underway in the aviation industry to develop an electronic guidance system of greater accuracy and integrity. Attempts are being made to devise improved radio-guidance techniques such as the wave-guide slide slope and the multiple-antenna ILS (MAILS). The Radio Technical Commission for Aeronautics Special Committee 117 has announced the preliminary results of a two-year study which recommends the configuration of a microwave instrument landing system which will eventually replace the present ILS. Tentative plans call for initial deployment of microwave ILS during the late 1970s, with more than 1000 installations projected by 1990. (Ref. 27)

There is a large body of opinion in the aviation industry which holds that the present ILS, which is a hybrid of instrument and visual guidance, has reached the limit of safe use at Category I. St. John (Ref. 28), for example, states that 150 feet is probably the lowest safe decision height with the present system if a manually controlled landing is to be made. Litchford in several recent articles already cited (Refs. 16, 18, 25) has advanced much the same conclusion, which he calls the "100-foot barrier". The burden of the many arguments advanced by Captain Richard H. Beck (see Ref. 2 for example) is that both the ILS and approach lighting system do not provide adequate safeguards at decision height below 200 feet.

To penetrate below Category I with safety and regularity requires two major improvements. First is an electronic guidance signal of greater inherent accuracy and freedom from distortion. This could be accomplished either by improvements of the present ILS or by a replacement system such as the microwave ILS. The second improvement is a better way of providing instrument guidance down to, and visual guidance below, the decision height. Many authorities consider the head-up display to be the solution and, in fact, believe the Category II use to be the primary justification for adoption of the head-up display in civil aviation.

INSTRUMENTS

A popular description of a modern aircraft cockpit is the "clockshop". The term is not inapt if one considers that instrument panels and consoles in present jet aircraft typically contain well over 200 separate dials, indicators, and guages -- several of which give multiple items of information. While not all are in use at one time, the array is nevertheless formidable.

For basic reference during critical flight phases such as approach and landing, missed approach, or takeoff the pilot makes primary use of about 6 to 8 instruments:

ADI - presents artificial horizon and command attitude (flight director) information basically, but in the approach it may also provide raw localizer and glide slope deviation, approach speed indications, and radar altitude.

HSI - shows compass, radio directional information, and other data relating to the horizontal situation.

Secondary Compass - is a repeat of the dual HSI information shown at the co-pilot's station plus direction to VOR navigation aids and ILS compass locator data (LOM and LMM).

Airspeed Indicator - presents IAS, Mach number, and maximum speed indications.

Altimeter - provides altitude (QFE or QNH)* based on barometric pressure data.

Radar Altimeter - indicates absolute altitude (height above terrain) as sensed by downward-directed radar.

IVSI - presents instantaneous vertical speed (altitude rate) as derived from barometric pressure data.

In addition, the pilot may have reference to a clock (for elapsed time), the autopilot and ILS annunciator panel, and the compass comparator. A typical arrangement of basic flight instruments is shown in Figure 22.

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* With a QFE setting the barometric altimeter is adjusted so as to read 0 when the aircraft is on the runway. The altimeter therefore will indicate height above the runway elevation. With QNH the altimeter is set to read the field elevation above sea level. Since terrain elevation is measured and shown on charts with reference to sea level, the altitude of the aircraft in relation to terrain obstacles can be read directly. To obtain height above the runway, the airport elevation must be subtracted from the altimeter reading.

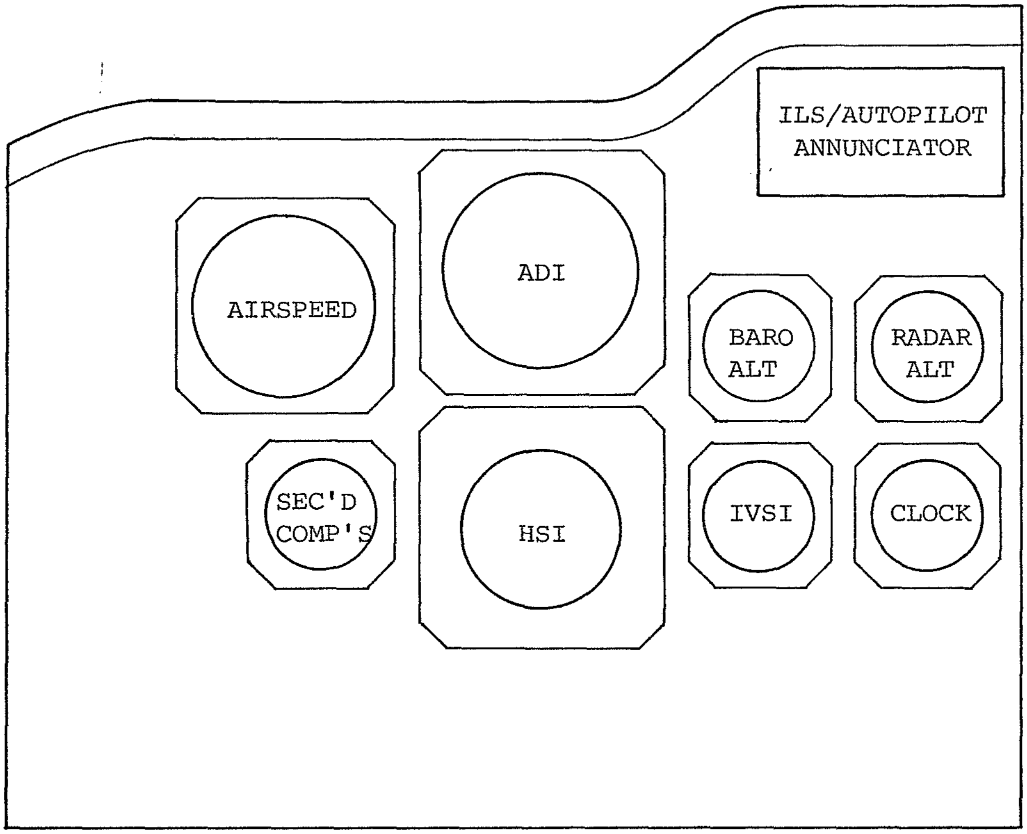
ILS/AUTOPILOT ANNUNCIATOR
ADI
AIRSPEED
BARO ALT
RADAR ALT
SEC'D COMP'S
HSI
IVSI
CLOCK

Figure 22

Except for improvements in the flight director indications of the ADI and the addition of the radar altimeter, these basic flight instruments have remained substantially unchanged over the last 40 years. The pilot's phrase, "Doolittle dials", is both a reference to the antiquity of these instruments and a conscious pun on the value in modern, complex aircraft. Numerous studies have shown that the present panel instruments have just about reached the limit of useful evolution, especially as guidance for the more critical flight maneuvers. Among the shortcomings of these instruments are the lack of integration, inappropriate size and scaling, location in relation to the external field of view, type of information presented, and level of illumination -- each of which is discussed below.

Integration of instruments may be taken in two senses. The simplest meaning is the combination of several different indices within a rather small visual area, often within the confines of a single display or indicator. The notion is to fit as many items of information into as compact an area as possible. The addition of ILS deviation pointers, airspeed and radar altitude information to the basic ADI/Flight Director is an example of this type of integration. Integration, however, can go farther; and in its second meaning the term refers to combining several items of information into a common frame of reference. Integration in this sense is more than just a physical aggregation; it involves presenting related items of information in a single set of coordinate axes to form a visual or spatial analog of the flight situation. The several CRT displays (either head-up or panel mounted) which have been developed for military aircraft are examples of this type of integration.

In either sense of the word, present civil aviation instrument panels are not integrated. The instruments are dispersed over a visual area of 30° or more, which can hardly be called compact. Altitude information is presented in azimuth-elevation coordinates. Directional and navigation information is in range-azimuth or rho-theta coordinates. Airspeed, altitude, and vertical velocity are shown in numerical form, either on circular scales or digital readouts or both. To form a coherent picture of the flight situation the pilot must integrate these disparate indications mentally. The cost in time and effort is a sizeable addition to the pilot's burden, especially when he must compare instrumental information with visual information extacted from the external scene (which is in natural or real-world coordinates).

The size and scaling of panel instruments is in many cases inappropriate for critical flight tasks which call for precise control. Complaints are chiefly directed at present day attitude and flight director instruments. Two examples will serve to illustrate the point.

Pitch attitude on the ADI is read by the displacement of the artificial horizon with respect to an aircraft symbol which typically measures 0.094 inches high by 2.0 inches wide. The scaling of the artificial horizon is usually about 1° = 0.065 inch. Thus, a change of 1° in the pitch of the aircraft is represented by a movement of 0.065 inch on an instrument located 25-28 inches from the pilot's eye. In terms of visual angles this means 1° of aircraft rotation in pitch is indicated by a symbol displacement of about 7.5 minutes of arc. This scale factor of 1:8 is available only on the larger and more modern ADIS. Lami (Ref. 29) states that a scale factor of 1.17 degrees is not uncommon in modern jet aircraft attitude instruments.

Scaling of the 1:8 to 1:10 is considered high sensitivity; and the new ultra-precise ADI designed for the Concorde will have a scale factor of 2.4 mm. per degree, which is to say 1:6.

At the approach threshold a 32-microamp localizer beam deflection is equivalent to 75 feet of displacement from the runway centerline. Since this is half the width of the standard all-weather runway, the pilot must keep the aircraft track within 35-40 feet of the centerline to allow for gear width and to prevent running off the runway surface after touchdown. This distance corresponds to a 16-microamp localizer deflection, which is represented on the ADI by a needle movement of about 0.15 inch. The difference between a safe touchdown and one with the landing gear off the runway is thus shown by a difference in needle position of only 0.15 inches (or 24 minutes of arc), which is only about 1-1/2 times the width of the needle itself. (Ref. 30)

The deficiences of panel instrument scaling is by no means confined to the ADI or even to approach and landing. 100 feet of altitude is denoted by a 1/8 to 1/10 of the full revolution of the pointer on altimeters. The difference between 600 and 700 feet per minute of vertical velocity is only a little more than a needle width on a typical IVSI. The difference between V_1, V_R, and V_2 on an airspeed indicator often amounts to 10° or 12° of revolution of the pointer.

Present panel instruments are also subject to criticism because of their location in relation to the pilot's area of interest. The pilot's basic dilemma has always been that when he looks out of the cockpit he cannot see the instruments and when he flies by instruments he has no external visual reference. The head-up display was originally conceived as a solution to this dilemna. Naish (Ref. 31) calls this locating the instrumental information in a more "efficient" position with respect to the pilot's total visual task. The consequences of having to shift vision from inside to outside the cockpit and vice versa during low altitude maneuvers are well-known and they have been amply discussed in Chapter IV. Many of the advocates of the head-up display consider the elimination of the need for inside-outside transition to be its major advantage.

Despite the wealth of information arrayed on present instrument panels, many observers believe there is not enough or that it is not of the right kind. The pilot's ultimate concern for control of the aircraft in the vertical dimension is the relation of his flight path angle to the horizon. There is no one instrument in the cockpit which gives him this information. He must derive an estimate from readings of altitude, airspeed, and vertical velocity. A considerable improvement in performance of precise vertical control tasks can be effected if the pilot is given a direct display of his flight path angle. (See, for example, Ref. 32, 33.) Similarly, speed control (especially in low-speed regimes) is greatly facilitated by a display of angle of attack information. Yet, no commercial transport has an angle of attack indicator even though such instruments have been standard in military aircraft for several years. As a final example, no visual or instrument system now in use in civil aviation provides guidance for the flare maneuver, which consequently has to be conducted solely by external visual reference. Cramer (Ref. 34) reports significant improvement in flare and touchdown performance with a display using radar altimeter inputs. Beck (Ref. 35) considers improved flight path angle control below 200 feet and flare anticipation and guidance to be among the principle advantages offered by a head-up display.

The illumination of aircraft instruments is of concern for two reasons. First, the illumination of the instrument panel is seldom uniform. There are dark spots and "hot" spots, i.e., individual instruments which are far below or far above the average level of illumination. This problem is further complicated by accumulated dust particles on the instrument glass which diffuse the image of the instrument face or produce glare. The second cause for concern about instrument lighting is the disparity which may exist between the illumination level in the cockpit and that of the external scene. When the pilot must transfer his vision from one to the other, the delay due to the brightness adaptation process slows the rate at which he can assimilate either instrument information or external visual cues. Here, too, is an area in which the head-up display can be of help. When viewing the HUD the pilot is already adapted to the illumination of the external surrounding. He is thus visually prepared to perceive and interpret external visual cues, which he would not be if he had just shifted his regard from an instrument panel of some different illumination level.

The foregoing is by no means a complete catalog of the problems associated with present-day aircraft instruments. The research literature contains many studies of other problems, some of which are not so much shortcomings of the instruments themselves as they are of information sensing and mechanization techniques. Among these are the inaccuracy and lag of barometric pressure instruments, the lack of a suitable compromise between barometric and radar altimetry, QNH vs QFE altimeter settings, angle of attack and drift angle sensing, and precession of gyroscopically stablized instruments. Since these are basic problems of information sensing and derivation, the head-up display offers no better solutions in this regard than do standard instruments.

The purpose in raising these questions is simply to indicate why no fully adequate solution to the pilot's information needs, head-up or otherwise, has yet been devised.

PROCEDURES

Lighting systems, electronic guidance equipment, and instruments are each part of the solution of the low-visibility problem. The final elements of the solution are the pilot himself and the way he makes use of these aids. The success of the low-visibility system depends in part, therefore, on operating procedures. The capabilities and limitations of the ground and airborne equipment tend to shape and constrain how they will be used. Still, there is a certain freedom of choice about procedures. The selection of an optimum procedure is important because inefficient or inappropriate use of the equipment can degrade the safety and effectiveness of the system just as much as equipment faults themselves.

The low-visibility procedures now in use have evolved over years of experience, which includes a certain amount of trial and error as well as enlightened innovation. While regulatory bodies such as the FAA and ICAO have established general rules governing operating practice, the choice as to how to implement these rules is still left up to the individual air carrier or operator. This arrangement seems to be mutually satisfactory. The FAA and ICAO show high respect for the prerogatives of the aircraft operators and avoid (either by choice or force of circumstances) dictating too scrupulously and specifically what procedures are to be followed. The only constraint imposed by these regulating bodies is that the individual operator's procedures conform to the general precepts of safety and sound practice. The operators, in turn, believe that they not only have the right to make decisions regarding specific procedures but that they are in the best position to do so because of the immediacy of their experience. They also believe they should be allowed to make specific selections and modifications of procedures which their experience leads them to expect will be in the best interest of themselves as private enterprises or of the public which they serve.

The following comments on procedures should not, therefore, be taken as a suggestion for tighter regulation or stricter conformity to a given set of rules. The intent is only to examine the procedural aspect of the low-visibility problem to see what effect it has on the pilot's guidance and control tasks and to identify areas in which the head-up display might offer relief.

The flight crew of a civil aircraft normally consists of a pilot (Captain) and co-pilot (First Officer). For some aircraft and for some airlines a third crew member (Flight Engineer) is present. In addition to his duties as a pilot, the Captain acts as commander of the aircraft. The First Officer's duty is to act as an assistant to the pilot, which in addition to flight control tasks includes responsibility for radio communication, record keeping, management of non-flight-control systems, and navigation. Some of these responsibilities may be assumed by the Flight Engineer if there is one. Normally the pilot controls the aircraft or monitors the performance of the autopilot, and the First Officer attends to all other tasks at the pilot's direction. Occasionally these roles may be reversed for training purposes or at the pilot's discretion but this is not important for most of the following discussion.

Most of the concern about procedures center around the approach and landing phases, especially in low-visibility conditions. Beck (Ref, 36) has offered a detailed description of the customary U.S. procedures and of alternates employed by British and French airline crews. The following is a condensed version of Beck's analysis of approach and landing procedures and of the problems encountered in low visibility.

> "When the airplane starts down the glide slope, the assumption must be that the Captain will manage the approach, that any allocation of crew duties will be such that there will be no abrogation of the prerogative of command, and that he, the Captain, will make the decision as to whether the approach is to be continued or a go-around executed.
>
> "And just how is this all to be accomplished? At present, there appears to be three general methods, (which shall be called)...Case I, II, and III.
>
> "Case I. The Captain hand flies the plane or, if on automatics, exercises complete control of the entire approach to the DH. At this point, the First Officer, who is looking out the window, indicates whether or not the required visual reference exists. Then the Captain looks up and makes his decision whether to continue or whether a missed approach must be executed. This is the general route toward which most of U.S. Carriers have directed their plans and thinking.
>
> "(In)...ideal approach conditions,...the aircraft is progressing satisfactorily down the approach path. The Captain is either flying manually by using raw data of the localizer and glide slope as well as computed command information, or is on automatics and is monitoring the response of this automatic equipment to the ILS inputs and is, in fact, exercising complete control of the flight. Since the airplane is and continues to remain "in the slot," he has just about formed an opinion regarding the success of the approach.
>
> "The First Officer meanwhile, is performing his assigned functions, such as monitoring his panel instruments and calling out certain altitudes as the aircraft progresses down the glide slope.

Some airlines require the First Officer to cross check his panel instruments with those of the Captain's. This results in a definite disruption of his scan pattern as well as introducing the problem of parallax. At some pre-determined point, this First Officer will have to start looking out the window for outside visual cues. Since altitude is perhaps the most important reminder the Captain wants before his arrival at the minimum decision height, someone will have to call it out if the integrated crew concept is to be maintained. If a Pilot-Engineer is a member of the crew, he could do it. If it is a two-man crew, the First Officer will have to divide his attention between the cockpit and the outside world, and this will require a constant focusing and refocusing of vision. As the DH is approached, the First Officer will now begin to pick up fragmentary outside cues and will then usually direct his entire attention toward identifying them.

"The basic concept of tracking should be mentioned at this point. The aircraft is doing one of three things: tracking on or parallel to, tracking away from, or tracking toward a desired path over the ground. At approach speed and at a low altitude with restricted visibility, tracking is determined by first observing a known object such as a light, for example, then observing another light or series of them and comparing them with what is first seen.

"Experience has shown that, in order to do this, a pilot must see a horizontal segment of lights equivalent to about three seconds of reaction time. At approach speed of 140 knots, the required segment will be at least 700 feet. To mentally digest this information, evaluate it, and decide whether the aircraft is or is not tracking as desired may take a fraction of a second or it may take several seconds, depending on the clarity, readability, and simplicity of the cues. ...This delay can be complicated by having the plane in the not uncommon position where it is yawed to the left, for example, due to a crosswind, and the autopilot has placed the plane to the left of the centerline. Fragmentary cues begin to appear to the First

Officer outside the window to his right. Since the First Officer may never have been exposed to a situation like this before, either under actual conditions or by simulation, there is grave doubt as to whether he will be able to quickly and accurately determine lateral tracking velocity or a positive tracking tendency.

"Finally, when the First Officer, in his judgment, has sufficient cues he will say, as one carrier has stipulated, "Runway in sight," if the runway and/or the approach light system is visible. The Captain then will look up and proceed to land his airplane. If the First Officer states, "Minimums..No runway," this means that the runway and/or approach light system is not visible, that no identifiable visual cues exist for continuing the approach by visual reference, and now the Captain must rotate the aircraft, apply power, and execute a go-around. This then is a very general description of Case I.

...There is a visual time lag involved when going from outside visual cues to instruments and back again when under conditions of reduced visibility. Applying this fact to the duties of the First Officer when the airplane is approaching the 100-foot DH, it becomes obvious that there exists considerable area for error by either incorrectly reading the panel instruments, especially a barometric altimeter, or by improperly assessing the outside cues, or both. To this visual lag, now add the seconds, or fractions thereof, for the time involved to say the words, "Minimums -- No runway," plus the time for the Captain to hear these words and put them into action in the form of control inputs, plus the fact that it takes a large jet transport nearly 2 seconds to respond to control inputs, and you will end up with a fairly formidable total time involved that could easily exceed 4-5 seconds. Remember that at the 100-foot decision height, the airplane is only 6 seconds from the threshold, and that it doesn't come to this 100-foot point and stop, but will be descending <u>through</u> this altitude. Therefore, by the time the aircraft has started to deviate from its descent, it will be considerably less than 100 feet from the ground.

"The Royal Aircraft Establishment at Bedford, England, has found that the shortcomings of visual control in pitch are one of the major safety problems in a low visibility landing when present day techniques are used. They have concluded that satisfactory visual pitch performance in a Category II approach will not be realized until the pilot sees the runway threshold and his aiming point beyond. On a glide slope of 3 degrees with an RVR of 1200 feet, they concluded that the pilot's eye would have to be as low as 70 feet to be able to have this proper judgment.

"Let's toss another real "hooker" in the pot and stir it around for a minute. Again, we will assume the ideal approach has occured up to the point where the aircraft has arrived at the 100-foot DH on localizer and on glide slope, there were sufficient visual cues, and the Captain has decided to continue the approach. Somewhere between 100 feet and the touchdown, the Captain has become involved in a non-homogeneous air mass, and a "blob" of fog has drifted across the runway. near to the RVR transmissometer site but not affecting its readout, or there has been a rapid deterioration of visibility. Either of two following events could occur.

"First, the Captain, who has been in contact visually, will have had the farthest lights obscured. This rapid foreshortening of his visual segment, or his loss of visual cues may immediately cause him to belive he has inadvertently "pulled the nose up" and thus cut off his view of the nearest lights. Unfortunately, since the lights farthest away have been lost from view, the natural tendency for the pilot is to push forward on the yoke and lower the nose. The resultant increase in the rate of descent could very well be so rapid as to place the aircraft in an unrecoverable attitude, resulting in an undershoot or an uncontrolled contact with the runway.

"Second, an attempt might be made to execute a missed approach. If this is commended, it must be remembered that both pilots will undoubtedly be "head-up" looking out the windows. Thus, neither of them can be exactly cognizant of the plane's rate of descent, heading in degrees, or bank angle.

It therefore follows that one pilot, undoubtedly the Captain, will have to return to the panel instruments and suddenly attempt to absorb the totally different environment of head down instrument scanning, allow for eye adaptation from long range to short range focus (possibly under red lights, at night), immediately recognize and accurately assess the panel situation display, and at the same time begin the execution of rotation and power application, perhaps using non-computed pitch guidance data. All this must be accomplished in a 123-ton vehicle that is traveling at 140 knots, is sinking at the rate of some 700 feet per minute, has a 145-foot wing span, and is well below 100 feet from the ground. Certainly, this type of maneuver can be classified as a very low-grade calculated risk.

"Case II. The First Officer flies the plane, or if on automatics, exercises physical control on the approach manager. At some predetermined altitude, the Captain starts looking outside the window for visual cues. When the DH is reached, it is called out by the First Officer (or Pilot-Engineer) and the Captain then decides whether to continue or whether a missed approach must be executed. If the approach is to continue, the Captain physically takes control. If a go-around is to be made, it is commanded by the Captain and executed by the First Officer.

"This second method of approach has not yet received any great degree of acceptance in this country, although its merits have generally been recognized. It is presently employed by a number of European airlines, most notably British and the pilots of Air France's...night postal service.

"The aircraft is manuevered to the ILS localizer by either the Captain or the First Officer. Once established on localizer, the control of the plane, either manually or automatically, is conducted by the First Officer, while the Captain acts as an overall monitor and as an Approach Manager. This follows the old axiom that 'the easiest approach for a Captain to make is to have the co-pilot do it.'

"Once again if we employ the ideal approach conditions, we find the aircraft is progressing satisfactorily down the approach path, the First Officer, of course, is under more of a strain than the Captain since he is presently exercising control, but the Pilot-in-Command has more leisure to assess the conduct of the approach, the stability of flight, to monitor programmed airspeed, pitch angle, lateral guidance, rate of descent, and if there is any observable error, how the First Officer or the autopilot is compensating for and correcting these errors. In this manner, by having an overall picture of the progress of the flight, he will begin to form a preliminary decision regarding the possible success of the approach.

"At some predetermined altitude, say 300 or 400 feet above the runway, the Captain must now take what might be considered a calculated risk and assume that the airplane will continue properly on the ILS, that the First Officer will properly monitor raw and computed information as well as the automatic equipment, and that he, this Captain, must now go "head-up" and start looking for outside visual cues which he cannot yet see. Usually, the Captain will announce this action of completely divorcing himself from instrument panel scanning by stating, "Going head-up," and by placing his right hand on top of the First Officer's left hand, which has been on the throttles. Adaptation to proper eye accommodation should begin to occur, and he should start to pick up fragmentary cues that will now augment his assessment of the approach and allow him to begin to formulate an opinion.

"On arrival at the 100-foot decision height, if the aircraft is "in-the-slot," and if the Captain does have sufficient visual cues, he will then usually say, "I have control." Whereupon the First Officer, his right hand still on the control yoke, will remove his left hand from the throttles, leaving the transition from automatic flight (or First Officer control) to manual control for flare and landing directly under the jurisdiction of the Captain. The First Officer remains "head-down," continually scanning the panel so that if an unexpected go-around is to be made for any reason, on a command from the Captain he will be able to rotate the aircraft to a climb attitude while the Captain pushes the throttles forward.

"It should be mentioned at this point that experience has shown that when the Captain begins to see visual information, there is a tendency for him to be tempted to take over manual control too soon -- that is, when he has adequate azimuth guidance but poor vertical guidance. It should be acceptable for him to remain on auto pilot for a second or so past the 100-foot DH if he feels he has sufficient visual cues. He does not really need to physically assume manual control until he approaches the flare point. He will thus be able to get accustomed to and be better able to interpret these visual cues. To physically fly an airplane and orient oneself in low visibility is extremely difficult.

"On the other hand, if the aircraft arrives at the decision height and the Pilot-in-Command has said nothing or has not assumed control, the First Officer, whose left hand is still on the throttles, should be required to automatically make a missed approach. The policy on British European Airways, whose pilots make an average of 60 landings and take-offs per month, is to train their First Officers to make an approach expecting to make a go-around unless they hear the Captain say, "I have control" at or before the altitude at which they have been told to commence the overshoot. These procedures in no way abrogate the prerogative of command, since they are predetermined decisions from the Captain that require compliance.

"The pilots of Air France's Night Postale, who fly the mail within the boundaries of France using predominately DC-3's and DC-4's, utilize these same general principles but approach the problem slightly differently. About 80% of their crews are "frozen", they are taught voice rhythm, they are required to use specific words at specific times during the approach, and they employ a Flight Engineer in the third seat whose main duty is to read and call out radar altimeter values. This instrument, incidently, is a "go-no-go" item. The First Officer flies the complete approach and handles the throttles, which are rimmed for him by the Flight Engineer, beginning at the 500-foot point, to keep power equalized. As the plane starts to become contact, the Captain, who is looking outside, will advise the First Officer what corrections to make when there are proper and sufficient visual cues. The First Officer is what the French call "transparent" in pitch and throttles, i.e., he can be overriden by the Captain. But in the axes of yaw and roll, he is "fixed" or immovable until the Captain says he has control and physically takes over the landing. The First Officer is also required to stay "head-down" on panel instruments until the airplane comes to a STOP on the runway. If he has any tendency to look outside and disrupt his scan pattern, a shield is placed in his window so he cannot go visual. If a go-around is required, the Captain says, "La gomme," a word meaning "the rubber," and one that cannot be confused with any other work or phrase used during the approach. At this command, the First Officer executes the missed approach. The French have conducted this operation in Category II limits for over 20 years, and they have found this system remarkably successful.

"In any case, both the French and the British require the rotation and go-around to be executed by the First Officer, and once the airplane has been established in the proper pitch angle and is in a positive climb, the Captain can "clean up" the flaps and gear. When the Captain has re-established himself back on the panel instruments, he may, at his discretion, assume the physical handling of the flight controls.

"Case III. The Captain flies the plane or, if on automatics, completely controls and monitors the entire approach down to the DH solely by the use of a Head-Up Display he then makes the decision to continue or go-around. The Head-Up Display may be used by the Captain as the primary method of guidance with the panel instruments being utilized by the First Officer as a back-up, or the reverse situation can be employed where panel information is the primary source of guidance being flown or utilized by the First Officer, while the Head-Up Display is used as a monitoring system by the Captain. In either case, if a missed

> approach is to be made, it can be executed by the Captain utilizing the Head-Up System, or by the First Officer using panel instruments.

"Let's go back once more the the ideal approach and use the head-up display for controlling or monitoring the flight path. Assuming the aircraft is on localizer, the glide slope, stable and progressing satisfactorily, we find that the Captain will now be head-up looking out the window. If it is night time, he is maintaining his dark adaptation and since the display he is observing is focused on infinity, he is observing the symbology in his foveal or central vision, and thus his eyes are therefore on long range focus. At one glance he is able to continually monitor his command information, his deviation from the desired path, his airspeed, his altitude, and his pitch, yaw, and roll, with no time lag involved.

"If the airplane is coupled to the auto pilot or is being flown by the First Officer using panel instruments, the Captain has a positive and immediate source of information regarding the accuracy of the flight, the deviations that may exist as well as the rate and direction of any errors. If the Captain is hand flying the aircraft, he is utilizing command information that is being monitored and cross-checked by the First Officer on the panel. During the descent, the First Officer can call out required altitudes as well as note any deviations or malfunctions that he might observe.

"As the aircraft approaches the decision height, any fragmentary cues that may be appearing outside the window will be immediately seen by the Pilot-in-Command because he is looking through the optical combiner and can see them without focusing his eyes and with no obstruction to his vision.

"Thus, when the plane arrives at the DH, the Captain will know immediately whether or not he has sufficient visual cues, and therefore his decision will not only be accurate but will be instantaneous. If he can see enough, he can disconnect the auto pilot and land. If he cannot, he is able to instantly rotate the aircraft, apply power, and climb out by using command go-around information that can be programmed onto the

> head-up display either by manually activating a yoke button, or automatically by throttle advancement.
>
> "In this type of an approach, crew duties and monitoring of instruments can be integrated and coordinated to whatever depth an airline might deem advisable. There will be no misunderstanding as to what each person is to do, no overlap of control there will be an excellent method of providing redundancy of information, and there will be no infringement of the prerogative of decision and command.

Beck's analysis of procedures and their relation to the approach and landing problem is so thorough that no further comment is required. His argument for the use of the head-up display in low-visibility is one of the most cogent which has been advanced, and it is a view shared by the author of this study.

The procedural problem is not, however, confined to approach and landing or to missed approach, even though these may be the most severe manifestations. The low-visibility takeoff is also a problem, in part because of the procedures which have been adopted to compensate for certain deficiencies in the guidance system. As pointed out in Chapter III in the discussion of control requirements for takeoff, the pilot has two major concerns: runway alignment and monitoring of airspeed. The first task is accomplished almost solely by external visual reference while the second entails observation of the airspeed indicator on the instrument panel. To avoid having to look up and down continually, it is common to resort to the procedures of having the co-pilot call off critical airspeeds as they are reached successively. This verbal reporting procedure has certain inherent lags, and there is a dual possibility for error -- either in the reporting or in the understanding.

This has led some observers to conclude that the head-up display could offer a significant advantage in takeoff. First, if airspeed were presented on the HUD, the pilot would have this information available directly while looking outside. Moreover, it would allow him to correlate airspeed with the other visual cues from the runway which he uses to assess the progress of the takeoff. If the compass heading of the runway or far-end localizer information were also presented on the HUD, the pilot would have a supplement and corroboration of the visual cues used for maintaining runway alignment and/or flight path information would aid control of the aircraft at rotation and on the climbout, when the forward view of the horizon is cut off by the nose of the aircraft. With present procedures the pilot must revert from visual to panel instrument reference at this point, which is analagous to the missed approach procedure with all of the inherent problems described by Beck above. An additional advantage offered by the HUD, some contend, is facilitation of the noise abatement procedures which are executed at just about the time the pilot is converting from visual reference and adapting to panel instrument displays.

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CHAPTER VI

THE ROLE OF THE HEAD-UP DISPLAY

Taken together, Chapters III, IV, and V constitute a statement of problems which exist in present civil aviation operations. Although the chief problem is approach and landing, concern is not limited to this phase of flight. Takeoff, rollout and taxi, and missed approach also present certain inherent difficulties. Nearly all these problems stem from the same source -- the nature of the pilot's visual tasks and the deficiencies of present means of guidance. Even in the best conditions of visibility, guidance is not wholly satisfacotry. The effect of the shortcomings in the guidance system is intensified by reduction in external visibility. Generally, the lower the RVR, the greater the concern about system performance requirements and the adequacy of existing visual and electronic aids. In some cases, the present aids not only fail to solve the basic guidance problems, they also contribute new ones of their own. Additional complication is introducted by individual aircraft performance variables, particularly the increased size and weight of new jumbo jet and SST classes of aircraft.

This chapter is devoted to an examination of specific roles which the head-up display could play in solving or alleviating the guidance problems enumerated in the preceding three chapters. The potential contribution of the head-up display is disucssed under four topical headings:

- VFR Approach and Landing
- IFR Cagetory I/II Approach and Landing
- IFR Category III Approach and Landing
- Other Flight Phases

In this discussion basic head-up display concepts will be outlined. Inevitably this will lead to discussion of the information content of the display for specific purposes and of the format and method of presentation. This should not be taken as an attempt to indulge in an exercise of display design. The intent is only to explain display concepts, and any particular illustration of the concept should be taken as no more than an example of the form which the display might take.

VFR APPROACH AND LANDING

To control the aircraft on the approach so that a given flight path can be attained and held, the pilot must have information relating to his position with respect to the desired track, the rate at which he is moving toward or away from the track, and his acceleration with respect to the track (i.e., the rate at which his rate of movement is changing). Since the flight path is made up of horizontal and vertical components, the pilot has a total of six variables to be controlled (three in each axis). Implicit in this analysis is the assumption that the pilot has some way of knowing or discerning the location of the desired track, as well as his position and movement with respect to it. In Chapter IV it was established that the pilot derives this information from visual cues provided by the relative positions and movement of the horizon, the extended runway centerline, the aiming point, and the impact point (the zero-velocity or X-point). Supplementary information in the form of airspeed, attitude, altitude, and range to the runway is also used to confirm the indiciations given by the basic cues.

Of the two axes of control, the vertical is more difficult to manage than the horizontal. In part this is due to the lesser stability of the aircraft in this axis, particularly in the high angle of attack approaches characteristic of jet aircraft. Vertical control is also more difficult because of the poorer quality of the visual cues which relate to it. In general, a pilot cannot determine directly, from his view of the ground, his angle of descent at any given moment. He can only deduce it over time by observation of the movement of the impact point with respect to the horizon and/or the aiming point. Instrumental information from within the cockpit (speed, pitch attitude, altitude, and vertical velocity) also helps to form an appreciation of his angle of descent, but these references are not available to him without looking away from the external scene.

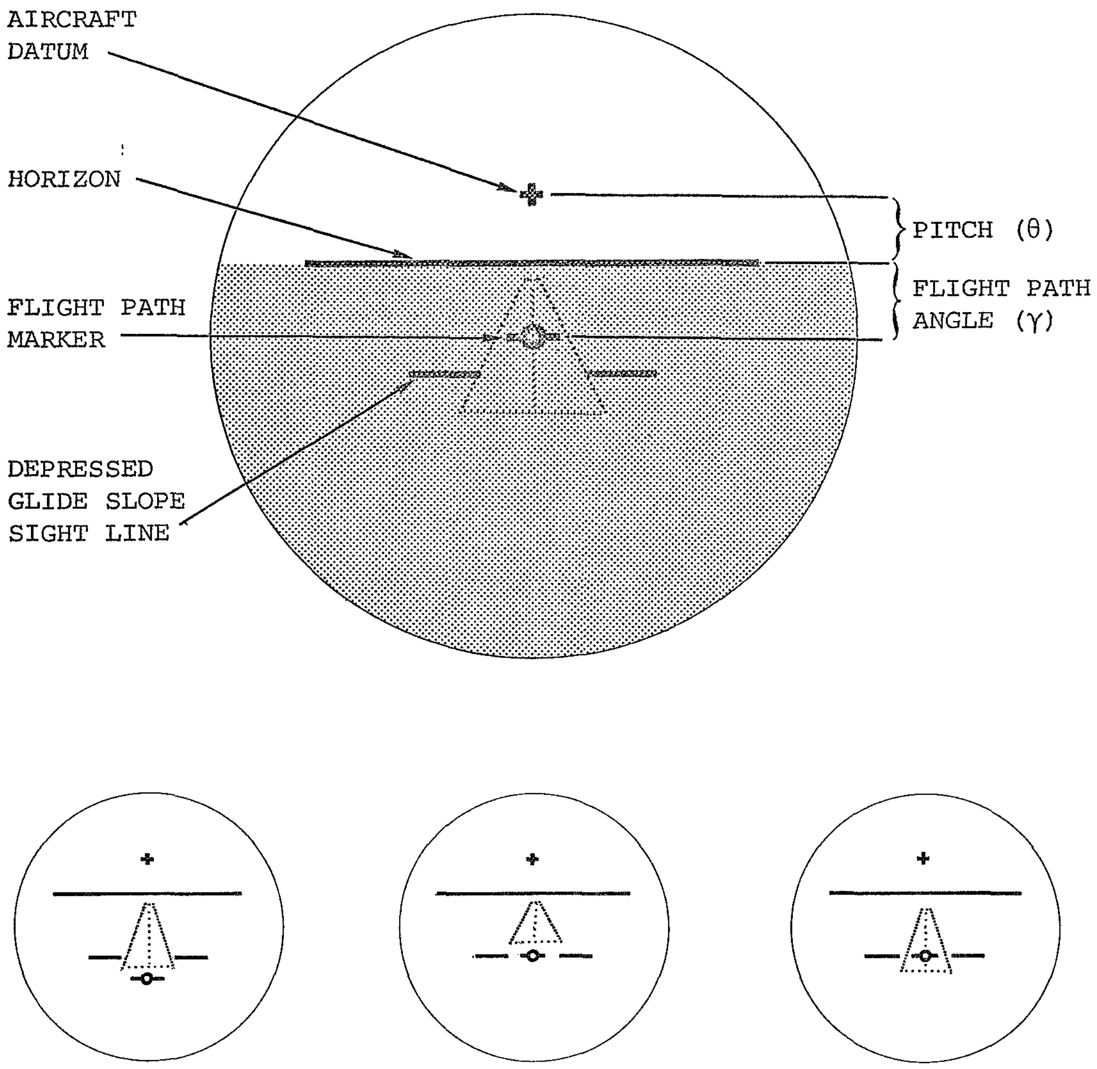
The visual ground aids, such as VASI, which have been developed for the purpose of aiding the pilot in controlling his vertical approach path are not fully satisfactory. The VASI is inflexible in that it provides guidance only to a single point on the runway and does not allow the pilot to compensate for variations in aircraft size, weight, trim condition, runway surface condition, runway length, or whatever. Furthermore, there are too few VASIs in relation to the number of runways regularly used by civil aircraft in VFR conditions. Those installations which do exist are often placed on the longer and better equipped runways and not on those for which no other approach aid exists.

The head-up display could serve as a source of guidance information for the unaided visual approach and as an adjunct to VASI approaches. Basically, this type of head-up display is an airborne VASI, which provides an artificial enhancement and supplement of naturally available cues. The VFR HUD is not, however, a replacement of natural cues nor is it a self-sufficient device. It is useable only if the pilot can also see the runway, the intervening ground plane, and his desired point of contact with the runway (the runway aiming point).

A display of this sort would be a significant aid to VFR approaches. It might be improved by the addition of certain information which now is obtainable only by referring to panel instruments, e.g., airspeed and altitude. The head-up display would thus permit the pilot to see all that which he now uses in the way of natural visual cues plus visual sighting aides plus instrumental information which he now can get only by looking away from the external scene.

Figure 23 is an illustration of the basic elements of a head-up display of the airborne VASI type. It consists of an artificial horizon for basic attitude reference, a depressed sight line to indicate the desired glide slope angle, and a flight path marker which shows the actual vertical flight path angle of the aircraft. The pilot's task is to sight along the glide slope line to the desired touchdown point on the runway and to fly the aircraft so that the flight path marker is aligned vertically with the glide slope line. A display consisting of these three elements was suggested about 15 years ago by the work of Calvert (Refs. 1, 2) and Lane and Cummings (Ref. 3). It represents minimum display for VFR approach.

Figures 24A and 24B show two augmented forms of the basic display. In Figure A the display contains, in addition to the basic elements, an indication of runway centerline and runway heading to assist in making estimates of lateral track error and cross track velocities. The position of the runway centerline symbol, determined by the difference between aircraft and runway heading, denotes crab angle. The lateral displacement and move-



AIMING POINT CORRECT BUT FLIGHT PATH ANGLE TOO STEEP

A/C is passing through desired glide slope but flight path angle is too steep.

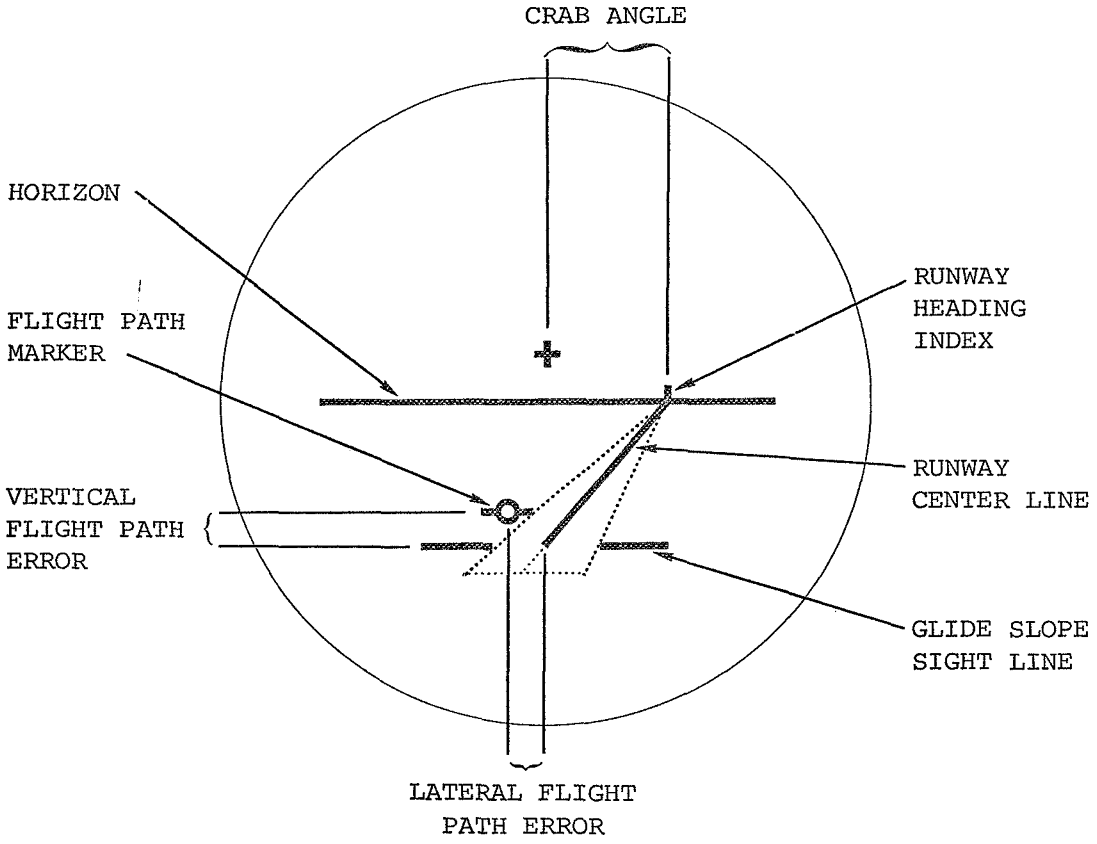
FLIGHT PATH ANGLE CORRECT BUT AIMING POINT SHORT OF RUNWAY

A/C is below desired glide slope and flight path angle indicates A/C will remain so.

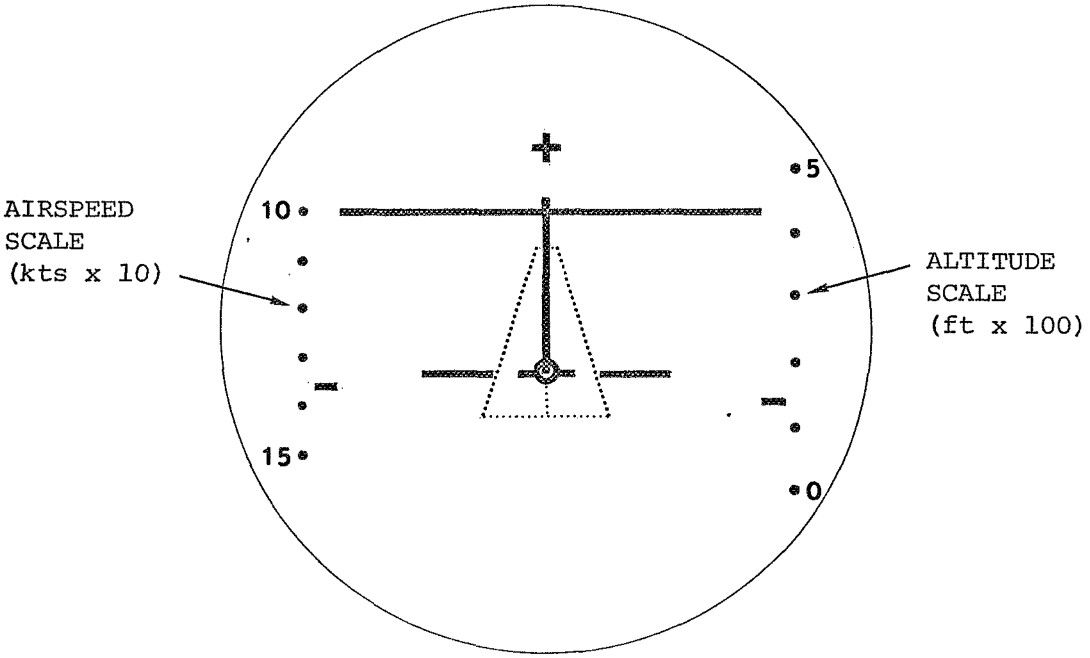
FLIGHT PATH ANGLE AND AIMING POINT CORRECT

A/C is on desired glide slope and flight path angle indicates A/C will remain so.

Figure 23



A. BASIC VFR HUD WITH RUNWAY CENTER LINE ADDED



B. AIRSPEED AND ALTITUDE SCALES ADDED

Figure 24

ment of the flight path marker with respect to the runway centerline symbol indicates track error and cross track velocity respectively. It should be noted that the placement of the runway centerline symbol is not determined by signals from ground equipment. It is derived wholly within the aircraft from a setting of the known heading of the runway and a sensing of the magnetic heading of the aircraft.

Figure 24B shows the same display supplemented with instrumental indications of airspeed and altitude. Obviously, other combinations are possible. Airspeed and altitude scales could be presented on the basic display of Figure 24 without the addition of the runway centerline. Angle of attack or angle of attack error could be substituted for airspeed. Vertical velocity might be added alongside the altitude scale or integrated with it in some fashion. As stated in the introductory remarks, there is no attempt here to recommend display designs, but simply to offer examples of the form which the display concept might take.

A head-up display offers several distinct advantages for the VFR approach. It allows the pilot full freedom in selecting the desired approach aiming point, making it possible to compensate for aircraft and runway variations and yet retain the same angular display indications. The head-up display provides a clear and accurate horizon reference. The real world horizon (the apparent meeting of earth and sky) is not always usable because of low flying cloud banks, rising terrain beyond the runway, sloping terrain, or the irregularities of city skylines. Furthermore, not all airports are level. Judgments of the correct approach angle to sloping sites are difficult to make by unaided visual means, but considerably easier with a head-up display which serves as a sighting aid. The head-up display also would help in making approaches over water and smooth featureless terrain, where the absence of textural cues from the ground may lead to deceptive altitude and flight path indications. Finally, because the head-up display provides clear and constant angular reference points, the effects of atmospheric turbulence, wind shear, and trailing vortex from preceding aircraft are less likely to produce the confusion which they do when the pilot is flying by unaided visual reference.

Apart from certain technical considerations which will be taken up subsequently, the satisfactory use of the head-up display in visual approaches rests on three assumptions. First, the understanding of the reqired visual cues is sufficiently correct to assure that the displayed indices are indeed those needed and used by the pilot for horizontal and vertical control. This is one of the most thoroughly studied topics in all of aviation, and while the mechanics of the visual process are not known completely, there is wide and ample agreement on basic principles. (See Ref. 4, for example.) From this research, it is safe to conclude that a presentation of horizon, glide slope, runway centerline, and flight path references is consistent with the basic principles and sufficient for VFR guidance. The remaining two assumptions have to do with what is not presented on the display. They are 1) that the pilot is familiar with aircraft and runway variables and knows how to compensate for them, and 2) that the landing site is well enough defined from some point onward in the approach for the pilot to detect the proper aiming point. Since these are identical with the assumptions now made for the unaided VFR approach, the imposition of these conditions for satisfactory use of the head-up display adds nothing new.

The theoretical advantages offered by the HUD as a visual approach aid must be set against some of the technical difficulties which arise in implementing such a display. Sleight (Ref. 5) points out that a display consisting of only a horizon and a depressed glide slope sight line may not be as easily flyable as a flight path director because the double integration which has to occur to go from an indication of position error to an estimate of the necessary rate of correction to be applied to aircraft attitude. The addition of a flight path marker (velocity vector) symbol helps alleviate the problem, but not entirely.

Flight trials of several forms of head-up displays embodying a depressed sight line and a flight path marker have been conducted by the Royal Aircraft Establishments at Farnborough and Bedford (Ref. 6). Among the variations tested were a flight path marker alone (both simple error and quickened), a depressed sight line alone, and combinations of the two (with and without quickening of the flight path marker). Studies were also made of the effects of introducting a third element which acted as a director steering symbol in conjunction with the flight path marker which denoted simple angular error. The best results, in terms of control accuracy and amount of pilot error expended, were obtained with a display which was quickened with rate inputs or lagged by introducing a simple time constant. These results were not conclusive, however, and the feeling was that additional experiments would be necessary to refine the display dynamics.

The major difficulty in implementing the head-up display is the problem of finding a suitably accurate method of sensing vertical and horizontal flight path angles. With present systems these angles are not sensed directly, but are derived from measurements of angle of attack and crab angle, both of which are obtained from vanes or probes inserted into the airstream. This method does not yield measurements of sufficient accuracy and sensitivity. It is almost impossible to locate the probes so as to get a true measure of the undisturbed relative airflow, and there are "dead bands" and lags inherent in pressure sensing devices. Inertial reference systems can eliminate the problem by providing direct measures of the horizontal and vertical components of the flight path angle, but they have not yet reached a state of development where they are fully acceptable for civil aviation use.

On the whole, however, the technical drawbacks of the head-up display in the VFR approach application are far outweighed by its enormous theoretical and practical advantages. The concept is basically sound, and its practicality is limited only by technological difficulties. The importance of the technical problems should not be belittled, but they do not constitute _per se_ an argument against the HUD concept or against its potential value in the VFR approach. Rather, the questions of technology represent only obstacles to be overcome in the realization of an improved VFR ance system.

The head-up display concept described thus far is only for use in the approach; it is not a landing display. To make it so, additional indications are required. These are flare and decrab guidance. Of the two, information relating to the flare maneuver is the more important and difficult to present. Adequate decrab guidance is probably afforded by the lateral position of an aircraft datum marker (denoted by + in the examples of Figures 23 and 24) with respect to the actual or symbolic runway centerline.

In performing the flare and touchdown the pilot makes almost exclusive use of external visual cues for guidance. The flare and touchdown maneuver, however, is a very complicated interplay of altitude, sink rate, and airspeed variables. The changes in visual cues which result from these relationships are difficult to interpret correctly, with the result that it is not always possible for the pilot to establish a definite correlation between control inputs and changes in the visual scene. Landing, therefore, never becomes truly intuitive, but must be learned and re-learned to maintain proficiency. Landing, as presently conducted, is largely an attitude control maneuver in which a change in flight path angle is guided by a vertical shift in the aiming point and effected by rotation of the aircraft in pitch. The aircraft responds rather quickly in pitch, but the consequences of rotation in terms of altitude, sink rate, and airspeed are not manifested until some time later. As a result, pilot control of these variables lags, i.e., he must evaluate them by visual means and by "feel" after they have occurred. Pilot uneasiness is greatest in situations like this where he is behind instead of ahead of the flight situation. Moreover, airspeed and vertical velocity are impossible to estimate with any accuracy by visual means alone. The best indications are obtained from instruments located on the panel, out of the pilot's external field of view. This has led to speculation that the head-up display would be of great value as a supplement to natural visual cues in flare and touchdown.

Figure 25 shows three ways in which the head-up display could be used to provide landing guidance. Version A is a simple and straightforward solution in which the depressed sight line is shifted upward from the approach angle to a shallower angle appropriate for flare. This corresponds to what the pilot now does in visually controlled landings. The pilot's task is to adjust pitch attitude so that the flight path marker is centered on the sight line symbol in its new position. The addition of airspeed and altitude (or vertical velocity) scales, preferably in expanded form for vernier

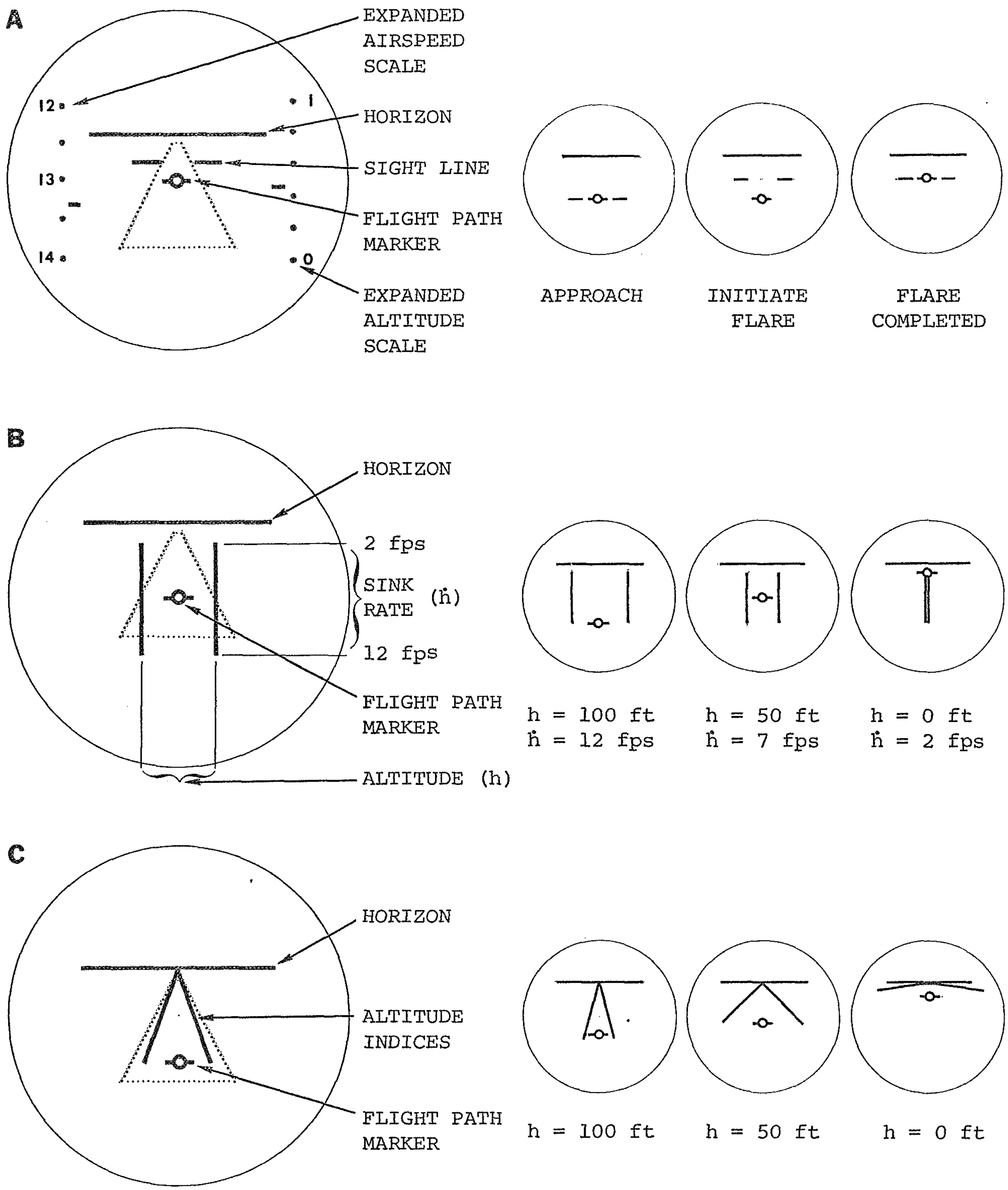

A
EXPANDED AIRSPEED SCALE
12
13
14
1
0
HORIZON
SIGHT LINE
FLIGHT PATH MARKER
EXPANDED ALTITUDE SCALE
APPROACH
INITIATE FLARE
FLARE COMPLETED
B
HORIZON
2 fps
SINK RATE ($\dot{h}$)
12 fps
FLIGHT PATH MARKER
ALTITUDE (h)
h = 100 ft
$\dot{h}$ = 12 fps
h = 50 ft
$\dot{h}$ = 7 fps
h = 0 ft
$\dot{h}$ = 2 fps
C
HORIZON
ALTITUDE INDICES
FLIGHT PATH MARKER
h = 100 ft
h = 50 ft
h = 0 ft

Figure 25

reading, would provide other information to monitor the progress of flare and touchdown.

Versions B and C are more sophisticated solutions. Version B (suggested by Gaidsick, Ref. 7) introduces a new symbol to indicate that flare should be initiated and to guide its execution. The vertical position of the flight path marker with respect to the bars is an analog of sink rate. The space between the bars is an analog of altitude. As altitude decreases, the bars come closer together, and the pilot's task is to control the aircraft in pitch so that the flight path marker moves upward, denoting a decrease in sink rate. At touchdown the bars come together, and the flight path marker should be positioned on top of the bars. It should be noted that no exact starting position for the flare profile is prescribed. It matters only that the sink rate be low when altitude reaches zero, and not how this condition is arrived at.

Version C (suggested by Davis, Ref. 8) makes use of the fact that the edges of the runway appear to move outward and upward as the aircraft nears touchdown. A similar movement of a runway centerline symbol, which splits into two parts each rotating toward the horizon, is used as an analog of altitude and sink rate. Altitude is denoted by the angular separation between the "runway edges", and sink rate by their rate of motion. By controlling the aircraft in pitch so that the flight path marker remains aligned with the base of the triangle formed by the runway edge sysbols, a coordinated reduction of sink rate with altitude is achieved.

All three versions require an altitude signal (preferably radar altitude) to initiate the change in display configuration, and Versions B and C also require sink rate and computation of the director equation. A limited amount of simulator and flight testing has been conducted for each of these displays (Version A by RAE/Farnborough, B by NASA Flight Research Center, and C by USAF Flight Dynamics Laboratory). The results are encouraging but preliminary, and more work needs to be done to establish their utility. As a concept, however, the use of the HUD for flare and landing guidance offers promise, not only because of the general advantages which a HUD offers in the VFR situation, but also because it can provide assistance in conducting a maneuver for which external visual reference alone may not be entirealy adequate.

In summary, it can be said that the head-up display offers a number of advantages for approach and landing in VFR conditions. It provides an enhancement of visual reference points used to determine critical flight angles. It can supplement the available guidance information with instrumental indications of those aircraft parameters which are difficult to control by natural visual cues alone. The head-up display is capable of presenting an integrated, skeletal representation of the flight situation in a format which is superimposed upon, and in the same coordinates as, the natural external scene. Finally, the head-up display permits greater flexibility in its use than existing ground visual aids, and it affords more immediate and sensitive indications of deviations from the desired flight path. These advantages constitute a strong argument for the head-up display in and of themselves. They gain more weight when one considers how the use of the HUD in VFR conditions could help bridge the gap to IFR, which is the subject of the next section.

IFR CATEGORY I/II APPROACH AND LANDING

The simple difference between VFR and IFS is that in the former the pilot can see the landing site and in the latter he cannot, at least until very late in the approach sequence. The consequences of this difference are far from simple however.

The present concept of IFR operations divides low visibility into three statra: Categories I, II, and III, with the latter two further divided into substrata which represent intermediate stages on the road to all-weather operations. There is a fundamental distinction between Categories I and II and Category III. The rules for Categories I and II permit the pilot to descend only to some prescribed minimum altitude on instruments, but not to continue unless he has established adequate visual reference for completing the approach and landing. In Category III the pilot will be permitted to continue all the way to touchdown and rollout without visual reference. Categories I and II are, therefore, "see-to-land" operations, while Category III is true "blind landing". It is this distinction which leads many to conclude that there are only two, not three, classes of reduced visibility operations. The author of this study believes the distinction is valid, and it is the reason for dividing the discussion of the IFR application of the HUD into two parts -- Category I/II in this section and Category III in the next.

All IFR operations are alike in that the lowered conditions of visibility prevent the pilot from seeing the critical real-world reference points he uses for guidance. The visual guidance loop is therefore open -- in that when the pilot makes control inputs, he receives no visual feedback of results from the external scene. In Category I/II the visual loop becomes closed when the pilot breaks out of the weather and can see the runway or some markings closely associated with it. In Category III the visual loop remains essentially open throughout the approach and landing.

However, the closing of the visual loop in Category I/II does not occur simultaneously for the horizontal and vertical axes of control. The horizontal loop is closed when the pilot can see a sufficient number of approach lights to establish his lateral track with respect to the extended runway centerline. The vertical loop remains open until such time as the pilot can see the aiming point on the runway and a short distance beyond. The vertical loop may open again in Category II when the aircraft is flared and the aiming point is shifted further down the runway. Thus, there is no one clearly definable point at which the transition to visual reference occurs. It is a zone whose extent depends on both the RVR and the flight profile.

Morrall (Ref. 9) summarizes the problem of vertical flight path guidance and control as follows:

> "The main safety problem in bad weather landing using present-day techniques is considered to be the shortcomings of the visual control in pitch during the final phase of the approach and landing especially in low visibilities...In making his decision whether to continue with the landing or not after becoming visual, the pilot must assess not only his position relative to the ideal flight path, but also his velocities, both cross track and vertical, to determine where the aircraft is going.
>
> "Whilst it is reasonable to expect a proficient pilot to be able to assess the aircraft's position and velocity in the horizontal plane by looking at a segment of approach lighting which includes only one cross bar, it is more difficult, if not impossible, to make a similar assessment in the pitch plane from the same picture. Even gross errors may be difficult to detect in the time available after visual contact in operations to the lower decision heights of Category II. It is believed that visual control of the aeroplane in pitch begins to become reliable when the pilot can see as far as the point on the ground to which his approach path is leading. For a glide slope angle of 3° and

> a slant range of 400 metres this occurs when the pilot's eye height is as low as 70 ft, and even for a slant range of 800 metres the eye height is 140 ft. This means, to achieve high standards of safety in these visual conditions, instrument guidance in pitch is required to heights of around 50 to 100 ft."

Concern with the problem of instrument to visual transition dominates the discussion of Category I/II operations. Not only does the length of transition time vary, the process may have to be reversed if visual reference is lost at flare or if there is a sudden and unexpected reduction in RVR. Moreover, the transition is seldom complete. A study by Hanes et al. (Ref. 10) showed that pilots continue to make use of panel instrument information after going head-up and until the aircraft is very close to the ground. The prime advantages claimed for the head-up display in Category I/II are that it eases the problem of transition and that it permits retaining essential instrumental information while looking out of the cockpit.

Flight and simulation trials conducted by BLEU at RAE/Bedford have confirmed that the head-up display makes the transition from panel instruments to external information easy and natural. Contact with the external cues was made at the earliest possible time, and pilots were able to transfer without abandoning instrument guidance. Although pilots taking part in the studies were not briefed in the method of combining external visual cues and head-up information, the natural method adopted by them was to continue to use the HUD for vertical guidance until considerably later than they began to use the external world for lateral guidance. This confirmed the pilots' own realization that external cues were deficient for vertical guidance until the threshold or beyond. (Ref. 11)

The rationale for the head-up display in Category I/II is predicated upon three major uses. First, the HUD must ease and improve the transition from instrument to visual reference, both by enabling the pilot to be head-up at the time the first faint cues come into view and by giving him reliable artificial reference points by which to interpret these cues. This is the pivotal feature of the HUD. The second use, implied in part by the first, is to provide a display of instrument information down to the decision height (where the transition takes place). The third use is to furnish instrument information needed below the decision height as a supplement to the natural cues for flare and touchdown guidance. Thus, as an instrument, the HUD functions throughout the approach and landing sequence. As a visual sighting aid, it functions from the decision height on to completion of the landing. In essence, the head-up display acts as a bridge across the hazardous portion of Cateogry I/II approach and landing, an area where neither instrument nor unaided visual guidance is wholly adequate.

Naish (Ref. 12) has stated the properties of the Category I/II head-up display and the design features which make these properties possible. They are summarized in Table VIII. While some may take exception to certain details and there may be alternative ways of phrasing, Naish's version may be let stand as a generally acceptable statement of desirable characteristics about the head-up display for application to the Category I/II approach and landing.

There is also rather close general agreement on the information content of a Category I/II head-up display. Baxter (Ref. 13), for example, has laid down the following as the basic elements of a HUD which makes use of ILS information:

- Attitude Reference
- Runway Heading or Track

TABLE VII

PROPERTIES OF HEAD-UP DISPLAY (HUD)

PROPERTY	ORIGIN OF PROPERTY	MEANS OF IMPLEMENTATION
Continuous transition between instrument and visual flight.	Display and forward view in same position.	Reflecting collimator.
Ease of learning.	Display and forward view interpreted by similar rules.	Pictorial display conforming with forward view.
Accuracy of use.	Sufficient information presented in unified scheme.	Flight director and attitude information represented in common framework.

DESIGN FEATURES OF HEAD-UP DISPLAY (HUD)

CONTENT	Sufficient for accurate flight
	Not causing excessive obscuration
	Unaffected by use
FORM	Dominated by shape of chief symbols
	Dominated by speed of chief symbols
	Conformable with background
	Conformable within itself
	Comprising unique symbols
	Comprising simple symbols
	Avoiding interfering symbols
ALIGNMENT	Allowing common centers of interest
	Suppressing false information

- Runway Location
- ILS Localizer and Glide Slope Deviation
- Flight Path
- Airspeed
- Flight Direction

Others (e.g. Green, Ref. 14) suggest that additional information may be advisable. Among these are altitude, vertical velocity, range to touchdown, and event markers (such as outer, middle, and inner marker indications). There are differences of opinion on the subject of information requirements, which stem from differing interpretations of the pilot's control tasks and from varying estimates of the value of certain types of information for given purposes. For example, a study conducted by the USAF Instrument Pilot Instructor School (Ref. 15) concluded that pilots found path angle information more meaningful than vertical velocity for glide slope following. Others may take issue with this either because the study dealt with pilot preference rather than demonstrated need or because they have a higher opinion of the value of vertical velocity as an ILS-independent confirmation of glide slope following.

It is probably impossible to arrive at a comprehensive list of information requirements which will be satisfactory to all, nor is it necessary to do so for the purposes of this study. In principle, it can be said that the Category I/II HUD should contain all the information necessary for a VFR HUD since the visual guidance problem remains the same across IFR and VFR conditions. In addition, for Category I/II use the HUD must display ILS information since this is the primary guidance system down to the decision height. Finally, the HUD must present any instrument information deemed necessary for proper aircraft control or for corroboration of visual guidance below the decision height. Further, the form of the ILS and instrument information must be such that it is compatible with the visual guidance information. If the HUD is to be used for landing as well as approach (and this seems highly desirable), information to guide the flare, decrab, and rollout must also be presented.

While it is not too difficult to achieve agreement in general terms on information content, there are several opposing schools of thought on the format and symbology of a Category I/II head-up display. This is a questions which no amount of *a priori* reasoning or deductive argument can resolve. Empirical evidence from flight and simulation experience offers the best hope. The examples given hereafter are those which have been subjected to tests by use, and while this is no assurance as to what may be optimum, it is at least an indication of their workability.

Figure 26 is an illustration of five head-up display designs. Since the major concern is the presentation of ILS information in conjunction with visual guidance this aspect of the design has been emphasized. For the purpose of comparison, each display is shown for the same two approach conditions -- on localizer and glide slope and in the process of correcting for a high and to the right situation.

At first glance these five displays may seem radically different from each other. In fact, there is substantial underlying similarity in their static and dynamic properties. In all cases, the basic reference system is azimuth and elevation coordinates which correspond to the pilot's forward external view. The visual analog is that of a single-point perspective view of the earth projected onto an imaginary vertical plane ahead of the aircraft. The movement of display elements which represent real-world objects (such as the horizon or the runway) is referenced to aircraft

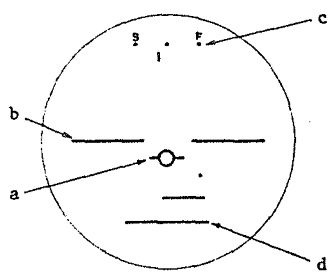
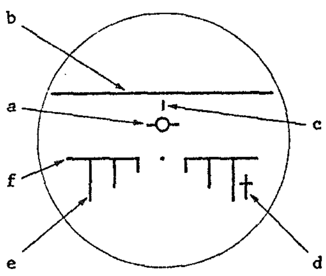
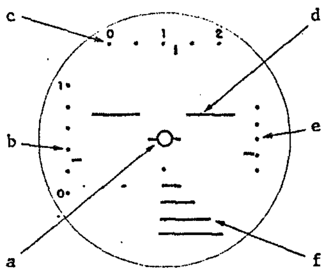
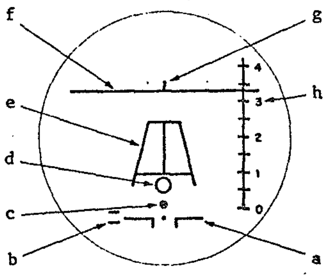
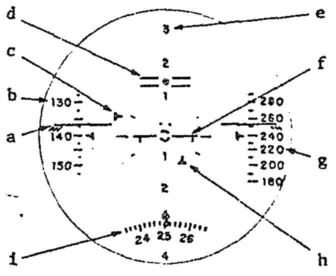
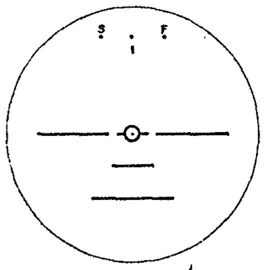
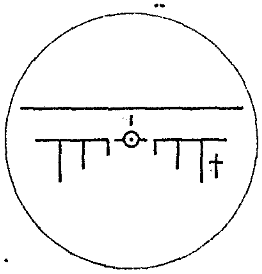
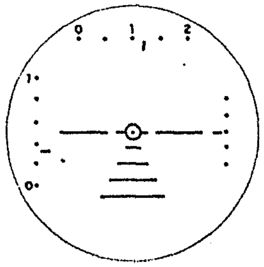
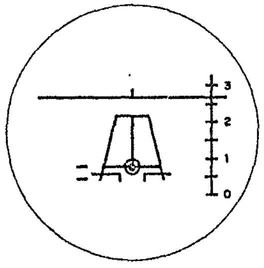
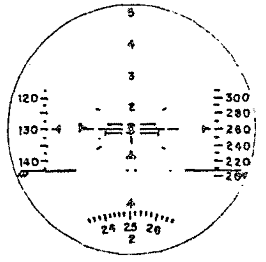
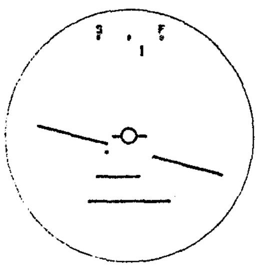
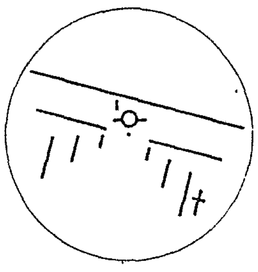
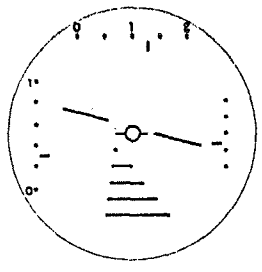
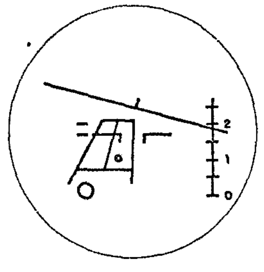
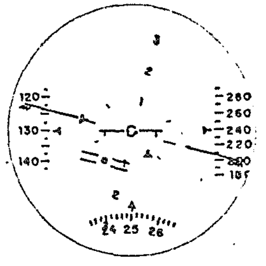
	McDONNEL-DOUGLAS/ELLIOTT	SAAB POLE TRACK	SPECTO	SPERRY	THOMSON-CSF L-193
BASIC CONFIGURATION	 a. Aircraft Datum (fixed) b. Horizon Bar c. Speed Reference Symbol d. Flight Director	 a. Velocity Vector Symbol b. Horizon Bar c. Speed Error Indicator d. Ref. Altitude Pole & Index e. Pole Track & Aiming Dot f. Glide Path Line	 a. Aircraft Reference Symbol b. Altitude Scale & Index c. Airspeed Scale & Index d. Horizon Bar e. Angle of Attack Error f. Flight Director Symbol	 a. Flight Path Marker b. Airspeed Index c. Deviation Dot d. Flight Director Symbol e. Runway Symbol f. Horizon Bar g. Heading Index h. Altitude Scale	 a. Horizon (green) b. Airspeed Scale & Index (amber) c. Glide Slope Indicator (red) d. Flight Director Symbol (blue) e. Pitch Scale (green) f. Aircraft Symbol (amber) g. Altitude Scale & Index (green) h. Localizer Indicator (red) i. Heading Scale (amber)
ON LOCALIZER AND GLIDE SLOPE					
CORRECTING FOR HIGH-RIGHT ERROR					

Figure 26

coordinates. This is a so-called "inside-out" reference system, in which display elements with earth counterparts move as the real objects appear to do when viewed from within the cockpit. Director or command symbols are "fly-to". For those displays with a flight path marker (or velocity vestor symbol) the movement of the symbol with respect to the earth plane corresponds to what the pilot would see if a thin pencil beam of light representing his instantaneous flight path were projected onto the terrain ahead of the aircraft.

There are differences among the displays, however, and one of the reasons for selecting these examples was to illustrate some of the important differences of head-up display philosophy. Perhaps the most basic of these is the question of just what sort of analog should the head-up display be. As indicated earlier, the HUD in its Category I/II use is both an instrument and a visual sighting device. As a sighting device, the compatibility of the display format with the external world is of paramount importance. Compatibility implies two things. First, display elements should correlate in position and movement with real-world counterparts. Second, the display should be isomorphic with the real world, which entails correspondence in shape and laws of perspective. On the other hand, the head-up display is also an instrument, and many of the parameters of flight which must be displayed do not fit into a natural reference system. Airspeed, vertical velocity, and range to go are three such parameters which are shown on some displays in Figure 26 as scales rather than in pictorial fashion. Obviously the head-up display cannot be purely a skeletal, pictorial display or purely a replica of the instrument panel. Some compromise must be struck. The displays illustrated in Figure 26 are a range of such compromises, with the highly pictorial SAAB Pole Track display at one extreme and the head-up instrument panel of the Thomson-CSF L 193 at the other.

Closely allied to this question is the issue of scale factors for the HUD. If the display is to be a visual analog which correlates with the real world (i.e., if it is to be an angle-sighting device), then the scale factor must be 1:1. One degree of symbol movement must correspond to one degree of real-world movement. This is fundamental; and if the display is to be used as an airborne VASI in VFR also, it is categorically imperative.

Not all experts accept this statement, however. The view held by some research workers at RAE/Farnborough (Ref. 10) and Naish (Refs. 17, 18) is that it is not only possible to fly a HUD with a non-unity scale factor, it is desirable. They contend that a 1:1 display appears overly sensitive to the pilot, which results in either oscillatory tracking performance or in an inordinate expenditure of effort to follow display indices. The introduction of a compressed scale factor, especially in pitch, decreases the effort required to fly the display but also decreases the accuracy of tracking performance. The optimum balance between effort and tracking accuracy can be achieved, according to this school of thought, by a scale factor between 1:5 and 1:8 (1° of HUD symbol movement represents 5° - 8° of real world movement).

The McDonnell-Douglas/Ellion HUD in Figure 26 is an example of a display with a compressed scale factor; the others are 1:1 in scaling. Without pursuing the matter further, it is apparent that the questions cannot be resolved without more experimental evidence. Both types of displays have been flown with successful results, but never in comparison with each other. It must be added, however, that the proponents of a non-unity scale factor represent a minority view. Most of the research literature and most informed opinion holds to the view that 1:1 scaling is absolutely essential if the HUD is to be used as a sighting device to supplement and aid visual reference. It also appears that the more one tends to regard the HUD as a substitute instrument panel, raised and super-imposed on the external scene, the strong is the disposition to accept a non-unity scale factor. Clearly, this is a topic on which more research is needed.

Another major question of HUD design for Category I/II application concerns the nature of the dynamic laws used to present steering or director information. The position of the flight path marker symbol in relation to a desired approach path symbol is, in effect, a statement of simple angular error. As noted in connection with the VFR HUD, such a display is flyable, but it requires a great deal of pilot attention and effort. More satisfactory results, in terms of both accuracy and pilot work load, can be obtained by supplementing the simple error indication with information on rate and its derivatives.

Behan and Siciliani (Ref. 19) have offered a penetrating analysis of the problem and the outlines of the solution. The following is a paraphrase of their views.

Flying the approach may be construed as a tracking task in which the pilot is tracking a ramp input with the aid of a compensatory display. The approach path which the pilot wishes to fly is the ramp. The display is compensatory in that both the index of desired performance (the desired approach path to the runway) and the index of actual performance (the flight path symbol) move independently of, and are read in relation to, a common reference system (the horizon). In the VFR case the position of the depressed sight line in relation to the desired touchdown point on the runway is the index of desired performance. The position of the flight path marker in relation to the glide slope sight line is the index of actual performance. The pilot's task is to fly so that the flight path marker and the real-world runway both are aligned with the glide slope sight line. In IFR the view of the runway is obscured, and its location is shown by ILS information. The tracking task is complicated by the fact that the pilot must infer the error in the present position from a projection of the future position of the aircraft. This has important implications for understanding the period of transition from instrument to visual flying.

Laboratory studies of compensatory tracking tasks provide the following generalizations:

a) Performance of a compensatory tracking task is aided by including the first and second derivatives of error (rate and acceleration of error, respectively) in the input to the display (Ref. 20)

b) When control is unaided in relation to the display, compensatory tracking is superior to pursuit tracking with a simple input (Ref. 21)

c) With a shallow ramp input (which is the case in approach and landing), there is a tendency for the pilot to lead the input, i.e., to overshoot the desired touchdown point and land long (Ref. 22)

d) A compensatory indicator can give a more precise picture of the situation through use of high display gain (Ref. 23)

e) When the desired output is time-invariant (as in the approach and landing case) the compensatory tracking task is equally as efficient as the pursuit tracking task (Ref. 21, 22)

Behan and Siciliani conclude:

> In view of the present analysis of flying the final approach as a tracking task utilizing a compensatory display, considerations of the possibility of negative transfer of training lead to the conclusion that whatever instrumentation is developed should present a compensatory-type display. Transfer of training refers to the effects of the performance of one task on the performance of another. Transfer of training may be negative or positive. If the

> performance of one task facilitates the performance of the other, the transfer is positive. In the given situation, it is desirable that the transfer of training from the VFR to the IFR landings be positive. Thus, it is desirable to make the landing task under IFR conditions as much like the landing task under VFR conditions as is possible.
>
> "The same maneuvers must be accomplished for a VFR as for an IFR landing. The difference is the information which the pilot has available to him to accomplish the maneuvers...The task of the pilot does not change during the IFR landing, apart from the demands made on him by instrumentation and by the IFR approach pattern peculiar to the airport of intent."

Confirmation of the foregoing analysis can be found in the results of flight trials conducted by BLEU and by the SAAB organization in Sweden. Baxter (Ref. 24), commenting on these trials, states:

> "The combination of displacement and rate information in the vertical plane results in much more rapid corrections of flight path errors than is possible with pure director displays. Whereas the director display forces the pilot to make an exponential closure on the desired glide path, the displacement plus rate display enables him to fly straight in at an acceptable closing angle and then, when he is almost there, make a sudden change in flight path to line up with the desired glide path. I found that, during a run from 6 miles to threshold, I was able to make three major excursions from the desired glidepath and correct them all out again before landing."

Similar conclusions were reached in a USAF study (Ref. 25) where it was found that pitch commands augmented with barometric vertical velocity, accelerometer, and vertical gyro inputs lead to superior glide slope following performance.

A final question of HUD philosophy for Category I/II approach and landing concerns the relation of the HUD, the pilot and the autopilot. This is part of the long-standing debate on manual vs. automatic control for reduced visibility landings. The British view tends to favor fully automatic approaches, all the way to touchdown. In this case, the pilot's role is to act as a monitor and manager of the automatic system. The HUD becomes a means for the pilot to exercise his functions as monitor and manager, but not to act us a back-up to the autopilot. If failure of the automatic system occurs, the pilot should initiate a missed approach. The British contend that manual control, with or without the HUD, is not sufficiently safe and reliable to contrive the approach in the event of autopilot malfunction. (For a concise summary of the British view, see St. John, Ref. 26.)

The view prevalent in the U.S. and in France is quite the contrary. There is a firm belief that the pilot must be kept in the control loop. This means acting not only as a monitor of the autopilot, but also as a manual controller in two circumstances: first, to take over control at some minimum height for completion of the landing and, second, to act as a back-up to complete the approach and landing in case of autopilot failure.

There is no need to become embroiled in the debate here. However, it must be pointed out that the position one takes on manual vs. automatic control has important consequences for the head-up display. Not only will the doctrine of use differ depending on one's point of view on autopilots, the form and content of the HUD will be affected. A HUD intended as an approach monitor need contain only glide slope and localizer information and an index of autopilot performance (e.g., a flight path marker). A HUD used for manual control might well contain, in addition to these elements, some sort of flight director information for the approach and flare, decrab and rollout guidance for the landing.

Thus far, the discussion of the head-up display for Category I/II has dealt with theoretical concerns. It is also necessary to inquire how the head-up display measures up in actual use. Flight tests and simulator evaluations of the HUD have been conducted for several years. Generally, the results show that many of the claimed advantages of the HUD can, in fact, be realized. While it is not possible to present all the experimental evidence, the following will indicate the tenor of the findings.

The FAA conducted extensive flight and simulator tests of the Sperry HUD at NAFEC in 1965. (Ref. 27) This is the Sperry HUD illustrated in Figure 26. The results indicated that pilots exhibit superior performance in both assessment and control tasks when using the HUD as compared with panel instruments. The measures of control performance were deviations from glide slope and localizer and lateral and longitutional dispersion of the touchdown point. Measures of the pilot's ability to assess the flight situation were the time to detect artificially induced autopilot errors and the longitutional maneuver distance to recover. A measure of pilot confidence in the display (HUD vs. panel instruments) was obtained from the altitude at which take-over from autopilot control occurred. The major findings of the study were:

a) Pilots can descend to considerably lower altitudes with steady localizer and glide slope standoffs, and recover safely from these situations when using the windshield displays compared with panel instruments. (Localizer: 240 ft. for panel instruments vs. 136 ft. for a HUD with a director and 185 ft. for a HUD without a director; Glide Slope: 194 ft. for panel instruments vs. 42 ft. for a HUD with a director and 63 ft. for a HUD without a director.) (All values are means.)

b. Pilots can recover from lateral offsets using substantially smaller maneuvering distances with a windshield display as compared with panel instruments. (The mean values were 5600 ft. for panel instruments, 2715 ft. for a HUD with a director and 3850 ft. for a HUD without a director.)

c) Differences in performance of pilots using head-up displays with and without flight directors were smaller than any differences in which a panel display was involved.

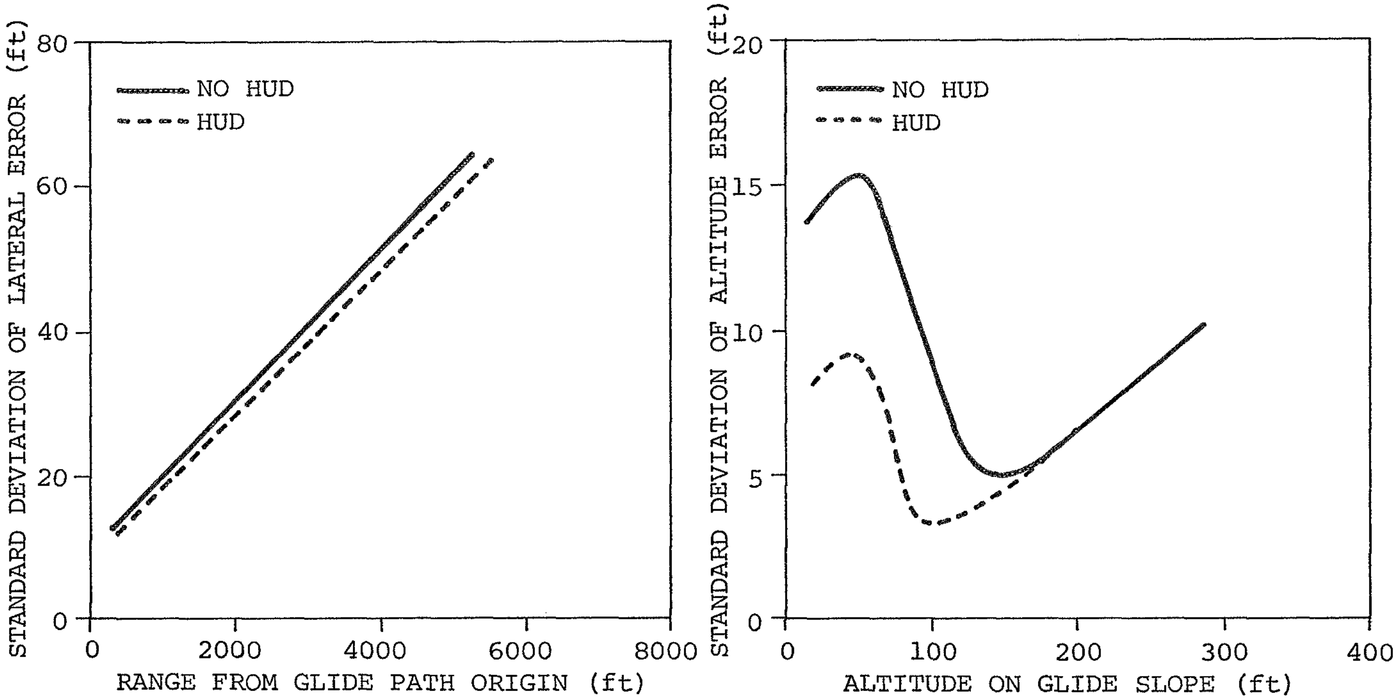
d) Where differences existed, a HUD with a flight director was superior to the same display without a flight director.

e) Behavior of pilots during the low weather approach was more comparable to VFR conditions with the HUD than with panel instruments.

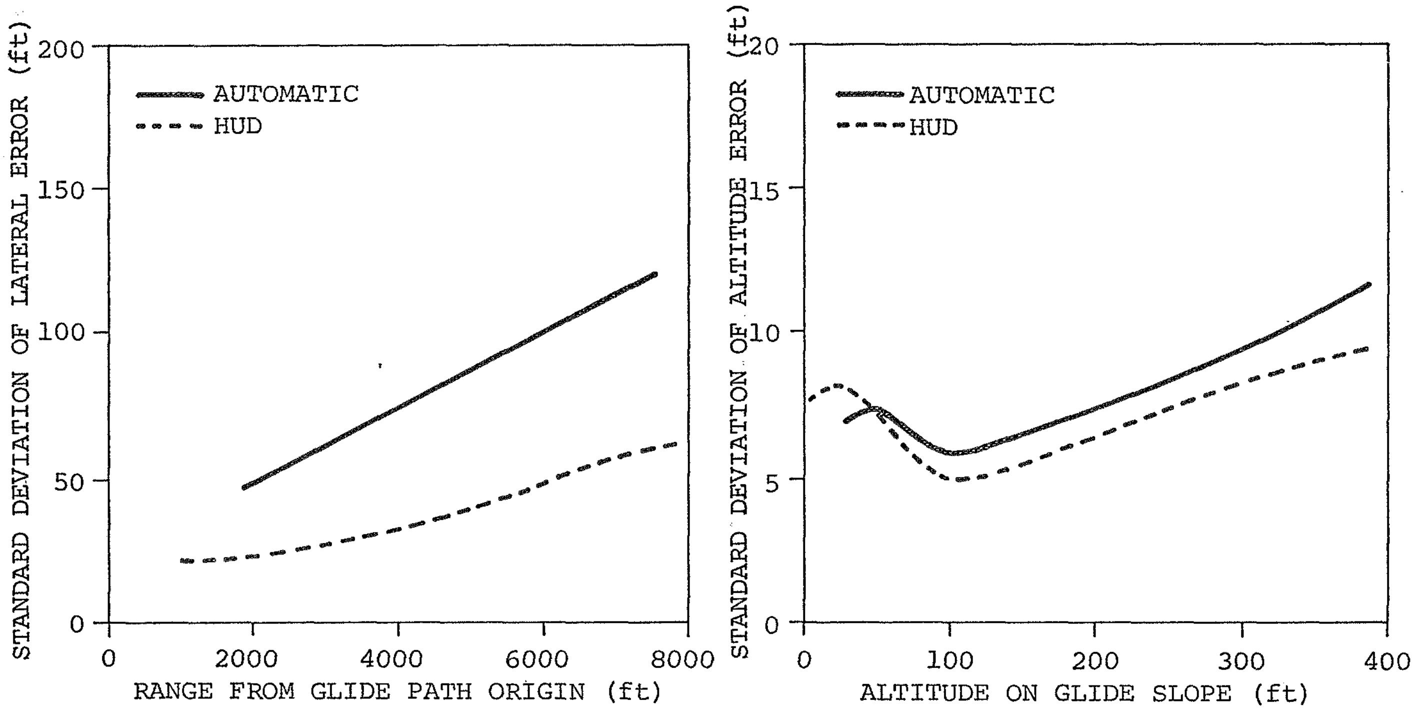
f) The HUD images can be made to overlay the real world with sufficient accuracy for low weather approach and landing using state-of-the-art equipment.

Morrall (Ref. 28) reports the results of flight tests carried out by BLEU with a HUD in a Varsity aircraft. A total of 64 approaches were flown to touchdown; with measurements of flight path deviation from localizer and glide slope taken by ground theodolite recordings. The results were compared with data on then current civil aviation automatic approaches followed by manual take-over using visual guidance and with data on an experimental BLEU fully automatic approach system. The findings are summarized in Figure 27 . The general conclusion was that pilot performance using the HUD as an aid to manual control was superior to that attainable with either of the other systems. In particular the HUD conctributed to a marked improvement in pitch performance in the altitude range of 140 ft. down to 50 ft., the zone where the transition to visual reference normally occurs in Category II.

Stout and Naish (Ref. 29) present the results of HUD flight tests conducted by McDonnell-Douglas as part of the DC-10 developmental program. The display used in these tests is shown in



HUD vs AUTOMATIC APPROACH FOLLOWED BY MANUAL TAKE-OVER USING VISUAL GUIDANCE



HUD vs BLEU FULLY AUTOMATIC APPROACH SYSTEM

(Data from Morrall, Ref. 28)

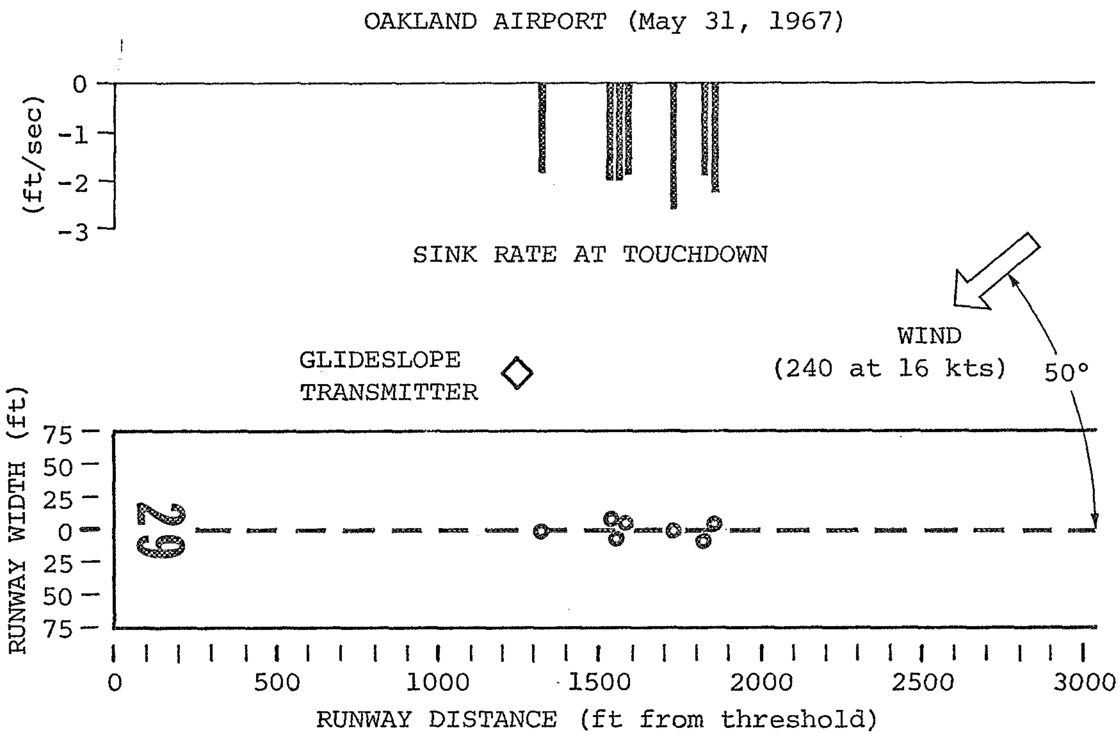
Figure 27

Figure 28. In seven landings at Oakland Airport on May 31, 1967, the rate of descent at touchdown averaged about 2 feet per second. No touchdown was at less than 1.75 feet per second or more than 2.75 feet per second. The dispersion of the touchdown point from the threshold was between 1300 and 1800 feet longitudinally and within ± 10 feet of the runway centerline. See Figure 29.

Stout (Ref. 30) reports a later series of trials with the same display. A total of 25 pilots representing a cross-section of FAA, airline, military, and McDonnell-Douglas personnel flew manual approaches and landings by sole reference to the HUD. Results similar to those described above were attained. Figure is a sample flight record of an approach to touchdown using the head-up display.

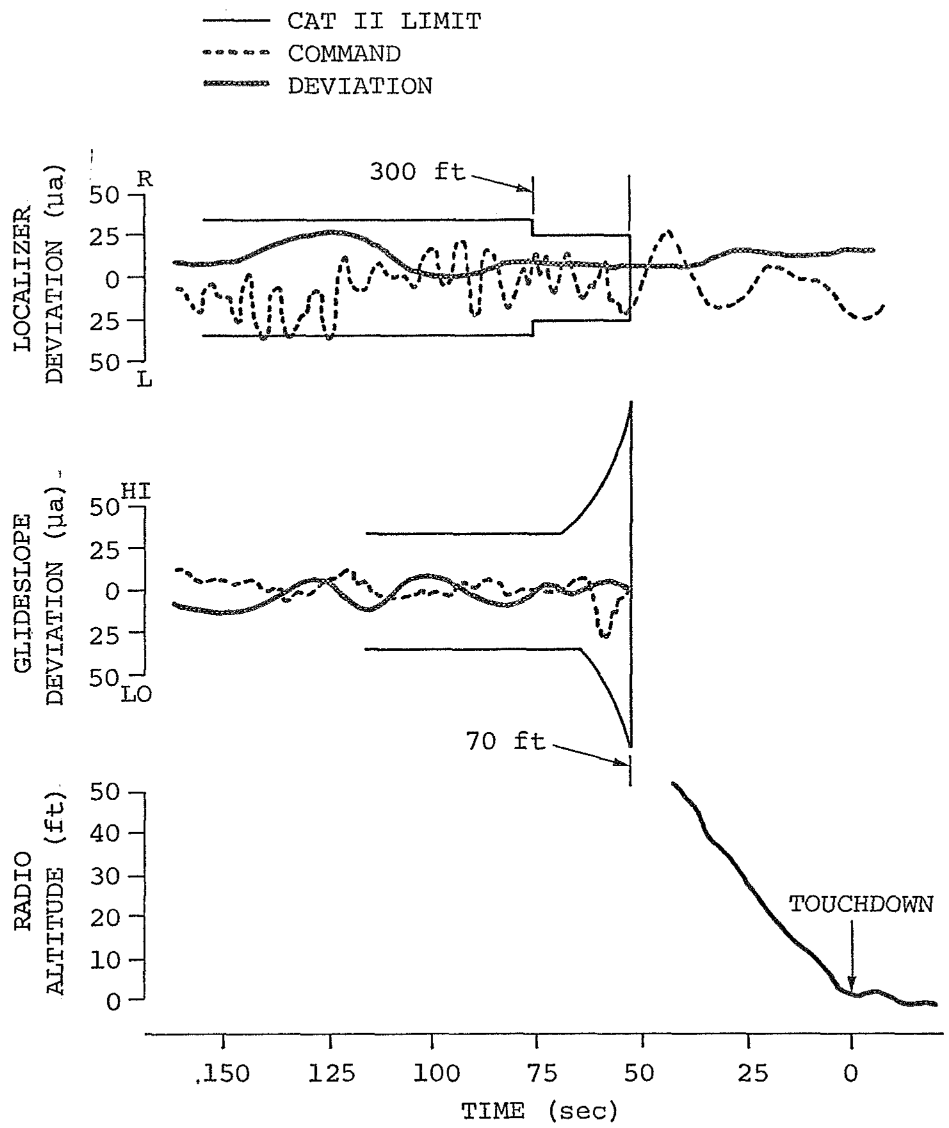
While the evidence from these and similar evaluations of the head-up display is not fully conclusive, it does lend very strong support to the case for the HUD in low-visibility operations. The flight test and simulation experience amassed to date indicates that the putative advantages of the HUD can be realized and that the concept is fundamentally sound and practical. However, the evidence also indicates that there are controversial areas such as symbology and usage doctrine which require further study before the HUD can become operationally acceptable.

The advantages offered by the head-up display in Category I/II operations may be summarized as follows. The HUD provides a natural and easy-to-use method of making the transition from instrument to visual reference. It does so because it enables the pilot to be head-up at or prior to the decision height and still retain the necessary ILS guidance information within his visual field. The ability to display other instrumental informa-


OAKLAND AIRPORT (May 31, 1967)

(Adapted from Stout & Naish, Ref. 29)

Figure 28



(Adapted from Stout, Ref. 30)

Figure 29

tion along with localizer and glide slope indices is an added advantage because it provides an independent indication of approach and landing parameters by which the pilot can corroborate his judgment of the progress of the operation. Finally, the ability to display flare, decrab, and rollout guidance allows the pilot to use the same display all the way through to completion of the landing. This last advantage gains importance in light of the shortcomings of the present, purely visual means of guidance in the last steps leading to touchdown.

These advantages result in a number of practical benefits for the pilot. First, by serving as a glide slope extension, the HUD aids in vertical control in low visibility, which is probably the most serious problem posed by Category I/II operations. By providing fixed and readily discernible reference points, the HUD also helps minimize the problems produced by wind shear and turbulence. The deterioration in quality and usability of information from standard panel instruments below 200 feet is compensated by the HUD, which helps bridge the gap through improving visual reference at these low altitudes and through providing more sensitive indices for vertical control. Panel instruments because of their location and highly compressed scale factors are not suitable in the last 15-20 seconds of the approach and landing sequence. Category II is a transitory condition, where RVR is seldom stable. The HUD helps cope with sudden and unexpected reductions in the range of visibility by providing a continuity of visual and instrumental reference. Finally, the HUD helps the pilot throughout the approach and landing in his role as manager and monitor. At the decision height, when as aircraft commander he must make a critical go/no-go decision, the HUD gives him two independent sources of information, visual and instrumental, both visible simultaneously and in the location which experience and prudence tells him he should be looking.

The final, and perhaps most significant, benefit to the pilot offered by the HUD is described by Stout and Naish (Ref. 31)

> "The HUD buys the pilot time. Time is the most precious commodity on board the aircraft, especially during the last 200 or 300 feet before touchdown. A few seconds saved at points scattered along the approach course is all that is needed to appreciably lower the pilot's workload. Lowering the workload automatically decreases the anxiety buildup. A low anxiety level insures a greater degree of pilot confidence both in his own ability and in that of the total system."

These advantages are not limited to commercial transport operations. As Baxter (Ref. 32) pointed out over seven years ago in an FAA sponsored study of the use of the HUD in general aviation:

> "It seems desirable to provide all the basic flight information needed for instrument flight in a single clear and concise presentation, so that it can be easily and rapidly assimilated and the response required of the pilot will be self-evident. If this flight information can be presented in a form somewhat similar to the natural visual information in the outside world, the consequent transfer of training between VFR and IFR flight should be a great advantage to the general aircraft operator...
>
> "The Projected Symbolic Display has been chosen for evaluation by FAA as a civil transport aircraft display, mainly on the basis of its high information content and compatibility with the outside world. Clearly, some degree of similarity is desirable between the instrumentation used in civil transport aircraft and that used in general aircraft, since many civil pilots fly aircraft in both of these categories. It therefore seems logical to develop and evaluate a simplified version of the Projected Symbolic

> Display for general aircraft. Another point in favor of this display for general aircraft is that it offers the prospect of substantial simplification without a critical loss of information content."

These advantages have been recognized by pilots for some time. Behan and Siciliani (Ref. 33) conducted a survey of pilot preferences and acceptance factors relating to displays for landing in reduced weather minima. The results indicated that the pilots sampled preferred a display which:

a) Is presented in the forward external field of view.

b) Contains information about the position of the aircraft with respect to the glide slope.

c) Presents a picture of the landing situation.

d) Includes airspeed information.

The general pilot endorsement of the head-up display is also reflected in the official positions taken by airline pilot organizations. The ALPA All-Weather Flying Committee has issued several statements urging the use of the HUD in both VFR and Category I/II IFR. IFALPA supports the principle of the HUD as a basic aid in transition from instrument to visual reference in low-visibility approaches. Other uses for the HUD recommended by IFALPA are on the approach to non-instrumented runways, in other low visibility flight situations (e.g., takeoff and initial climb), during turbulence upsets, and in reestablishing manual control from automatic control in exacting flight regimes. The British Air Line Pilots Association (BALPA) has also issued an official position paper (Ref. 34), portions of which are quoted below.

> "In operations to Category II limits, at decision height the pilot must transfer from instruments and revert to visual cues. The provision of a head-up display in Category II operations will enable the captain to monitor the approach from the display, and maintain accurate pitch control to 50-ft. using a Category II ILS installation...

> "BALPA believes that head-up displays can provide valuable assistance to the pilot in effecting a safe transition from instrument flight to visual flight in Category II and Category III conditions...
>
> "The decision as to whether the visual references are adequate for a landing to be made in Category II minima can only be made by the aircraft commander. This means that he must be "head-up" for at least several seconds before reaching minimum decision altitude...
>
> "Some aircraft operators' all weather operations programmes have acknowledged the existance of these problems but have tended to attempt to carry out these new demanding tasks by reliance on traditional equipment and procedures. This is to be deprecated, and a system which permits the captain to both look out and to receive information on the achieved accuracy of the approach would be welcomed by BALPA. A head-up display is such a system...
>
> "In the approach case, a HUD would permit the captain to simultaneously receive and correlate both "internal" and "external" information...
>
> "In the missed approach case, the captain can receive, via HUD read-outs, the aircraft altitude, attitude, speed and other valuable information relative to the missed approach. With this information there will be less requirement for the captain to immediately return to "head-down" in order to perform or monitor the performance of the missed approach...
>
> "When Category III operations are undertaken with full automatic landing equipment, a HUD can provide "roll out" information compatible with the information used by pilots during visual operations...
>
> "For all these reasons BALPA strongly recommends an airline evaluation of HUD before Category II operations are authorized for two pilot crew aircraft.

IFR CATEGORY III APPROACH AND LANDING

As a concept, Category III envisages operations to and along the runway surface in severely restricted visibility. The ultimate goal of Category III is true "blind"landing, i.e., operations without external visual reference. Current thinking calls for this goal to be approached in steps, in which the permissible RVR for landing is reduced progressively from 700 feet, to 150 feet, and finally to). In all cases, however, the decision height is 0, which means that the pilot is committed to a landing no matter what visibility may exist on or in the vicinity of the runway.

Although the feasibility of blind landing and takeoff was first demonstrated on September 4, 1929 by James Doolittle at Mitchel Field, Long Island, the intervening 40 years has not brought the operational realization much closer. Full Category III operations remain more of a tantalizing goal than a practical reality. Criteria for Category IIIA operations have been issued by the ICAO, FAA, and equivalent national regulatory agencies in England and in France. Foreign carriers such as BEA and Air France have gained Category IIIA certification within their own countries and expect to maintain regular operations in visibility down to 700 feet RVR. Some U.S. airlines hope for Category IIIA authorization by 1971.

There are, however, grave misgivings about the wisdom of descending into Category III with the present equipment. The accuracies required for safe Category III operations are much tighter than the established tolerances of the present ILS and automatic flight control systems. Some observers even feel that the Category III certification requirements for ground and airborne equipment are not sufficiently defined to serve as valid criteria for assessment of system capability. An exposition of the technical and operational problems, such as that offered by Litchford (Refs. 35, 36, 37) leads to the inescapable conclusion that

Category III differs from Category I/II not just in degree but in kind, which poses a major challenge.

The work of the Radio Technical Commission for Aeronautics, Special Committee 117, is one indication of the industry's concern with the integrity and accuracy of electronic guidance systems for Category III. (Ref. 38). The extensive effort, especially by the British, to develop improved duplex and triplex autopilots is an indication of another Category III problem area. Finally, there is the industry feeling that, even if suitable electronic guidance and autopilot systems can be developed, this would still not be enough for safe Category III operation. The contention is that there must be some other system to replace the pilot's lost visual reference in Category III and to act as an independent verification of autopilot and ILS performance. This is the so-called Independent Landing Monitor (ILM) which derives its information from a non-ILS source but which is compatible with both the ILS and the pilot's basic visual framework. The nature of the ILM has not yet been determined. Some suggested methods of implementation are high resolution airborne radar, microwave transponder beacons, IR and UV sensors, lasers, and other electro-optical means. (Ref. 39)

However, from the active discussions and work now going on (and the attendant controversies), the outlines of a Category III system have begun to emerge. Category III requires an improved electronic guidance system, most probably a microwave ILS. Most, if not all, of the approach and landing will be flown under automatic control. This calls for highly reliable and accurate autopilot and autothrottle system, better probably than those which now exist. To replace visual reference some sort of ILM will be needed. The role of the pilot in all this is still subject to debate. One school, notably represented by the British, holds that the pilot's role should be that of a monitor and a manager. He should not exercise manual take-over or back-up functions. An opposing opinion is current in this country and in France. The principle of automatic control of approach and landing is accepted, but not the interpretation of the pilot's role. This viewpoint maintains that the pilot, in addition to acting as a monitor and manager, should also exercise manual control functions either in the event of automatic system failure or during the final portions of the landing.

The role of the head-up display in Category III is by no means certain. Opinions of the potential value of the HUD tend to divide along the same lines as in the automatic vs. manual control debate. St. John (Ref. 40) sums up what is largely the British view as follows:

> "The pilot should positively be discouraged here from making decisions based on external visual cues, in view of the likelihood of their being misleading. The reliability of the automatic landing system whould be such that its integrity is impared rather than enhanced by such action. Any monitoring must be made on instrumental information, and the most reliable form of such information, is likely to be head-down. There would therefore appear to be no case for fitting a HUD for Cat III operations. Two possible exceptions, however, present themselves:
>
> (a) Due to partial failure to the redundant autopilot en route, an aircraft with a notional Cat III capability might only be able to land in Cat II conditions, in which case the Cat II case, discussed below, applies.
>
> (b) In Cat IIIB conditions, it is believed that rollout guidance should be provided instrumentally rather than visually. The pilot will be loath to keep his eyes inside the cockpit during this phase, and the combination of visual cues and instrumental information from HUD might provide additional safety."

The counterargument rests on three premises -- the unusability of instrument guidance along below 200 feet, the need for the pilot to remain in the control loop in some capacity, and the psychological dependence of the pilot on external vision. The guidance furnished by electronic means cannot be accepted for descents to very low altitudes without some sort of independent verification. In Category I/II this is accomplished best by visual reference with the aid of the HUD. In Category III the ILM would provide this corroboration, and the HUD is the natural and logical place to present this information for two reasons. First, it would be consistent with landings in VFR and Categories I/II, which constitute more than 99% of the cases and represent the dominant pattern of experience. Second, if there is visual guidance to be extracted from the real-world scene (no matter how meager), the pilot will want to make use of it, and this requires that he and the display be head-up. Since the ILM would by only a redundant source of reference for the pilot and would not furnish guidance signals to the autopilot, this information would be the prime reference for manual take-over by the pilot. The pilot would want this information in the location where experience impels him to look and where he can also take advantage of any external cues which might help supplement the ILM.

Neither the arguments for nor against the HUD in Category III are completely convincing. Probably the strongest point for the HUD is that it would provide a source of information which is consistent with the VFR and Category I/II experience. Having the display superimposed on the external field of view would permit the pilot to practice with the Category III system and gain confidence in it in better visibility conditions where he could establish the correlation of ILS and ILM information with the observable runway. The most effective rebuttal of this line of reasoning is the point raised by St. John. The pilot must be discouraged from placing reliance on external visual cues in very low RVR's because of their deceptiveness and unreliability. If he were head-down, there would be less danger that he would abandon the superior ILS or ILM guidance in favor of external visual reference.

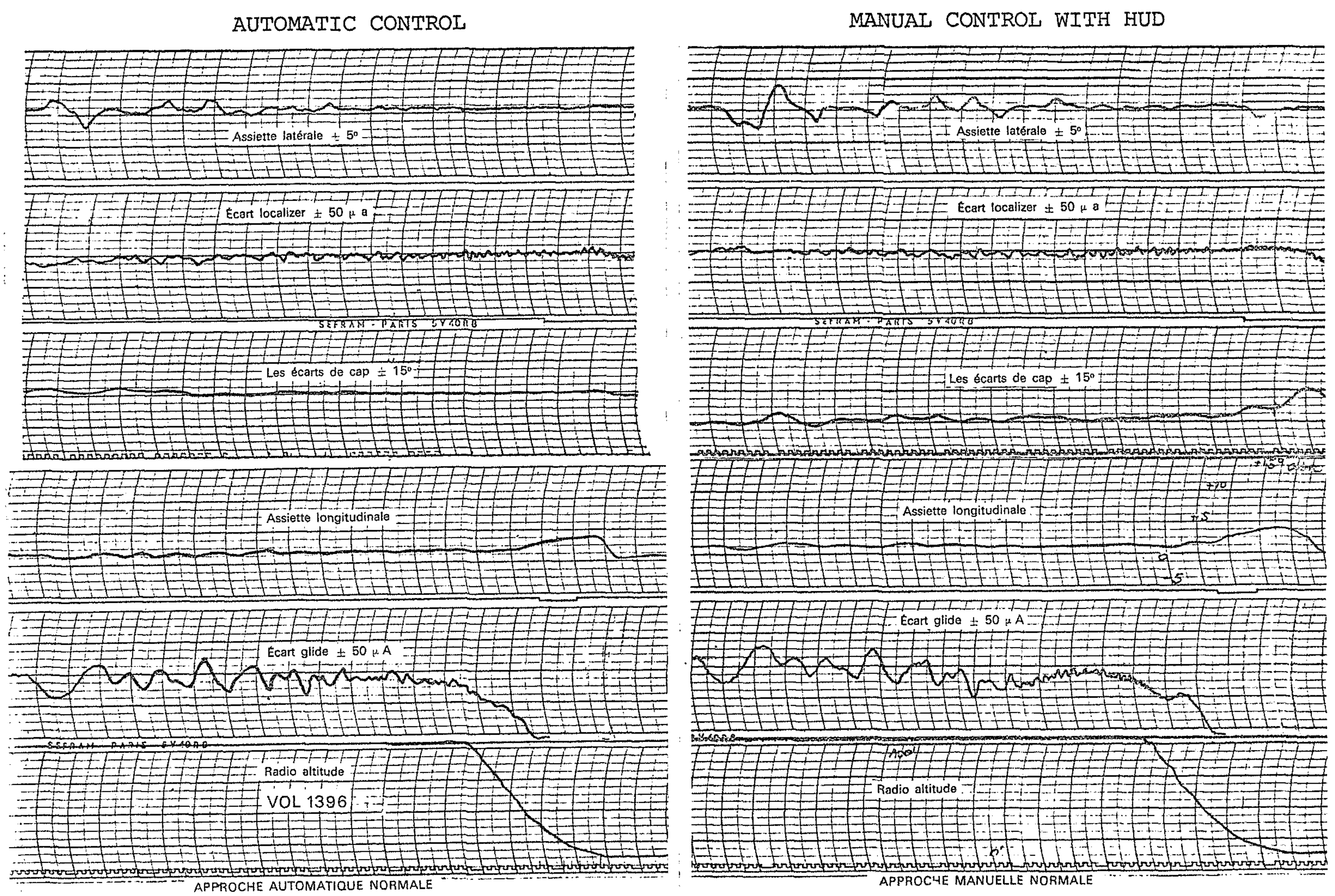
The use of the HUD in Category III thus remains an arguable matter. The concept of such a display, quite apart from the advisability of employing it, can be presented however. Since Category III does not require the pilot to see to land, the HUD must serve as a full substitute for the visual world. This implies the use of an ILM, which is an independent source of information to replace the visual cues normally used to verify the correctness of electronic guidance in approach and landing. The HUD must also present ILS information since this will be the primary guidance system for automatic or manual control. The display for Category III must be compatible in format and method of use with the HUD for Category I/II and VFR, and it must be usable in such conditions to allow the pilot to gain the necessary experience. In short, the HUD must be a complete guidance and reference system.

This is a set of requirements almost impossible to meet. The problem is not so much one of display technology as it is of how to find the sensors and information processors needed to make the required inputs to the display. The nature and quality of the ILM is the key to successful use of the HUD in Category III, and this is not a display problem *per se*. It is also apparent that the particular display solution adopted for Category III operations will depend heavily on whether or not the pilot is in the control loop and in what capacity. This is not a display problem, but a problem of doctrine. Present head-up display technology is probably adequate to incorporate any of the proposed choices of ILM sensors and any of the decisions on operational philosophy. The question is not whether the information can be presented head-up but what information is desired.

Only a limited amount of flight testing has been performed for a Category III head-up display system. The tests of the McDonnell-Douglas display described by Stout and Naish in the preceeding section were actually designed to show the feasibility of the HUD in Category III. The results showed that the HUD can meet Category III requirements, providing one is willing to accept ILS guidance without some independent confirmation of its accuracy. As noted above, the prevailing view is that ILS alone does not provide adequate assurance of safety. This is not a criticism of the HUD but of its source of information.

Similar flight tests have been conducted by the French Centre d'Essasi de Vol at Bretigny. The display used was the Thomson-CSF L191, which is similar to the L193 shown earlier in Figure . The results of these tests and of later trials of the L193 have not yet been officially released by the French Government. However, Lami (Ref. 41) describes the results of one of these test flights. The graphs shown in Figure 30 represent approaches recorded at Bretigny for two runs on the same day, one using manual control with the aid of an L191 HUD. Lami points out that the errors using the HUD are of the same magnitude as ILS noise and therefore represent not pilot error but defects in the guidance source. He also notes that the glide slope deviations using the HUD are small and that they can be superimposed almost perfectly on the automatic approach trace.

The results, as indicated by this sample are admittedly


AUTOMATIC CONTROL

MANUAL CONTROL WITH HUD

From top to bottom the graphs show roll, localizer error, heading error, pitch, glide slope error, and radar altitude.

(Based on data taken at the Centre d'Essais de Vol, Bretigny, France, and reported by Lami, Ref. 41)

Figure 30

impressive. However, like the test described by Stout and Naish, the Bretigny trials required the pilot to place his full confidence in the ILS and the HUD. At the risk of overinsistence, this is a solution which is probably not acceptable in routine civil aviation operations. An independent landing monitor must be included before most will condone the use of the HUD in Category III.

OTHER FLIGHT PHASES

The approach and landing applications of the head-up display represent its most important uses and are the prime justification for its adoption in civil aviation. Approach and landing, however, are not the only phases of flight in which guidance and control problems exist, and the head-up display offers promise in these other areas, too. The use of the HUD in takeoff, rollout and taxi, and in missed approach could provide several significant advantages over that which now exists in the way of ground aids, aircraft equipment, and procedures. However, all these benefits (either singly or in combination)probably do not constitute a sufficient reason for incorporation of the HUD as standard equipment in civil aircraft. The basic case to be made for the HUD is as an approach and landing aid, and it is upon this use that its future rests. Still, the potential value of the HUD in other flight phases is a strong ancillary argument.

TAKEOFF

As discussed in Chapter III, takeoff presents two major problems regardless of the conditions of visibility. First, there are the conflicting demands made on the pilot's attention. He must look out of the cockpit for guidance during the takeoff roll, but he must also monitor airspeed which is presently available only from a panel instrument. Second, there is the problem of the loss of external attitude reference at rotation, which means that the pilot must convert and adjust to panel instruments at the critical moment of becoming airborne. In effect, this is the problem of instrument landing in reverse.

The head-up display offers a neat solution to these problems. Because airspeed information can easily be presented on the HUD, the pilot could have this essential information in view while guiding the aircraft down the runway by visual reference. Because the display of attitude is a basic feature of the HUD, the pilot would have a ready indication of pitch information during rotation and lift-off. Other items of information which would be of value are heading for holding the proper climbout corridor and airspeed (or angle of attack) indices for execution of noise abatement procedures.

As an airspeed indicator the HUD offers two distinct advantages over present instruments. The range of critical speed values (V V_R, V_2, etc.) is represented by only a small portion of the dial on a standard airspeed indicator. Often the difference between V_1 and V_2 + 10 knots is only a few needle widths. On a head-up display this range can be expanded to almost any scale length which seems desirable. The second advantage of the HUD over the present panel instrument is that critical speed values can be shown on the display either by some settable reference marks or "bugs" or by some pre-computed means.

In reduced visibility the HUD provides an added advantage since it could display guidance information for holding alignment with the runway centerline. The lateral guidance information could be derived either within the aircraft from a compass setting of runway heading or externally from more sophisticated sources such as a far-end localizer or a buried-cable guidance system.

In Category IIB perhaps, and in Category III certainly, the available guidance from a view of the runway will not be adequate. The head-up display represents a natural and logical location for presentation of lateral guidance information, either as a supplement or replacement of natural visual cues.

The takeoff is exclusively a manually controlled maneuver at present. Arguments have been advanced for either an automatic takeoff or for a directed takeoff. No attempt will be made here to present a case for either. However, if one or the other should be deemed advisable, the head-up display could well be used as the source of information for monitoring an automatic operation or performing a directed maneuver.

Finally, the value of the head-up display as an attitude control instrument should not be overlooked. The scale factors of 1:10 to 1:17 which exist in present panel instruments are not suitable for precise control of a pitch attitude. The head-up display with a scale factor of 1:1 would undoubtedly promote improved rotation and climbout attitude control, even if there were no improvement in present attitude sensing systems. In the case of the SST and the jumbo jet where the climb angle must be held within tight tolerances to assume proper obstacle clearance without getting into an unstable climb attitude, the expanded pitch scale presentation of the HUD seems to offer distinct advantages.

ROLLOUT AND TAXI

In Category III the guidance problem does not cease when the aircraft touches down on the runway. The pilot will also need information to control the rollout direction until he stops (or to monitor the rollout if the operation is automatic). Since the visual segment will be extremely foreshortened in Category IIIA and IIIB and non-existent in Category IIIC, the pilot will also need some indication of runway remaining. Both are problems of information sensing, not necessarily of information display, and both have been somewhat neglected in the study of techniques for Category IIII operations.

Several solutions to the rollout problem have been proposed, and in nearly all of them the head-up display has an important role to play. St. John (Ref. 42) has been quoted earlier as representing the prevailing British opinion in the use of the HUD in Category III. While he believes that there is little case to be made for the HUD in Category III insofar as landing is concerned, St. John does prefer the HUD as the means of presenting rollout guidance.

A similar view is propounded by Warren (Ref. 43), who is also British and the Manager of the Airborne Display Division of Elliott Flight Automation Limited. Warren suggests a HUD which presents directional guidance derived from magnetic heading or from a far-end localizer. In addition he advocates display or runway remaining information on the HUD, which can be obtained simply (but somewhat unreliably) from rotation of the wheels in comparison with a preset value for runway length. Runway remaining information can be had better but more expensively from a sensitive DME at the far end of the runway or from a sensor system in the runway with an aircraft pickup. Again, this emphasizes the point that deriving the information, not displaying it, is the major problem to be overcome.

Coldwell (Ref. 44) has reported studies carried out by BLEU. Landings were made in actual and simulated Category III conditions, using manual control of rollout direction based on various methods of guidance. Some of the significant findings were as follows:

> "As the Runway Visual Range drops below 250 yards the visual guidance provided by runway markings by day and centerline lighting by night become insufficient for the pilot to perform safe visual roll-out. Thus, for some time, BLEU have been working on systems for blind guidance...
>
> "Many such roll-outs have been performed successfully in Varsity and Comet aircraft...A Category II ILS localizer has been found to provide a satisfactory lateral guidance signal along the runway. Combined with heading information from the compass it has provided the control signal displayed on a director instrument...
>
> "Touchdown velocity was about 95 knots, and the distance used to reach a standstill ranged from 3,200 to 7,000 feet; considerably more than is used in a visual roll-out. This was due probably to the emphasis placed on azimuth guidance and the lack of ground speed and distance information...
>
> "Earlier work in a Varsity fitted with a director display collimated and projected on to the pilot's windscreen showed promise in operations at London airport in RVR's down to 10 yards, the pilots being happier that the outside world clues (sic) would not be missed...
>
> "...We feel that these trials have shown that as operations move into visibilities in which visual control of roll-out is impossible, manual director guidance using ILS localizer will provide a safe and economic means of control in azimuth. The pilot can perform satisfactorily when this steering information is provided head-down, but prefers it to be presented head-up, particularly on a collimated display."

Experimental work in the U.S. has followed along the same lines as in England, although it was started somewhat later. The basic problems are known, and their elements have been defined, but there is little agreement either here or abroad on what constitutes a satisfactory solution. Litchford (Ref. 45), in an analytic study performed recently for NASA, has summarized the guidance problems in Category III operations, which include not only rollout after touchdown but taxiing as well. The taxi problem in very low visibilities was taken up in Chapter III. It is recalled here simply to indicate that, if a suitable guidance system can be developed, the HUD offers an available and attractive way of providing this information to the pilot.

MISSED APPROACH

Missed approach is an often neglected and much underrated application of the head-up display. The pilot's decision to make a go-around at the minimum descent altitude in Category I or II is not a choice of the lesser of two evils. The missed approach maneuver is every bit as demanding as landing, and the lack of a suitable display weighs just as heavily on the pilot whether he elects to continue the approach or abort it.

The elements of the low-visibility go-around problem and the complicating factors were examined in Chapter III under the headings of missed approach and procedures. With present instrument and procedures the pilot's task is the inverse of the process which he must accomplish in transitioning from instrument to visual reference at the decision height. That is, the pilot must go back from outside cues to the instrument panel to obtain guidance for the missed approach. The problem is complicated by the fact that the process is accomplished at an even lower altitude than the head-down to head-up transition and by the fact the go-around calls for an abrupt change in attitude and power. It is not just a question of continuing on down the approach path and making adjustments (as is the case in landing) but of converting to a completely different path and flight regime.

The general feeling among those familiar with the missed approach problem is that, because of the inherent delays in visual accommodation and the psychological process of reorientation to instrument reference, it is not a safe or sensible proposition to expect the pilot to transfer his attention from the outside world back inside the aircraft to execute a go-around. Moreover, the nature of the maneuver is such that simple instrument reference and "feel" are not adequate guidance. If the go-around is to be executed manually, some form of director guidance is highly advisable, if not absolutely necessary.

The solution employed by some British and French airlines circumvents the problem to some extent by having the head-down man (the First Officer) execute the go-around with flight director guidance, on order from the captain or by pre-arrangement. This requires a very high level of co-pilot training and close crew coordination. It would probably not be acceptable for U.S. carriers without a major change in operating philosophy and training programs.

The head-up display offers a solution which is more attractive than procedural changes. Since it allows the pilot to be head-up and still retain instrument guidance, the HUD is an ideal place to present go-around guidance. This may seem to be a circular justification (a little like justifying the purchase of a saddle by saying it would be nice to have if one had a horse), but not really. While it is true that the main purpose of the HUD is to provide guidance and assistance in making the transition at the decision height and in completing the landing, it is not the HUD which dictates that the pilot must be head-up at this point. It is the basic see-to-land concept of Category I/II which makes it necessary for the pilot to be looking out of the cockpit. Since the missed approach is a critical maneuver both in time and error tolerances, it is highly desirable that there be no break in the continuity of the pilot's reference and no impediment to rapid and correct execution of go-around guidance on a head-up display.

Flight and simulation studies conducted in England (See Refs. 46 and 47, for example) and in the U.S. (Ref. 48, for example) show that superior missed approach performance can be achieved using a HUD with flight director information. Part of the willingness of pilots to descend to lower altitudes with an HUD than with panel instruments is the feeling that they will be able to execute a safe missed approach if necessary. Some of this is due to the knowledge that director information will be available, but most of it comes from the awareness that there will be no need to transfer back to the instrument panel to get the guidance.

Apart from the obvious information needed to control the flight path of the aircraft, the missed approach application of the HUD imposes the following additional requirements.

a) The go-around guidance must be available on demand at any point in the approach. This could be accomplished by a switch in a convenient location, preferably on the control yoke.

b) The missed approach, being an instrument maneuver, will be conducted without corroborative visual cues. It is essential, therefore, that the system be monitored and that the HUD be flagged in the event of flight director failure.

c) If the flight director does fail, there must still be sufficient attitude, speed, and flight path information on the HUD to perform a safe (if less than optimum) missed approach.

The pilot's case for the use of the HUD in missed approach was eloquently put in the lengthy passage from Beck quoted at the end of Chapter III. It is interesting to note that Beck, as well as others who have studied the problem, do not consider the missed approach application of the HUD to be separate from the approach and landing application. Rather, the use of the HUD in the go-around is simply an extension to cover the everpresent contingency that the landing cannot be completed successfully. Its value in the missed approach is almost identical to its value in approach and landing. In both cases the HUD provides an efficient blending of visual and instrument guidance in a location where regulations, experience, and common sense require that the pilot's vision be directed.

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CHAPTER VII

TECHNICAL AND PRACTICAL CONCERNS

Up to this point the head-up display has been presented in a positive light, which some might find too optimistic. On the evidence adduced thus far it might well be asked why, in view of the manifold advantages offered by the HUD, has it not long since been put to use in civil aviation. To correct this possible imbalance of judgment, it is necessary to point out that there are valid reasons for showing caution about adopting the head-up display. In the enthusiasm which many have for the head-up display, its shortcomings are sometimes overlooked. The reason for not devoting attention to them up to now in this report is that most of the problems with the HUD are of a technical and practical nature. No serious theoretical arguments against the HUD have been advanced in the literature which has been reviewed. The objections, and there are several, all deal with implementation and not with the validity of the concept itself.

The purpose of this chapter is to outline the problems which remain to be solved before the HUD can find full acceptance in civil aviation. These problems may be divided into five types:

- Display Technology
- Technology of Associated Equipment
- Human Factors
- Doctrinal
- Commercial

Some of these problems have been touched upon already in various contexts throughout the report. They are recapitulated here along with the others so as to give a full picture of the technical and practical difficulties for which solutions must be found.

DISPLAY TECHNOLOGY

Despite years of intensive research, there still remain certain engineering problems in connection with the head-up display. Some of these are basic to the method of image generation and projection, and as such they probably never will be solved, only alleviated. Other problems exist simply because of the limitations in the present state of HUD technology. In time and with suitable effort these problems will be eliminated, or ways will be developed to circumvent them. The following is a brief discussion of the major technological problems to be overcome in implementing the head-up display concept. Of these, field of view and HUD optics are of the first type, i.e., inherent in the head-up display technique itself. Brightness, color, reliability and image generation are difficulties which arise from limitations of current technology.

FIELD OF VIEW

Field of view refers to the angular dimensions of the total image presented by the head-up display. There are actually several ways of describing field of view, and at the outset it is necessary to distinguish among them. For the purpose of optical analysis, it is convenient to treat the observer as though he had a single eye. The area of the image as seen by this "cyclops" is known as the <u>monocular field of view</u>. The factors which determine the size of the monocular field of view are the diameter of the aperature in the optical system and the distance from the observer's eye to the plane of the aperature. In fact, the observer has and uses two eyes in viewing the HUD image. The area which he can see with one eye or the other or both is called the <u>binocular field of view</u>. In addition to the two factors which determine the monocular field, the size of the binocular field of view is also a function of interpupillary distance (which for most people is about 2.5 inches). Thus, for an optical aperature of 6-inch diameter viewed at a distance of 25 inches, the monocular field of view is a circular area about 14° in diameter. Under the same conditions the binocular field of view is an area measuring 14° vertically and about 20° horizontally. (See Figure 31.) It should be noted that normal-sighted individuals do not perceive the left and right eye fields as separate, but as a single fused field.

The foregoing has assumed that the observer's head is fixed in relation to the optical system. To account for freedom of head movement it is necessary to introduce two qualifying terms, instantaneous and total. Here the familiar knothole analogy may be helpful. The aperature in an optical system functions somewhat like a knothole in a fence. For any given eye position the knothole allows only a certain portion of the scene beyond the fence to be viewed. By moving the eye about, however, additional areas may be seen. The instantaneous field of view (either monocular or binocular) refers to that area bounded by the optical aperature (the knothole) for any given, fixed eye position. The total field of view is the overall image area which can be seen by viewing from different eye positions. The total field of view, unlike the instantaneous, is not a function of the aperature size but of the restrictions on head movement at the viewing end of the system and of the total area represented by the image generating element at the other. The large circular area in Figure represents the total field of view, the smaller circle and the ovoid represent the instantaneous monocular and binocular field, respectively.

Obtaining a suitably large field of view is usually considered one of the major problems of head-up displays. The

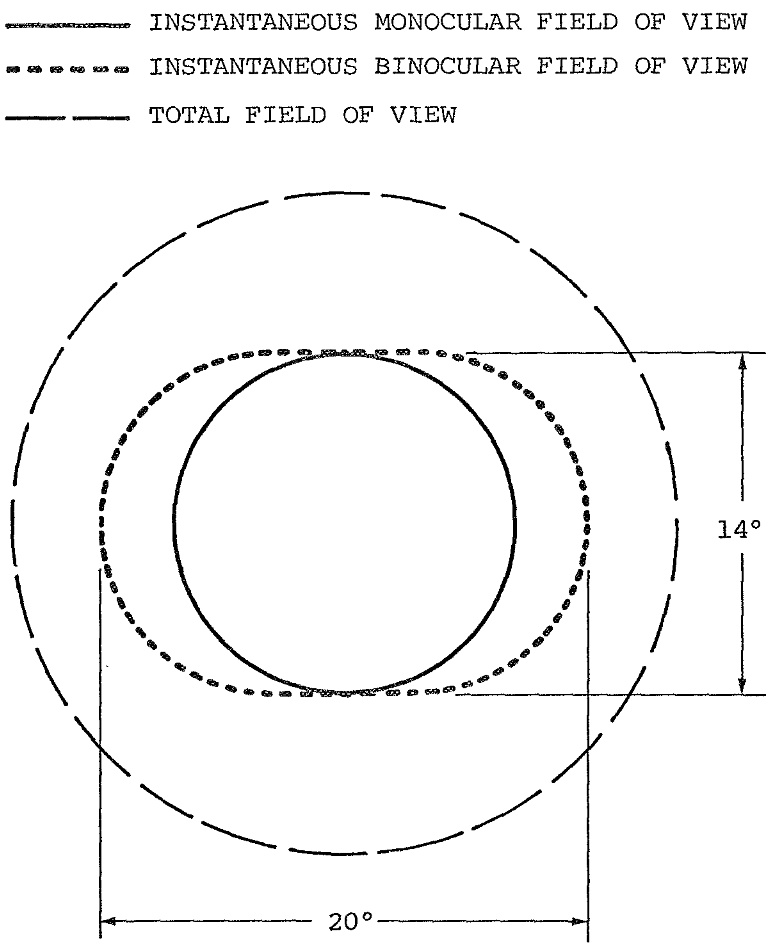

INSTANTANEOUS MONOCULAR FIELD OF VIEW
INSTANTANEOUS BINOCULAR FIELD OF VIEW
TOTAL FIELD OF VIEW
14°
20°

Figure 31

problem is particularly severe in tactical military aircraft where the field of view must cover a very wide dynamic range of elevation and azimuth lead angles for sighting air-to-air and air-to-ground weapons. This is complicated by the need to position the display (and hence the optical aperature) far enough from the pilot to allow for clearance of an ejection seat envelope. Neither of these constraints operate to the same degree in civil aviation systems. The field of view required in civil aviation generally covers a much narrower range of flight situations, and the display can be situated at closer viewing distances -- the only limitations being that the HUD must not interfere with the pilot's freedom of head movement or expose him to the risk of injury.

Estimates vary as to the required size of the HUD field of view for civil aircraft. A field of view between 25° and 30° is generally considered adequate. Obviously, the pilot would like to have as wide a field of view as possible, but this is not the same thing as what he needs or can use effectively. The required field of view can be derived analytically by considering the possible range of symbol movement for a particular flight phase, landing usually being taken as the most demanding case.

In the vertical dimension the lower limit of the field of view for landing is the cockpit cutoff angle, which is about 15° below a horizontal reference line through the pilot's eye position. The upper limit can be obtained by considering the maximum upward movement of a critical display element such as the flight director symbol or the flight path marker. In this case it would be safer to take into account not just the landing but the possibility of a missed approach. The maximum commanded climb angle in a go-around probably would not exceed 10° above the horizontal. This would yield a vertical field of view requirement of 10° upward plus 15° downward or 25° total. This should not necessarily be considered a requirement for instantaneous field of view, since some head motion would be permissible between landing and missed approach. However, for the moment, 25° shall be assumed to be the required instantaneous field of view.

The horizontal field of view requirement can be determined from the maximum range of movement necessary for a symbol such as the flight path marker which must overlay the projected impact point even at severe crab angles. An approach at 120 knots in a 15-knot crosswing would necessitate a crab angle of about 7°. Additional allowances must be made so that the flight path marker does not conflict with other display elements, such as air speed or altitude scales, which may be positioned on the edge of the field of view. Assuming 5°-7° to be adequate for such purposes, this yields a horizontal field of view requirement of 7° plus 5° (or 7°) in either direction or 25° to 30° in all.

An analysis of this sort gives results which are in almost perfect agreement with the generally accepted figure of 25°-30°, which has been arrived at by other, possibly different, lines of analysis and by empirical means.

The final question is can the required field of view be obtained with present optical systems? The answer is clearly yes. Optical systems with aperatures of 6 inches are easily manufacturable, and those of 9 inches have been proposed by some display manufacturers. The weight of a 9-inch system is rather high (50 lbs. or so), but this factor does not seem to be as important in civil transports as in military aircraft. With a 6-inch system and at a viewing distance of 18 inches, the instantaneous binocular field of view is 20° vertically and about 27° horizontally, which is slightly less than the requirements postulated above. If some head motion is permitted (± 1 inch vertically and ± 1.5 inches horizontally), a 6-inch system can fulfill the requirements. With a 9-inch system, the instantaneous binocular field at a viewing distance of 18 inches is 28° vertically and 35° horizontally -- well in excess of the requirements. If the viewing distance is increased to 25 inches, 9-inch optics gives a 20° x 25° instantaneous field of view, which would also be adequate if head motion were allowed.

Thus, it would appear that a number of design tradeoffs are possible and that field of view requirements for civil aircraft can be satisfactorily met, although perhaps at some penalty in bulk and weight. If the requirements are shown to be greater than those set out above or if an 18-inch viewing distance is unacceptably close, then present HUD optical systems will be marginal or even inadequate for some aircraft or flight phases. On the basis of currently available evidence, civil aviation field of view requirements do not seem to pose a significant technological problem. Final judgment must be reserved, however, until full empirical verification has been obtained.

Optical Systems

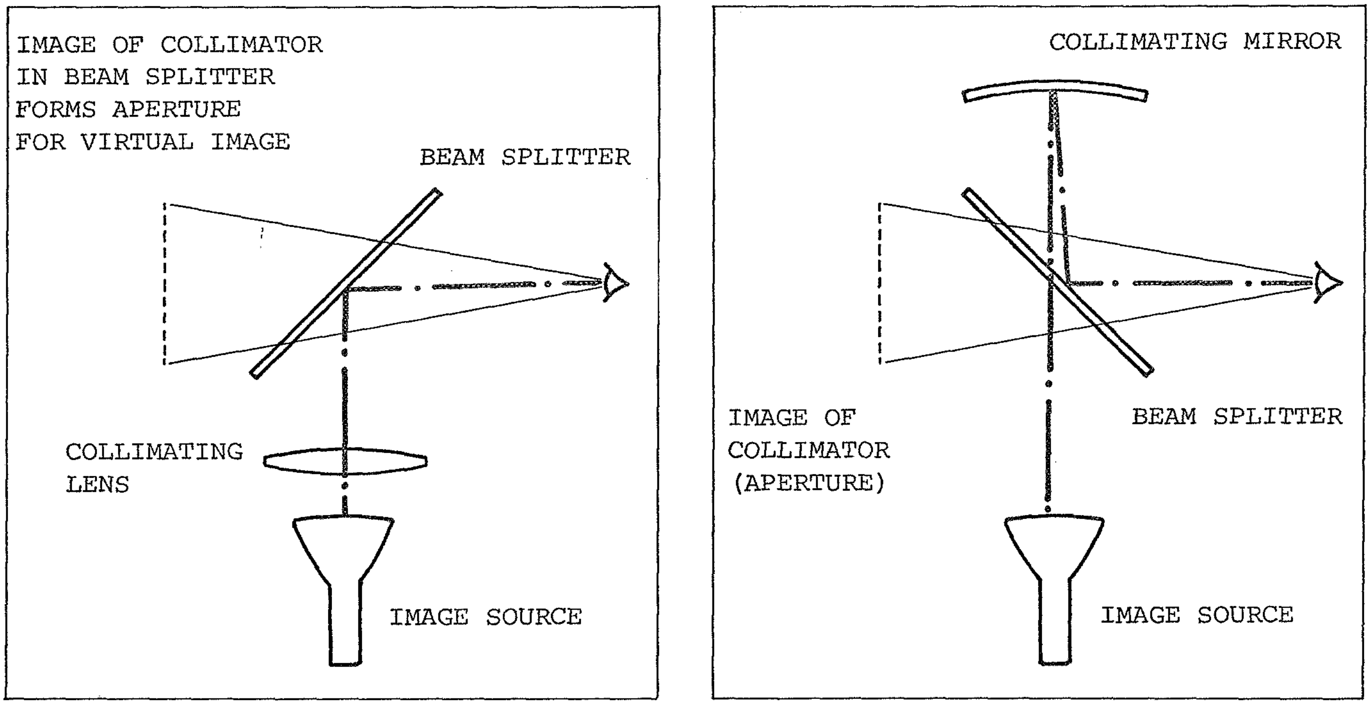
The key to the head-up display is the optical system itself, which is used to collimate and project the image. A number of techniques may be used for this purpose. Basically they are of two classes: refractive optics and reflective optics.

In a refractive system the image is generated, passed (refracted) through a collimating lens, and then presented on a combining glass (beam splitter) which allows both the image and the real world scene to be viewed simultaneously and in registry with each other. This method is so commonly used in head-up displays that it has come to be known as conventional optics. The elements of a reflective system are much the same, except that the collimating element is a mirror (a reflector) rather than a lens. Thus, the basic difference between the two systems is that with a reflective system the image source is situated on the same side of the collimator as the viewer, while in a refractive system the image source is on the opposite side of the collimator. (Ref. 1) Schematic diagrams of the two types of optical systems are presented in Figure 32. For the sake of simplicity, direct optical paths are shown. In practice, mirrors may be introduced in either type of system to fold the beam and create a more compact package.

The basic problem in a reflective system is getting the image source out of the way of the viewer's line of sight. This can be done in three ways:

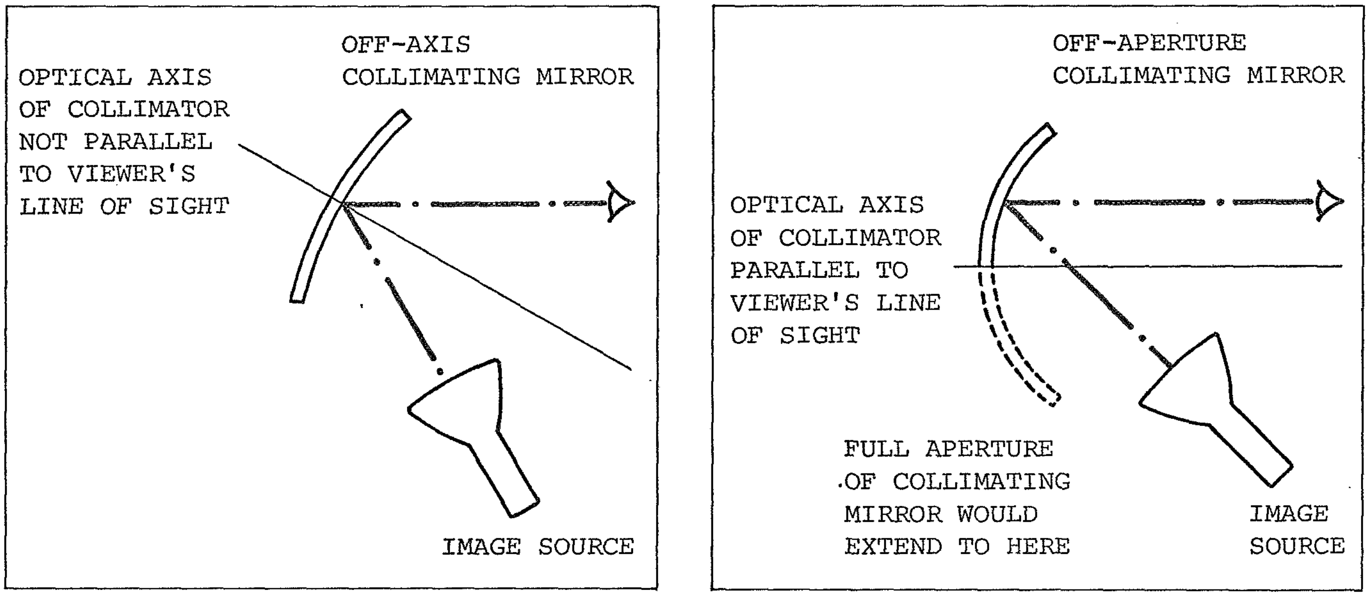
1. The on-axis reflector with a double-pass beam splitter (Figure 32B).
2. The off-axis system in which the collimating mirror also serves as a beam splitter or combiner (Figure 32C).
3. The off-aperature system in which the collimator still serves as the image combiner but in which the optical axis is parallel to the viewer's line of sight (Figure 32D).

Experimentation with reflective systems has been active for military head-up displays, largely because they offer large fields of view without the attendant weight problems of refractive optics. However, there are some disadvantageous consequences. Reflective systems tend to be more vulnerable to high



A. REFRACTIVE OPTICAL SYSTEM

B. ON-AXIS REFLECTIVE SYSTEM WITH DOUBLE-PASS BEAM SPLITTER



C. OFF-AXIS REFLECTIVE SYSTEM

D. OFF-APERTURE REFLECTIVE SYSTEM

(Adapted from Hamilton & Benson, Ref. 1)

Figure 32

ambient brightness, which produces spurious reflections or loss of display contrast. Reflective systems also suffer from problems of inaccuracy (distortion) as the image of interest moves further off the potical axis. Table IX shows a comparison of the advantages and disadvantages of refractive and reflective systems.

All the optical systems described so far are the so-called "gunsight" type, which are located at a relatively remote position from the viewer. An alternative is the "binocular" device. This usually is a refractive device (although reflective optics are possible) which is placed directly in front of the viewer's eyes and which he uses like a pair of binoculars. The Bendix head-up display developed in the U.S. is the prime example of this kind of device. Experimental binocular displays have also been developed by CSF in France and by RAE Farnborough in England. It should be noted that the term "binocular" does not imply any sort of stereopsis or three-dimensional image; it refers only to the fact that two optical systems (one for each eye) are combined in a unit which resembles a pair of binoculars.

Binocular devices offer the advantages of compactness and light weight and of very large fields of view. As a result of the short viewing distance (1-w inches) fields of view on the order of 30° vertically and 60° horizontally are attainable. The prime disadvantages of this device are its proximity to the pilot's eyes and the fact that he must move his head away from the display unit if he wishes to view the instrument panel. As a result the binocular device has not met with pilot acceptance and it has not enjoyed commercial success.

Optical systems of any type are never perfect. They all suffer from various inherent optical aberrations and distortions.

TABLE IX

TYPE	ADVANTAGES	DISADVANTAGES
REFRACTIVE	Proven optical design On-axis viewing Good accuracy (±1 mr at center, ±5 mr at periphery, typical) Relatively invulnerable to ambient light High optical efficiency Fewer optical surfaces to be kept clean	Large lens needed for large field of view Weight (55 lbs, typical) Difficult to achieve balance of focal length (f), size of image source, and accuracy (short f, small image source, but high accuracy)
REFLECTIVE ON-AXIS	On-axis viewing Short focal length with good accuracy Large field of view possible Low weight (30 lbs, typical)	Complex optical element (spheric section) Difficult to locate image source or collimater properly Vulnerable to ambient light Optically inefficient double-pass beam splitter More optical surfaces to be kept clean Collimating mirror obstructs pilot's vision Possible formation of dangerous solar images in cockpit
REFLECTIVE OFF-AXIS	Low weight (30 lbs, typical) Large field of view possible High optical efficiency	Very complex optical design (2 aspheric or conic sections) Long fical length required for collimation, hence large image source Pilot's body and hand movements can interrupt light beam
REFLECTIVE OFF-APERTURE	Simple optical design	Excessive optical error (astigmatism intolerable as little as 1° off-axis) More optical surface to be kept clean Location of image source a problem

While the science of correcting these inaccuracies has progressed to very sophisticated levels, errors can never be eliminated altogether. Several of these errors are important in the head-up display application. First, there is the possibility that the external scene as viewed through the optical system will be shifted out of its true location. This might be termed "static" error, and it is at its everest in off-axis and off-aperature reflective systems. Next, there is the possibility that a given symbol, as it moves off the optical axis, will no longer register with its real world counterpart. For a director symbol this type of error (which can be called "dynamic") is not of much consequence. The greatest error will occur when the director symbol is far off the null position, which is usually at or near display center and the optical axis. As the flight path error nears zero and tighter aircraft control tolerances are implied, the accuracy of symbol positioning due to optics also improves. The same is not true for a symbol such as the flight path marker (velocity vector or impact point symbol), which must be in accurate registry with the real world situation no matter where it lies in relation to the optical axis. An error of 10-15 milliradians (1/2°-1°) in position at the flight path marker (which might well occur for large crab angles or extreme angles of attack) is of serious proportion.

Two other types of error which may be important are collimination error and binocular disparity. The former could be a problem if the collimation were defective to the point that the image did not appear at optical infinity but at some finite and relatively close distance to the observer in relation to the external scene. Binocular disparity might manifest itself as a variety of visual problems (eye strain, double images, blurring of images, etc.) if there were a pronounced difference in the HUD image as seen by each eye.

Even though the whole question of optical errors is of great concern in relation to the HUD, very little investigation has been performed in this area. Flight trials conducted so far have not indicated that optical system errors constitute any impediment to successful use of the HUD. But the possibilities clearly exist. A major study of these potential sources of difficulty have been carried out by Theodore Gold and his associates at Sperry Gyroscope Company, Great Neck, N.Y., under the auspices of JANAIR. Some of the topics being considered are:

1. Absolute tolerance for binocular disparity.
2. Effects of symbols with image disparities overlaying the real world.
3. Visual discomfort as a function of binocular image disparity resulting from changes in head position and viewing angles.
4. Magnitude of permissible image disparity at the boundaries of the monocular and binocular fields of view.
5. The effects of retinal rivalry (eye dominance)
6. Tolerance for collimation error.
7. Minimum exit pupil size.
8. The effects of changing lateral head position.

The results of this study are in the process of publication at the present time. It should shed light on the nature of the visual problems attendant to the use of the HUD and on the ability of optical system technology to measure up to the user's visual requirements. Until such evidence is in hand, the adequacy of head-up display optical systems must remain an open question.

Display Brightness

Display brightness (or more properly, luminance) is of concern in two circumstances. First, the head-up display must be of sufficient luminance in high ambient light conditions to assure adequate contrast retention for good display visibility. Second, display luminance must be controllable through a range of ambient illumination from full sunlight to extreme darkness. This is necessary to assure a proper balance between the luminous intensity of the symbols and the illumination of the external scene. Of the two, achieving adequately high brightness has been the traditionally greater concern with head-up displays.

The generally accepted figure for the maximum background brightness against which the HUD must be usable is 10,000 foot-lamberts. Against this background a symbol luminance of approximately 1000-1500 foot will yield an effective symbol luminance of 11,000-11,500 ft.l. This is equivalent to a contrast ratio of 10-15%, the higher value being desirable to assure adequate detection and legibility of small symbols such as scale markings or alphanumerics (Ref. 2). Other sources (Refs. 3,4) suggest that a 15% contrast may not be sufficient and that 20-30% may be required for "comfortable" viewing. The distinction between adequate and comfortable is that adequate is an objective measure based on laboratory experimentation to determine the minimum usable display luminance, whereas comfortable is a subjective measure arrived at by allowing the observer to adjust the display intensity to a level which suits him. Because the relation between adequate (minimum usable) and comfortable has not been established and because there is some indecision as to which is the proper value to use, display luminance requirements cannot be stated with certainty. The issue is further confused by the questionability of 10,000 foot-lamberts as a standard high brightness background.

Some sources (e.g., Ref. 3) believe that 10,000 is too high and that 8,000 foot-lamberts is more representative of actual flight conditions. A 20% contrast under this condition would mean a display luminance of only 1600 foot-lamberts instead of the 2000 foot-lamberts which would be required against a 10,000 foot-lambert background.

Depending upon the characteristics of the optical system and the luminous intensity of the image source, present CRT head-up displays can deliver a luminance of between 1000 and 1500 foot-lamberts*. This is equivalent to the minimum usable intensity if 10,000 foot-lambers is used as a standard background brightness, but falls short of comfortable viewing requirements (2000-3000 foot lamberts). If an 8000-foot-lambert background is used as a standard, a display luminance of 1500 foot-lamberts will yield a contrast of 19%, which is virtually the same as the lower limit of comfortable viewing.

In an effort to achieve improved display contrast, some manufacturers make use of dichroic or trichroic color separation filters on the combiner. These filters provide an apparent increase in display brightness, by improving the color contrast between the display and the external background. The technique involves filtering out of the externally received light, a part of that which is of the same color as the dominant wave length of the image source. With such filters, display luminances of as low as 850 foot-lamberts provide comfortable viewing. (Ref. 5) Some find color separation filters

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* As will be seen in a later section on illuminated reticle systems, luminances of up to 3000 foot-lamberts can be achieved.

objectionable because they tint the external scene. On the other hand, the filters also tend to reduce the effects of haze, thereby rendering both the real world as well as the display more easily visible. This is a rather heated issue because it turns around subjective judgments. There has been no experimental work to establish the effects of dichroic and trichroic filters on the pilot's ability to discriminate and use external visual cues.

In the high brightness situation it may be concluded that head-up displays (at least the CRT type) offer sufficient luminance for adequate viewing. They may or may not meet the requirements for comfortable viewing, depending upon how one chooses to define a comfortable level and what standard background luminance is used. Further research on this topic is needed, as well as experimentation to establish the advantages and disadvantages of color separation filters.

The other concern with respect to HUD luminance, that of maintaining a proper brightness balance between the display and the external scene, is much less of a problem. A match between display brightness and the outside background is achieved by providing a control which allows the pilot to vary display luminance continuously from maximum down to effectively zero. Most head-up displays also incorporate an automatic brightness control feature which compensates for changes in background luminance such as might be encountered flying in and out of clouds or turning into or away from the sun. Both the manual and automatic brightness control features seem to work satisfactorily, and no complaints have been voiced.

In military HUDs there is some concern about attaining a display of sufficiently low luminance to maintain the pilot's dark adaptation and not to interfere with his ability to detect targets against very dark backgrounds (e.g., the open sea or the jungle at night). There is no true counterpart task in civil aviation. Even the blackest of "black-hole" airports have much more illumination than the dark backgrounds involved in military ASW or night combat operations. In fact, there is such a high level of illumination in the vicinity of most airports that it is doubtful the civil aviation pilot is ever truly dark-adapted. Misgivings about the utility of the HUD in civil aviation, both in terms of achieving a proper luminance balance with the external scene and of attaining a suitably low luminance level, appear unfounded.

Color

Color is generally recognized as an excellent coding dimension for visual displays. It commands attention and greatly facilitates search and recognition tasks. It has also been demonstrated that in some circumstances the use of color enhances performance in interpretation, reading, tracking, and higher cognitive tasks. Color lends itself readily to combinations with other types of codes, especially geometric shape and alphanumeric symbols. (Ref. 6) Lee (Ref. 7), in commenting on the case for color, adds the following example of how it may aid performance.

> "Color coding increases the ability of observers to rapidly separate task-relevant information out of a particular set of information (coded in one color) from a much larger set (coded in other colors).
>
> "Color coding techniques appear to be relatively task specific. Thus, in decoding tasks, color does not show any consistent superiority over other coding methods. However, color appears to be quite useful in search tasks -- serving as a cue to an operator such that non-relevant information is "filtered" out with only minimal attention."

The number of absolutely identifiable colors has been established experimentally to be ten or, if white is included, eleven. Among these are violet (4300), blue (4760), blue-green (4940), green (5150), yellow-green (5820), amber (6100), and red (6420) -- all figures in Angstrom units. The number of usable colors for coding purposes is generally agreed to be four or five (Ref. 8).

The use of color in head-up displays is regarded by most as an attractive prospect, not only because it would enhance the interpretability of displays with a large number of symbols but also because it would make the display more readable against real world backgrounds. Neither of these contentions has been conclusively established by experimentation, but they seem plausible.

Present CRT head-up displays do not have multi-color capability. Although there have been some experimental two-color CRT devices developed, they have not been put to actual flight test. The Tomson-CSF HUD, which was illustrated in Figure (Chapter VI), is a four-color display, but it uses illuminated reticles as the image source instead of a CRT. Reaction to this display has been mixed, but generally favorable. Those who like the display consider the use of color effective and a highly desirable feature. Those who are critical of the display find the use of color excessive, i.e., four colors are too many, and two would be preferable. It is interesting to note that the designers of the display do not regard multi-color capability as one of the justifications for using reticles in place of a CRT. They favor reticles for other reasons (which will be discussed later); the ability to provide a four-color display is considered by Thomson-CSF to be an ancillary advantage. (Ref. 4)

The Thomson-CSF experience with color is an instructive example of the considerations which must be taken into account. The basic color scheme of the CSF display is:

- Amber - air data
- Green - ground data
- Red - position error (e.g., ILS error)
- White - director information

Experiments with the scheme, which was selected more or less arbitrarily, revealed the need for modifications and limitations in the use of these colors. At night the color of director information was changed to blue, since white tended to appear too bright in relation to the other colors at low display luminance levels. Blue was not used by day because it cannot be discriminated against sky backgrounds. Yellow was originally tried as one of the display colors, but rejected because it could not be discriminated from white and amber. The heading scale (ground data) was originally green. Flight trials showed that for some unexplained reason this symbol was hard to see until its color was changed to amber. Flight and simulation trials also showed that form and sharpness of the image were more important than color as factors in differentiating display symbols from external light sources. For example, one symbol tended to be lost in the approach lights at night and experimentation with different colors produced no satisfactory solution. The problem was remedied when the shape of the symbol was modified. As a final point, Thomson-CSF flight trials demonstrated that the use of four colors has no effect on dark adaptation so long as the luminance level is kept sufficiently low. (Refs. 4, 9, 10)

In summary, it may be said that multi-color head-up displays offer several theoretical advantages. The incomplete evidence from the one multi-color display which has been tested indicates that these advantages are realizable in practice. The use of color seems to be desirable and, in the case of illuminated reticle displays, a practical benefit. Present CRT technology does not yet permit multi-color presentations, but this capability is being actively sought.

Image Generation

Many of the technical questions relating to the head-up display come to focus in the issue of how to generate the image. At present there are two proven methods: the cathode ray tube and illuminated, servo-driven reticles. Reticles are the older technique, having been used originally in the collimated gunsights of the World War II period. The CRT supplanted reticles during the 1950s. In fact, it was the development of CRTs suitable for airborne use which gave the original impetus to the concept of the HUD as a flight data display. In recent years, largely through the effort of Thomson-CSF, the illuminated reticle has re-emerged as a feasible method for generating complex displays for flight guidance and control.

The current debate over which of the two techniques is superior tends to divide along national lines. The British, who pioneered in the development of the CRT head-up display, firmly maintain it is the method of choice. The French are equally vigorous in their preference for illuminated reticles. Although the debate is conducted on technical grounds, one strongly suspects that political and proprietary concerns also have much to do with the controversy. U.S. views on the subject are mixed. Nearly all of the head-up displays developed and offered for sale in this country are CRT devices. Hence, there is a natural tendency of U.S. display manufacturers to defend their choice. Through the Thomson-CSF American licensee

(Librascope of General Precision Systems, Inc.) the L-191 and L-193 illuminated reticle HUDS have been given wide publicity. Evaluations of L-191 and L-193 have been conducted, or are not in progress, at FAA NAFEC, NASA Ames Research Center, NASA Flight Research Center, and USAF Flight Dynamics Laboratory. Pilot reaction to both the CRT and the illuminated reticle HUD has been favorable, and no clear preference is indicated.

The purpose here is not to enter into the debate. The following discussion of the two image-generation techniques is intended only to bring out the points of comparison and to indicate some of the more important technical questions which relate to the use of the HUD in civil aviation.

Brightness

Present CRT displays are limited to a maximum brightness of about 1500 foot-lamberts. Taking into account the efficiency of the optical system and the reflectivity of the combining glass, this translates into a luminance at the CRT face of about 10,000 foot lamberts. CRTs capable of 20,000 foot-lamberts output (i.e., 3000 foot-lambers display brightness) are under development, but these require extremely high voltages (10-15 kilovolts). Illuminated reticles can deliver display luminances of 3500 foot-lamberts for more. This is accomplished with incandescent light sources which can be made to have almost any luminance desired and which have power requirements in the 100-volt range.

Line Width

Symbol line widths on the order of 1-2 millirandians are attainable with CRT displays. The line width varies as a function of display luminance, the greater the brightness, the greater the energy illuminating the phosphor, and the broader the line width.

Reticle displays have line widths between 0.35 and 0.6 milliradians, and the line width does not broaden significantly as display intensity increases. While the reticle lines are finer, either method of generation gives line widths small enough not to obscure real world objects.

Image Quality

CRT symbols are subject to disturbance due to electromagnetic noise within the system. This results in irregularities in shape and a tendency for symbols to jitter. Reticle images are geometrically precise and exhibit much greater stability of position. Aesthetically, reticle images are superior, but there is no experimental evidence to indicate that the better quality image leads to improvements in performance or display usability.

Color

As indicated earlier, airborne CRTs do not now have multicolor capability. It can be achieved but formidable technological difficulties are encountered in balancing illumination levels of different phosphors and in collimating three or four images of different colors. With reticles color can be had for the asking.

Flexibility

With the CRT almost any sort of symbols and patterns of movement can be achieved. Also, the content and format can be varied at will. Reticle systems do not offer such flexibility. A display consisting of more than four symbols moving interdependently is difficult to accomplish by electro-mechanical means. Moreover, reticle displays offer much less freedom in the number and variety of symbols which can be combined in a given mode and in the number of possible different modes. The use of reticles also imposes certain constraints on how symbols can be manipulated. For example, a runway symbol which grows in size to indicate range to go is farily easy to create on a CRT but very difficult with reticles. Likewise, symbol deformation or shape variation (such as a skewing of a runway trapezoid to indicate lateral position error and cross track) is much easier on a CRT than on a reticle display.

The issue of CRTs vs reticles is far from settled, however, even though the latter seems to have some significant engineering advantages. In part, the decision turns around how much importance is attached to particular factors. CRTs have the advantage in flexibility and in wide acceptance by display engineers. Reticle systems are superior in terms of brightness, image quality, color capability, and perhaps reliability. Either technique seems viable in civil aviation applications, but only further test and evaluation can decide which is to be preferred.

In passing, it should be noted that the other image-generation techniques are being investigated. A holographic, three-dimensional HUD is in the process of development under JANAIR auspices. (Ref. 11) The USAF Flight Dynamics Laboratory is experimenting with a laster technique. (Ref. 12) Various peripheral vision displays (PVD) have been developed. (Refs. 13, 14, 15) These are interesting because they do not present an image in the pilots central cone of vision, but in his parafoveal field which is much more sensitive to rate of motion and which is not used now as fully as it might be to supplement the cues gained through central vision. A detailed consideration of these other methods of image-generation is not within the scope of this report. They are mentioned to indicate that other alternatives exist.

TECHNOLOGY OF ASSOCIATED EQUIPMENT

The ultimate success or failure of the head-up display in civil aviation is only partially dependent upon the resolution of technical problems of the display equipment itself. The practicality of the concept and the success of the implementation will also be determined by technical developments in other portions of the airborne and ground systems. The HUD is not a self-sufficient device. It is only a link between man and the machine, and its utility is interrelated with the nature and quality of the information which it transmits.

The following is a catalog of some of the major technological concerns for equipment associated with, but not part of, the head-up display. These problems are not treated in depth because they are not central to the purposes of this study and because they are questions of engineering not human factors. However, mention of them must be made to help complete the assessment of the practical concerns which surround the head-up display. None of these are properly criticisms or shortcomings of the head-up display itself. Instead they are indications of the general improvements needed in aircraft guidance systems, regardless of the method of display.

Attitude Reference Systems

The HUD is basically an attitude display, and the quality of the attitude information is of major importance. There is a general feeling that present gyroscopically stabilized attitude reference systems are not accurate and responsive enough for providing precise and sensitive indications on the HUD. To realize its full potential, the head-up display will probably require attitude information of the quality offered by inertial or doppler systems.

Flight Path Sensing

As indicated in Chapter VI, sensing and display of flight path angle is of major importance in the HUD concept. Present methods of measuring angle of attack and drift angle by means of vanes or probes do not produce sufficiently accurate readings, and they suffer from inherent lags and insensitivities. There is also some question whether the angular sensing of the data is the correct approach. Some feel that instead of deriving flight path information from rotational data, a better approach would be to sense translations of the aircraft by means of accelerometers associated with an inertial reference system and integrate these data over time to obtain indications of the horizontal and vertical flight path. Alternative flight path sensing methods under consideration are doppler systems and improved pressure differential sensors.

Other Instrumental Information

Altitude measurement poses a basic dilemma. Barometric systems provide altitude information in its most useful form, height above a known reference (either QFE QNH). However, the inaccuracy of pressure-derived altitude is such that it cannot safely be used at the low decision heights called for in Category II, and it is wholly unworkable in Category III. Radar altitude is very accurate, but since it is a measurement of the height above the terrain under the aircraft, it is misleading for approaches over gullies, small hills, or urban areas. Some method must be found to measure height above runway elevation accurately or, alternatively, to provide a smooth and level plane in the approach path so that radar altitude can be used.

The measurement of airspeed and vertical velocity also leaves something to be desired. Cane (Ref. 16) points out that trials of a Category III autothrottle system showed that airspeed signals were too noisy and had to be filtered to prevent excessive throttle activity. This resulted in a lag which, in turn, had to be compensated for by inputs from lateral accelerometers and vertical gyro sensors. Vertical velocity, which is also derived from pressure data, is notorious for the lag in readings following abrupt changes in the flight path. Here, too, inertial systems seem to offer a solution.

Flight Directors

Many believe that the success of the HUD as a guidance source for flare in landing and for missed approach turns around the availability of the proper director information. Flight director computers presently available are adequate for these purposes, but there still remains the task of integrating the flight director with the HUD and of establishing the proper dynamic equations and time constants for driving the HUD symbols.

Category III Equipment

As discussed in Chapter VI in connection with the potential use of the HUD in Category III, the key to blind operations is not so much the display as it is the source of the information to be presented. The applicability of the HUD in Category III is intimately bound up with the development of an improved ILS and an independent landing monitor.

HUMAN FACTORS

Human factors concerns play a major part both in establishing the need for the head-up display and in determining its characteristics for particular VFR and IFR applications. The pilot's tasks, needs, capabilities and limitations have been the principal theme of this report. The enormous volume of the research literature dealing with the human factors of the HUD indicates the intensive study which this aspect of the problem has received. Still, there are some uncertain areas. This section is a summary of the major problems on which human factors research must concentrate.

Protection of Visual Capability

The combining glass of the head-up display is a beam splitter which reflects a portion of the display luminance striking the surface, absorbs a small amount, and transmits the remainder. Usually only 15-20% of the display luminance is reflected to the pilot's eye, i.e., the reflectivity/transmissivity ratio of the combiner is about 15:85 or 20:80 (neglecting the absorptive properties of the glass, which are minor). However, the combiner is a two-way device; it acts in the same way on the light received from external sources. 15-20% of the outside light is reflected by the combiner, and the remainder is transmitted to the pilot's eye. It is this aspect of the combiner which is the cause for concern. Wallace (Ref. 21) has stated the problem in this way:

> "Some loss of light occurs through the combining glass of HUDs, varying from 10 to 20%, which could have the effect of making less visible the real world cues the pilot is seeking. Under such conditions, 1200" RVR, for instance, would not be 1200" to a pilot using HUD, but something less.
>
> "The achievement of sufficient contrast between actual visual cues seen through the glass and symbology (bright enough to be read, although attenuated in an optimum fashion) appearing on the glass is a far more serious matter. The question is whether a pilot will see real visual cues through the combining glass as rapidly and as clearly in the presence of Head-Up Display symbology

> as he will if the Head-Up Display glass and symbology were not there... Head-Up Display characters (whether lines or symbols, and even when optimized in intensity against ambient light conditions) might significantly reduce the pilot's ability to see actual visual cues... In addition, there is the possibility of interference between HUD patterns and the bright approach, touchdown zone and centerline lights required for low visibility operations. Such interference may prevent the pilot from making an accurate assessment of the real world -- or the display."

Wallace has, in fact, raised two important questions: Light loss through the combiner and interference of symbols with external light sources.

There can be no doubt that the combiner cuts down the available light from the outside world, and it is a matter of elementary physics to know exactly how much. The real concern is the effect of reduced light transmission on the range at which visual cues can be seen. The theoretical work of Koschmeider and Allard and the authoritative analysis by Middleton (Ref. 22) suggests that a combiner which reduces the light from an external source by as much as 20% will have a very small effect on the range of visibility, which varies roughly as the square root of intensity. Thus, a light loss of 20% would imply a reduction in visual range of only about 4 or 5% (50 to 60 feet in an RVR of 1200 feet). The appropriate formulas from Middleton are:

$$E = Ir^{-2\tau r}$$

or $$E = Ir^{-2}e^{-\sigma\tau}$$

where E = Illuminance
I = Luminous Intensity
r = Spectral Reflectance
τ = Transmissivity
$e = 2.718$
σ = Extinction (Attenuation) Coefficient

While the foregoing is well established theoretically, it should be subjected to experimental verification for the case of the head-up display. The FAA has recently concluded an agreement with the University of California at Berkeley to make such tests with a HUD in the fog chamber. Evidence from these experiments should help clarify the magnitude and importance of the light loss problem.

Wallace's second question, the possible interference of HUD symbols with external lights, also deserves careful attention. Many display experts contend that, so long as a proper balance is maintained between display and external lighting, no degradation of the pilot's ability to see natural visual cues should result. However, as Wallace points out, other experts disagree. The evidence from flight and simulation tests of the HUD suggests that there is no serious disruption of the pilot's visual capability. However, these tests were conducted with this specific problem in mind, and the evidence is largely subjective. It is the author's understanding that the FAA tests at Berkeley, mentioned above, will also include investigation of the existence and effects of the possible interference between the two visual fields. Until the results of these experiments are available, judgment on the subject should be reserved.

Perceptual Switching

One of the chief advantages claimed for the HUD is that it permits placement of display information in the same line of view as the outside world information, thus enabling the pilot to combine the two reference sources. The validity of this assertion is subject to challenge, however, and it has become one of the most important controversies surrounding the head-up display. Unfortunately, much of the discussion is conjectural, and, therefore, a matter of opinion.

The general debate turns around man's ability to perceive and make effective use of information from two super-imposed, but different, fields of view. One contention is that only one field can be attended to at any given time. To make use of the other, the observer must "switch" his attention, hence the term "perceptual switching". A corollary is that the importance attached by the observer to one field may inhibit his ability to switch to the other. As a result certain elements of information in the field of lesser subjective importance may be neglected or not perceived at all. The example frequently cited is the familiar case of the cadet pilot in aerial gunnery who becomes so intent on holding a target in his gunsight and getting a good score that he flies right into the target sleeve. A similar example has been asserted by some pilots who have flown the HUD on an approach. They believe they could become so absorbed in display indices that they would fail to note another aircraft sitting on the end of the runway.

There are two opposing contentions. The first is that, while such switching does occur, it takes place at a very high rate (i.e., several times per second). Thus, the observer is sampling each field so frequently that he has, in effect, a continuous view of each. The further contention is that the process is not entirely one of volition. The observer does it almost subconciously -- at least as far as perception is concerned. How he processes and acts upon the perceived information is more nearly a matter of volition, and it is a function of his mental set and his awareness of the importance of each field.

The other opposing view is that human perception and information processing is not a single-channel process. Man has multi-channel capacity which allows him to attend to two or more information fields simultaneously. The separate information sources are perceived and processed at the same time and the action which results is a product of an integration of the separate sources by a higher cognitive process.

The following, which is a sample of these conflicting views as they relate to the head-up display, will give the flavor of the argument. First, the remarks of those who oppose the HUD.

> "A related problem concerns pilot reaction to two sets of information in his direct field of view, the HUD symbology and external visual cues. It is possible pilots will not see both impulses simultaneously. A study made of pilot eye movement using HUD showed a strong tendency for the pilot to generate a fixation on the first object sighted in the real world to the exclusion of the display and other cues. He must, therefore, mentally switch from instrument to visual flight whereas with head-down, he physically moves his eye to the instrument panel or outside of the cockpit, an action which makes him very aware of the source of his flight information. If it is true a pilot must mentally switch from one cue to the other, one of the claimed advantages of HUD, seeing two kinds of information "at the same time" will not materialize.
>
> "In addition to the above problem is the one of the distraction caused by getting a fleeting glimpse outside visual cues while on instruments to the point safety is compromised. All of which adds up to the fact the use of HUD may not mean a pilot can violate the old axiom of "never fly instruments and visual at the same time." As one man experienced in the use of the optical gun sight stated: "It is very difficult to see something through something." (Ref. 23)

> "The ability of the average pilot, in limiting conditions, to accept visually and mentally both external and displayed information at the same time has not yet been demonstrated. Some pilots have found that the tunneling effect on visual scanning, experienced when stress is

> high, results in "seeing" only that information appearing in the centre of the fixated field of view. Others have found that they "see" either the external field or the collimated commands, with the relative brightness or movement determining which is unsuppressed; the implication is that mental capacity for accepting a number of discrete bits of information reduces rapidly as stress increases. It also seems that the visual effect of streaming approach and runway lights inhibits recognition of the small movements of symbols demanding the flare-out maneuver or displaying vital data.
>
> "In low visibility conditions and particularly in Cat 3 minima, the pilots sight line is necessarily coincident with the bottom of the windshield where visual information will first appear above the vision cut-off. Unless some means of adjusting the register of the symbols is available, it is unlikely that head-up information will be absorbed by the pilot in these conditions; if adjustment is provided, the displacement of symbols from the position occupied in good visibility may be quite confusing." (Ref. 24)

The following are two examples of the counterarguments:

> "It was concluded that use of a common field position permits combination of fields...
>
> "Qualitative conformation of the preceeding... was obtained in flight trials using a reflecting collimator to present an electronically generated display as part of the pilot's forward view... Two cases were examined (a) during visual take-off, when the pilot obtained visual information mainly from the external world, and (b) during an "instrument approach when the display field was of chief importance so that there was a change in the dominant field of information for the two cases. Successful take-offs were reported by 17 subjects, who stated that while information was drawn mainly from the external field they were aware of being able to acquire attitude information from the display in a monitoring role. Successful

"instrument" approaches were made by 13 subjects, using the display for guidance, who stated that they were able to see the ground to an extent governed by visibility.

"These results were useful in providing subjective evidence of combination in superimposed fields under the more exacting conditions of real flight, and they also indicated that the identity of the dominant field is of little importance.

"In order to develop a more rigorous method for assessing the ability to observe concurrently in superimposed fields, the display field (which was of adequate complexity) was presented in the laboratory...against an artificial background simulating the forward view in flight...

"Subjects were guided through the simulated external world by the superimposed display, by presenting turning demands at convenient positions in the simulated landscape. In this way it was possible to control the forward view while subjects used the superimposed field in a precise manner (with mean modulus heading errors less than 1°). It was arranged that after completing ten turns through 90°, each at a rate of 3° per second, the forward view would be that corresponding to the view along a runway during an approach, when a pilot would normally be very concerned about the alignment of his velocity vector with the runway. At this point, and without foreknowledge on the part of the subjects, the display was made to demand a slight deviation (about 3°) of flight path from the runway in order to see whether this divergence would be detected by subjects.

"All thirteen subjects who reached this point, by using the display with requisite accuracy, were observed to fly "visually" along the runway, ignoring the divergent display demand. From this it was clear that subjects observed concurrently and critically in both fields obtaining precise guidance from the superimposed display, while observing the visual background with the same care as in an approach. It was concluded that fields superimposed in a common position may

> be combined to an extent permitting critical examination of complex visual information, a result of some importance in the context of aviation." (Ref. 25)
>
> "The criticism that the head-up display divides, and hence weakens, the pilot's visual capability does not seem justified by experiments at the Centre d'Essais de Vol, Bretigny, with the Thomson-CSF L-193 display.
>
> "There is a school of thought which condemns the suggestion that it is possible to fly head-up on instruments by citing human factors (ergonominique) evidence as to the so-called sequential process of human perception. Since this is not the place to open such a discussion, we will confine ourselves to two remarks:
>
> - The arguments of this school are not, to our knowledge, supported by systematic experimentation.
> - The logic of the argument is superficial, and debatable. It would seem there is a confusion between perception and reaction. Even though motor reflexes are indeed a sequential process, the phenomenon of perception (as far as we know) is perfectly multi-channel."
>
> "Thus, we conclude that there is no reason for collimation of instrumental information in the external visual field to perturb the pilot's visual perceptive capacity, even though a certain amount of habituation is necessary -- just as learning to ride a bicycle requires an adaptation of the sense of equilibrium." (Ref. 26)*

The problem of perceptual switching must remain an open question until some more conclusive and reliable evidence is

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* The original is in French. The translation is by the author of this report.

presented. The question is basic to the practicality of the head-up display concept, and it may well be that perceptual switching is the issue upon which the HUD will stand or fall.

As a concluding remark, the author would like to suggest that the nature of the human perception and processing task may not be as important as the relation (the degree of similarity) between the display and external fields in determing the pilot's capacity to use the HUD. That is, whether the process is parallel or sequential may not be of practical significance. The real concern may be the isomorphism of the display with the real world. If display elements overlay their real world counterparts, if they have some similarity of shape, and if they respond to the same laws of motion, the conflict between aritifical and natural cues should be minimal or nonexistent. If the display design is well thought out in terms of the pilot's visual needs and the structure of the visual world, it may not matter much whether the process of information assimilation is switching, rapid sampling, or simultaneous perception and integration.

Symbology and Format

As indicated by the foregoing comment and by the discussion in Chapter VI of the various roles of the HUD, symbology and display format are important concerns. Present display designs exhibit a great variety of symbol shapes and arrangements -- so much so that it is evident no clear agreement exists on how best to present the information.

Symbology and format are complex subjects, and the available research literature is voluminous. In an earlier study (Ref. 27) the author surveyed much of the research material and presented a synthesis of current thinking. The work will not be recapitulated here since it would require a lengthy discussion and an excursion into somewhat marginal areas of interest. The following, which is an adaptation of the conclusions of a study done in 1953 by Senders and Cohen (Ref. 28), are offered as criteria of display design with respect to symbology and format. In some cases these criteria may be contradictory, but good displays are based on intelligent compromise.

Symbology

- Indications should be easily visualized or verbalized.
- Symbols should be interpretable quickly.
- Symbols provide a reading as accurate as necessary for the task.
- Changing or changed indications should be easy to detect.
- Information should be provided in an immediately useful form.
- Symbols should be free from error-producing features.
- The recognition of errors should be fostered, so they do not persist.
- Indications should be readable over the full range of operating conditions in which the display is to be used.
- Symbols should not be unnecessarily obtrusive.
- Symbols should give current information, i.e., lag should be held to a minimum.
- Clear indication should be given if the display or its information sources are inoperative.

Format

- A given symbol should be easy to find and identify.
- The number of indications should be as small as consistent with efficient operation.
- Symbol placement and movement should not result in interference or overlap.
- Critical indications should be readily discernible.

- Symbol arrangement should facilitate the integrated interpretation of related indices.
- Symbols should be positionally and dynamically correlated with real-world counterparts (where they exist).

DOCTRINAL CONCERNS

Assuming that the head-up display is deemed worthwhile as a concept for civil aviation and assuming further that technical problems are solved to everyone's satisfaction, there would still remain certain questions of operational doctrine and usage. These are matters in which conventional research can contribute very little since they are basically policy decisions which must be made by those responsible for the conduct and regulation of civil aviation operations. It would be presumptuous to suggest here how these decisions should be reached or what course they should take. The only purpose in pointing them out is to show the relationship between the head-up display and the broader concerns of operational philosophy.

Given that the head-up display is an aid to the pilot, the first question to be answered is "An aid to do what?" Should the HUD supply guidance for manual control? Should it provide information to monitor the performance of automatic systems? If it is to do both, how can these purposes by fulfilled in the display design? Ultimately all these questions revert to the more basic question of the intended role of the pilot in future civil aviation operations.

If the pilot is to serve solely as a system manager, exercising command functions but not actively participating as a controller, the head-up display could assist him by providing information on the present and predicted situation of the aircraft.

The managerial function also requires that the pilot have an index of automatic control system performance. That is, the pilot must be able to monitor the output of the automatic control system, but he need not have indications of signal inputs or of the control laws by which it operates. Pursuing this line of reasoning further, failure of the automatic system should not lead to a pilot takeover to complete the flight phase in progress at the time of malfunction. The automatic system should fail safe and fail steady such that the aircraft is brought to a stable and level flight path. Pilot intervention at this point would not be for the purpose of continuing the maneuver but for executing some alternative action. Under such a philosophy the HUD becomes a relatively simple "howgozit" display, with supplemental indications as to how to maintain (not establish) level flight in an emergency.

As an alternative philosophy, it is possible to conceive of the pilot as an everpresent manual controller. Automatic control systems, when used, are only a pilot relief and never substitute for the pilot in the control loop. Under this philosophy, the head-up display must serve additional purposes. Not only must it indicate the present and predicted position of the aircraft, it must also provide information necessary to conduct a given maneuver and to execute appropriate alternatives if the maneuver shows signs of getting out of tolerance. Thus, the HUD becomes not a monitor display but a prime (if not sole) source of guidance.

A third philosophy is a hybrid version of the first two. Prime control may be vested in automatic systems for flight phases requiring very precise control or for situations where it is desirable to relieve the pilot to perform other duties.

In these circumstances the pilot would use the HUD as a monitor display. However, the pilot retains the capacity to take over from the automatic system at any time, either as an option or in an emergency resulting from automatic system malfunction. Thus, the pilot and the automatic system work in parallel, and the pilot provides the back-up to the automatics in case of failure. In terms of display requirements, the philosophy calls for a HUD much like the second. The method of use would differ, however, depending upon which role the pilot exercised -- monitor or manual controller.

As a consequence of adopting any of the above operating philosophies or their variants, certain decisions as to usage doctrine for the HUD would have to follow. First, there might be the decision as to how to use the HUD in VFR where control is normally manual and guidance visual. Should the use of the HUD be mandatory, optional (as with VASI), or should it be used at all? Next, similar decisions would have to be made for the Category I/II case of IFR. Finally, a usage doctrine would have to be established for Category III.

Concommitant with these decisions, some determination would have to be made on who should have a HUD. Should it be the pilot alone since he is the aircraft commander and prime controller? If so, what shall be the co-pilot's role? And more important, if only the pilot has a HUD, how is the co-pilot going to gain the experience in its use necessary to make the eventual transition to pilot? An obvious solution would be to give each man a HUD, but this would double the cost of equipping the aircraft with head-up displays.

A final question is that of regulation. How can the government certificate the HUD for use and verify the pilot's competence with it? In interviews during the course of the study, this question was put to officials of the FAA and of the Air Registry Board and Board of Trade in England. Their answers indicate that it is far from clear how certification procedures should be conducted. Certification of the equipment is a fairly straightforward procedure in both countries. Approval to install and use a HUD (a "No Hazard TSO" in FAA parlance) could probably be obtained upon demonstration of equipment reliability and of the existence of methods to detect and isolate the effects of malfunction. Authorization to use the HUD as a primary or sole guidance source (an Operation Approval TSO) would be much harder to obtain, primarily because neither the FAA nor the Air Registry Board has yet concluded what the appropraite criteria are. Both the FAA and the UK Board of Trade have set down, for advisory purposes, a general framework for approval of reduced visibility systems. (Refs. 17, 18, 19, 20) The rationale and performance criteria of the HUD would certainly have to be consistent with these documents.

Demonstration of pilot proficiency is also an undecided matter at the FAA and the Board of Trade (which has responsibility for aircrew certification in the UK). Tests under hooded conditions, such as now used for establishing instrument pilot qualification,might not be wholly appropriate since the HUD is intended to be employed in conjunction with visual reference not in place of it. The proper test would involve a good quality, low-visibility simulator in the aircraft, but such a device has not yet been developed. Therefore, aircrew certification (like equipment certification) remains an open question as far as regulatory agencies are concerned. Obviously some suitable methods will have to be devised before government sanction of the HUD can be secured.

COMMERCIAL CONCERNS

Ultimately, after technical and doctrinal problems have been resolved, the head-up display will have to meet the test of the marketplace. Someone -- the management of an airline or an individual aircraft operator -- will have to make the decision to purchase the HUD, to incorporate it in his regular operation of the aircraft, and to acquire the necessary training. This is a matter of cost vs. benefit, which is within neither the scope of this study nor the competence of the author to deal with. What follows is only an attempt to relate the question of the applicability of the HUD in civil aviaiton to the context of the general requirements set out at the beginning of the report.

In Chapter II it was suggested that the HUD will have to be judged according to three standards: safety, practicality, and economy. Also offered was the opinion, that, while safety and practicality are largely considerations of benefit and economy a consideration of cost, the three criteria are not mutually exclusive or antagonistic. That is, it would be an oversimplification to regard the matter as safety and practicality vs. economy. It requires no elaboration here to see that safer or more efficient operation contains potential savings in operation costs and that economy implies much more than a favorable balance sheet. Yet, in the long run, it is necessary to ask and answer the question, "Does use of the HUD lead to measurable levels of improvement in operational capability and safety which can be related favorably to the economic factors of using the aircraft?" This is a decision which surpasses the realm of technology and behavioral science and lies in the hands of the owner and the manager.

This is not the first time such a decision has been confronted. The military services have faced it and have reached the conclusion that the HUD is not only worthwhile but highly desirable. Civil aviation has not yet followed the military example, partly because the factors involved in the military decision weigh differently in civil aviation, but only partly. The other major reason for the failure of the HUD to gain acceptance is that civil aviation does not feel a clear and present need for it. In military aviation the HUD represents the only practical way to accomplish visually guided or aided weapon delivery. This constitutes the justification for the HUD, and any other uses such as landing, terrain following, or takeoff are simply fringe benefits to be had at little or no extra expense. Civil aviation has no such immediate need, but it may emerge as low-visibility operations are extended into Category IIB and beyond.

Although details of the cost/benefit equation cannot be written here, it is possible to set down some of the factors which will come into play. Since they constitute two classes which must be balanced against each other, they are phrased as advantages and disadvantages. The list is not exhaustive, nor does the order indicate relative importance. The weighting of these factors and the addition of others are left to more capable hands.

Advantages

1. On the basis of preliminary evidence, the HUD offers significant improvements in manual control performance in both IFR and VFR.

2. The HUD saves time and eases the transition from instrument to visual reference in Category I/II.

3. The HUD facilitates the use of visual reference cues in VFR.

4. The use of a projected, see-through display conforms with the pilot's tendency and need to look out of the aircraft.

5. The HUD alleviates pilot anxiety in IFR by reducing his scan problem and hence his work load.

6. As an integrated display, the HUD further reduces the pilot's work load by requiring fewer transposition steps in assimilating information.

7. In fully automatic approach and landing the HUD provides a natural means for monitoring system performance.

8. The HUD is easy to learn to use, even by novices; training time is minimal.

9. The HUD may extend the capability to use airports which are marginal or inadequate with present ground and aircraft equipment.

10. Pilot acceptance and preference for the HUD is quite strong.

Disadvantages

1. The newness of the HUD has not allowed time to resolve all technological and human factors problems associated with its use.

2. To realize its full potential the HUD depends upon technological advances in associated guidance, information sensing, and attitude reference equipment.

3. The reliability of the HUD is generally lower than conventional electro-mechanical instruments now in use.

4. The HUD requires specialized maintenance equipment, personnel, and procedures.

5. Since the HUD would not replace existing instruments, it represents an add-on cost.

6. Present aircraft cockpits are not designed with the HUD in mind; modification and retrofit may be expensive.

7. Use of the HUD would necessitate modifications in present and well-established procedures and operating doctrine.

8. There are doubts about the pilot's ability to use superimposed instrumental and visual fields safely and efficiently.

9. The new and unconventional nature of the HUD fosters resistance and skepticism, perhaps out of proportion with the actual technical and human factors problems.

10. The HUD has not yet been proven in the test of day-to-cay operations.

With the exception of item 8, the disadvantages listed above apply to the head-up display, not as a concept, but as an operational device. Such difficulties are to be expected in the normal course of developing a new system for the improvement of safety or efficiency in aviation, and they do not constitute a refutation of the principle of the HUD nor a serious bar to its implementation. As a personal opinion, the potential value of the HUD justified the expenditure of effort necessary to solve the remaining technical and practical problems.

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APPENDIX A

ORGANIZATIONS AND FACILITIES VISITED

NASA

Ames Research Center, Moffet Field, California
Electronic Research Center, Cambridge, Massachusetts
Flight Research Center, Edwards, California
Langley Research Center, Hampton, Virginia

MILITARY

USAF, Aeromedical Research Laboratory, Wright-Patterson AFB, Dayton, Ohio
USAF, Aeronautical Systems Division, Wright-Patterson AFP, Dayton, Ohio
USAF, Flight Dynamics Laboratory, Wright-Patterson AFB, Dayton, Ohio
U.S. Army, Electronics Command, Fort Monmouth, New Jersey
U.S. Naval Air Development Center/Johnsville, Warminister, Pa.
U.S. Naval Air Test Center, Patuxent River, Maryland
U.S. Navy, ONR Branch Office, London, England

OTHER U.S. GOVERNMENT

Federal Aviation Administration, Washington, D.C.
FAA, National Aviation Facilities Experimental Center, Atlantic City, New Jersey

FOREIGN GOVERNMENT

Centre d'Essais de Vol, Bretigny, France
RAF, Institute of Aviation Medicine, Farnborough, England
Royal Aircraft Establishment, Bedford, England
Royal Aircraft Establishment, Farnborough, England
U.K. Board of Trade (Directorate of All-Weather Operations), London, England
U.K. Board of Trade (Directorate of Technical R&D), London, England
U.K. Ministry of Technology (Nav 4), London, England

PRIVATE AND INDUSTRIAL

Air Line Pilots Association, Washington, D.C.
British Air Line Pilots Association, London, England
Compagnie Generale de Telegraphie Sans Fil (Thomson CSF), Paris, France

Elliott Automation, Ltd., Rochester, England
International Federation of Air Line Pilots Associations, London, England
Smiths Industries, Ltd., Cheltenham, England
Specto Avionics Ltd. (Smiths), Feltham, England
Sud Aviation (Concorde Program), Paris, France
Syndicat National des Pilotes de Ligne

INDIVIDUALS

In addition to the above official contacts, interviews were conducted with the following individuals. While organizational affiliations are listed to indicate their background and area of interest, this should not be construed as official representation.

Captain Richard H. Beck, Pilot TWA
Former member of the ALPA All Weather Flying Committee
Present IFALPA delegate to the ICAO All Weather Operations Panel

Captain William Brown, Pan Am Flight School

Captain Edward Burke, Pilot Allegheny Airlines
Member (formerly chairman) of the ALPHA All Weather Flying Committee

Mr. Edward S. Calvert, formerly RAE/Farnborough, now retired

Captain J.L. DeCelles, Pilot TWA
Chairman of the ALPA All Weather Flying Committee

Captain R.C. Gerber, Pilot Pan Am
Former Chairman of the ALPA All Weather Flying Committee
Presently member of the IFALPA All Weather Committee and the ICAO All Weather Operations Panel

Captain Rene Lami, Pilot Air France

Dr. Charles F. Lewis, formerly NASA Flight Research Center Edwards

Mr. S. B. Poritzky, Air Transport Association

Captain Donald O. Portch, Pilot Braniff

Captain Harvey M. Thompson, Allegheny Airlines

Mr. John Woods, Sr., National Business Aircraft Association

Prof. Lawrence Young, Massachusetts Institute of Technology

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APPENDIX B

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HEAD-UP DISPLAY

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