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THE LANDING TASK AND PILOT ACCEPTANCE OF DISPLAYS FOR LANDING IN REDUCED WEATHER MINIMUMS

By

R.A. Behan and F.A. Siciliani

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SUMMARY

This report is devoted to the development of display concepts for landing an aircraft in reduced weather minima. The report is divided into six sections. The first, the introduction, explains the other five.

The second section is devoted to a statement of the factors which influence the all-weather landing problem. Factors of weather, aircraft, pilots, cockpit instrumentation, ground facilities, sociopsychological-legal problems, and the man-machine interface are considered.

The third section is an analysis of the VFR landing task. The results of the analysis suggest that the pilot makes three separate distance judgments: when to initiate the final approach; whether the aircraft will make it to the runway; when to initiate the flare maneuver.

It was found helpful to construe the information presented during the VFR landing task as a compensatory display which the pilot used to track a ramp to the runway aiming point.

The fourth section presents the results of a study of pilot acceptance of displays for landing in reduced weather minima. The study included a special consideration of the reliability and validity of pilot preferences. The results indicate that pilots prefer a wind screen display which presents a pictorial representation of the landing situation as well as the relationship of the aircraft to the glide slope and localizer. Pilots prefer a display which presents airspeed information, but not necessarily altitude. Pilots preferences were internally consistent (reliable) and they were valid as compared with human engineering recommendations for displays of altitude, airspeed and sink rate.

The fifth section presents a display for Category II weather landing which results from the analysis of the landing task and the results of the preference study; and presents two display concepts. It is felt that this display would be compatible with Category III requirements.

The final section presents a program of experimentation to refine the display suggested in the fifth section.

INTRODUCTION

This report is devoted to the development of a display for landing an aircraft when the ceiling is 100 feet and the Runway Visual Range is 1300 feet, i.e., Category II weather minima. The report is divided into six sections. The second section is intended to put the effort into perspective as regards all-weather landing. Section three, an analysis of the landing task under VFR conditions, is intended to develop the kinds of information needed to facilitate the decisions which the pilot must make and to elucidate the nature of the VFR landing display. The analysis is then extended to the IFR landing. Section four describes an acceptance study which was conducted with pilots to determine their needs and desires for information presentation in low visibility landings. Section five brings together the information from sections three and four, to develop the information requirements for an adequate display and to develop criteria by which a display could be judged. The sixth and final section suggests a program of experimentation for the evaluation of displays for all-weather landing.

Serendipity Associates wishes to express its appreciation to Mr. Pat Zinnato of Amcan Airparts, 10415 Burbank Boulevard, North Hollywood, who very kindly allowed us to take photographs for the stimulus materials of the pilot acceptance study.

We are indebted to the many American Airlines pilots who served as volunteer interviewees in the study. American Airlines management personnel cooperated in finding volunteers and in providing office space for the conduct of the interviews. We are particularly indebted to Captain Robert Baker who provided advice, assistance, and office space.

ALL-WEATHER LANDING

The purpose of this section is to put the present report into context. We will consider some of the factors associated with the problem of all-weather landing, and thus, hopefully, put the development of visual displays for all-weather landing into context.

Weather

First, consider the term "all-weather landing" itself. The intention of this term is entirely too inclusive. It is quite conceivable that all-weather landing will never be achieved, and that one would not want to achieve it. The goals for landing in reduced visibility are much more modestly stated, in terms of ceiling and runway-visual range, as (17):

Category I, 200 foot ceiling and 2600 feet visibility;

Category II, 100 foot ceiling and 1300 feet visibility;

Category III, operation down to and along the surface of the runway unrestricted by closed base and visibility conditions.

Aircraft

A second factor is the aircraft itself. There are two classes of problems here. One of these is the technique of landing the aircraft. Here we refer to the necessity for a crab approach in a crosswind and to the necessity for flaring the aircraft prior to touchdown. It would be very desirable if aircraft could be designed to eliminate these two maneuvers, at least for commercial aircraft.

The second class of problems associated with the aircraft is new vs. old aircraft. Aircraft last a long time. Except for very unusual situations, aircraft are very durable. This means that it may be a very long time before zero-zero weather landings will be routine for all commercial aircraft.

Pilots

A third set of factors in all-weather landing is that of pilot's and piloting technique. Pilots, being human beings, exhibit many of the characteristics of Homo sapiens. They tend to be creatures of habit, especially in emergencies. A further complication is that pilots have thousands of hours of experience in the older aircraft. If they did not have this experience they would not be in the positions in which they find themselves-since neither the airlines, the FAA nor the ALPA would allow them to sit in a Captain's seat. Further, there is justification for this emphasis on experience.

The point is that experience in older aircraft does not guarantee complete competence in landing an aircraft with different design and handling characteristics. The new aircraft are larger, they cruise at higher speeds, but they land at substantially the same speed as older aircraft. As a consequence, their handling characteristics on landing are poorer than those of the older aircraft. This means that the landing maneuver with the newer aircraft must be accomplished with much more precision than with the older aircraft.

Ground Facilities

The fourth factor is ground facilities and equipment. The first consideration is that there is no standardization as regards landing aid (e.g., Instrument Landing System) placement. At one airport the ILS may be at the approach end of the runway. At another--Logan Airport at Boston--it may be 3000 feet from the approach end of the runway. Thus airports are frequently not as long as the aeronautical chart indicates--at least as far as the zero-zero weather landing is concerned. It would seem desirable to have such matters standardized.

A second problem which follows immediately upon that of ILS placement standardization is the capability of the ILS equipment itself. The following quotation from the Airman's Guide for 6 October, 1964 speaks for itself.

> "BURBANK, LOCKHEED AIR TRML TWR: ILS glide slope
> rnwy 7 unusable below 1075' MSL."

The Lockheed Air Terminal is quoted as having an altitude of 775 ft. MSL. Thus the ILS is unusable after the aircraft reaches an altitude of 300 feet above the runway surface.

A third problem as regards airports is the runway width in relation to the decrab and roll-out maneuver. They are too narrow. The problem for the pilot-as Bob Baker[1] has remarked-" is to thread a needle with his aircraft." Now if one couples this with the fact the new aircraft are becoming more expensive, and that law suits are making passengers more expensive, the 25 million dollar Supersonic Transport will not have to go off a runway many times before it will be recognized that runways should be wider. The wider runway may be the only answer to the decrab problem when aircraft become more expensive, and precision landings in reduced visibility are required.

Instrumentation

The fifth factor is cockpit instrumentation. The instrument panel is straight up and down. Instruments near the top are nearly perpendicular to the pilot's line of sight. However, instruments near the bottom are presented at an angle of 45-50 degrees with respect to the pilot's line of sight. It would be a simple matter to tilt the lower portion of the panel about 45 degrees and present all instruments at a more appropriate viewing angle.

As regards engine instruments the pilot must infer percent of thrust from one of several meters. The one he uses depends upon the kinds of trouble he has experienced in the past with errors in a particular instrument, the altitude at which he is flying and the maneuver he is making with the aircraft.

Simple switches are designed so that the pilot must push his hand up and backward to turn them off for one instance, and up and forward to turn them off for another.

There are artificial horizons which roll over if the aircraft exceeds a bank of 60 degrees. Such an instrument is designed for straight and level flight and the normal banks of transport aircraft flight. However, an aircraft might be caught in turbulence and tipped up more than 60 degrees.

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[1] Manager of Flying Training, American Airlines, Los Angeles, California.

Finally, it must be remembered that the landing comes at the end of the flight when the pilot is not maximally alert, and when he needs a straightforward, simple display. Well-rested pilots can fly an aircraft with almost any kind of instrumentation, but not tired pilots.

Sociopsycho-legal

A sixth factor is the sociopsychological-legal considerations of flight. We consider first the legal matter. FAA regulation states--

> "91.3 RESPONSIBILITY AND AUTHORITY OF THE PILOT IN COMMAND
>
> (a) The pilot in command of an aircraft is directly responsible for, and is the final authority as to, the operation of that aircraft.
>
> (b) In an emergency requiring immediate action, the pilot in command may deviate from any rule of this subpart or of subpart B (Flight rules of right-of-way, acrobatic flight, ATC clearances, minimum safe altitudes, etc.[2]) to the extent required to meet that emergency.
>
> (c) Each pilot in command who deviates from a rule under paragraph (b) of this section shall, upon the request of the Administrator, send a written report of that deviation to the administrator."

It would be very interesting to observe the behavior of the Congress of the United States--to say nothing of the public in general--if the FAA should suggest a modification of 91.3 to read

> "(a) The pilot in command of an aircraft is directly responsible for, and is the final authority as to, the operation of that aircraft, except when landing under zero-zero minimums, when the final responsibility is that of the automatic all-weather landing system."

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[2] Insert ours.

Social psychological aspects are of two kinds. The first of these is the expectation which pilots have concerning their role in landing the aircraft, in relation to their legal responsibilities. Pilots are--and will in the future--be critical of, will not accept and will not use any kind of a landing aid, regardless of how good it is, if the operation of that aid makes it impossible for the pilot to "keep ahead of the aircraft," or if the operation of that aid tends to put the aircraft in an unusual attitude during the landing phase of flight (18).

The second aspect for consideration is as regards the attitude of the public toward the delegation of responsibility for landing the aircraft. Little or no information is available at present, but it would be wise to determine public acceptance attitudes early in the game.

Man-Machine Interface

A seventh and final factor is that of a realistic attitude toward the man-machine interface as regards landing in zero-zero weather. There is always some finite probability, no matter how small, that automatic equipment will fail. Thus, the pilot will always be there, if only to back-up an automatic system. Now, the nature of the landing task requires that the pilot have certain information displayed to him, if he is to adequately back-up an automatic system. Furthermore, the pilot cannot, if he is to obtain this information play the role of a passive monitor of the automatic system. If he does he will not acquire the information he needs. The reason is that not all of the information can be imparted via a single information channel. In landing an aircraft, regardless of extra-cockpit visibility, the pilot uses and needs visual, kinesthetic and motion cues. Thus, we use the term display in a much broader sense than it is conventionally used, i.e., visual display. Further, in utilizing these kinds of information the pilot is not concerned alone with what the aircraft is doing. He uses this information along with a knowledge of the aircraft handling characteristics to infer what the aircraft will do in the immediate future. He behaves in such a way as to stay ahead of the aircraft. Thus, even if the automatic route should be adopted, the possibility of electronic failure is such that an adequate man-chine interface will require an information display which provides visual, kinesthetic and motion cues which afford a present denotation and an intention for the immediate future. Without such, the pilot cannot stay ahead of the aircraft.

It is thus seen that the present report is devoted to a small, albeit important, part of the reduced visibility landing problem. It is concerned with the visual display of information to facilitate the task of landing under these conditions.

THE LANDING TASK

Introduction

The problem is to develop a display which will assist the pilot to make a safe landing in reduced weather minima. For Visual Flight Rule (VFR) conditions this includes selection of the point to begin the final approach; flying the final approach leg toward a selected aiming point, avoiding over- or undershooting; initiation of flare; guiding the aircraft through touchdown and roll-out. For Instrument Flight Rule (IFR) conditions, exactly the same things must be accomplished. However, the cues for initiating the various phases of the landing and the procedures for conducting each phase are based on other information inputs.

Under present IFR techniques and procedures, information concerning aircraft position and attitude relative to the optimal landing profile is presented visually on instruments. The pilot flies the instruments until the aircraft breaks out of the overcast. From this point on he is expected to complete the landing under contact conditions. The transition from instrument to contact flying requires some finite length of time.

The problem then is to analyze the task which the pilot must perform under VFR conditions, determine what can be done to enhance the performance of this task and then to develop a set of display concepts which will provide the necessary information. The display concept should allow the retention of as much of the VFR task during IFR conditions as is possible. This latter requirement derives from principles of transfer of training.[3]

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[3] Transfer of training (17) refers to the inhibitory or facilitating effects of the performance of one task on the performance of a second task. Transfer of training may be negative or positive. If the performance of the one task inhibits the performance of the second, the transfer is negative. If performance of the one task facilitates performance of the second, the transfer is positive. In the given situation, it is desirable to make the landing performance as much alike in IFR and VFR conditions as is possible. Then the transfer from the VFR to IFR landings will tend to be positive.

The VFR Landing Operation

The landing operation can be described in two ways: What the aircraft does and how the pilot accomplishes this. Since the former is the easier, we will start with that. For purposes of the present discussion, we will assume VFR conditions in the daytime, a straight-in approach with no adverse winds.

The Landing Profile.- Figure 1 shows a typical landing operation profile which consists of four phases:

1. Letdown

2. Initial Approach

3. Final Approach

4. Flare, Touchdown and Roll-out

Letdown

The pilot initiates the letdown phase after reaching some predesignated point on cruise. This point may be a radio beacon, a town or other ground point, or a Distance Measuring Equipment (DME) distance from the airport runway. The purpose of the letdown phase is to descend from cruise altitude to an appropriate approach altitude.

Initial Approach

After the approach altitude is achieved the aircraft is in the initial approach. During the initial approach phase the aircraft is slowed and the pilot will make such banking turns as are necessary to line up with the runway center line. The initial approach phase ends when the aircraft reaches the point at which the final approach leg must begin.

Final Approach

The final approach leg brings the aircraft down toward the aiming point of the runway at an angle which may be dictated by the flight dynamics of the aircraft or by ground-based landing aids. The selection of the proper point for initiating the final approach and detection of pitch and lateral deviations from the proper approach path are most important tasks. Maintenance of the approach path is important if the aircraft is to land safely. The final approach phase ends with the aircraft approaching runway threshold,

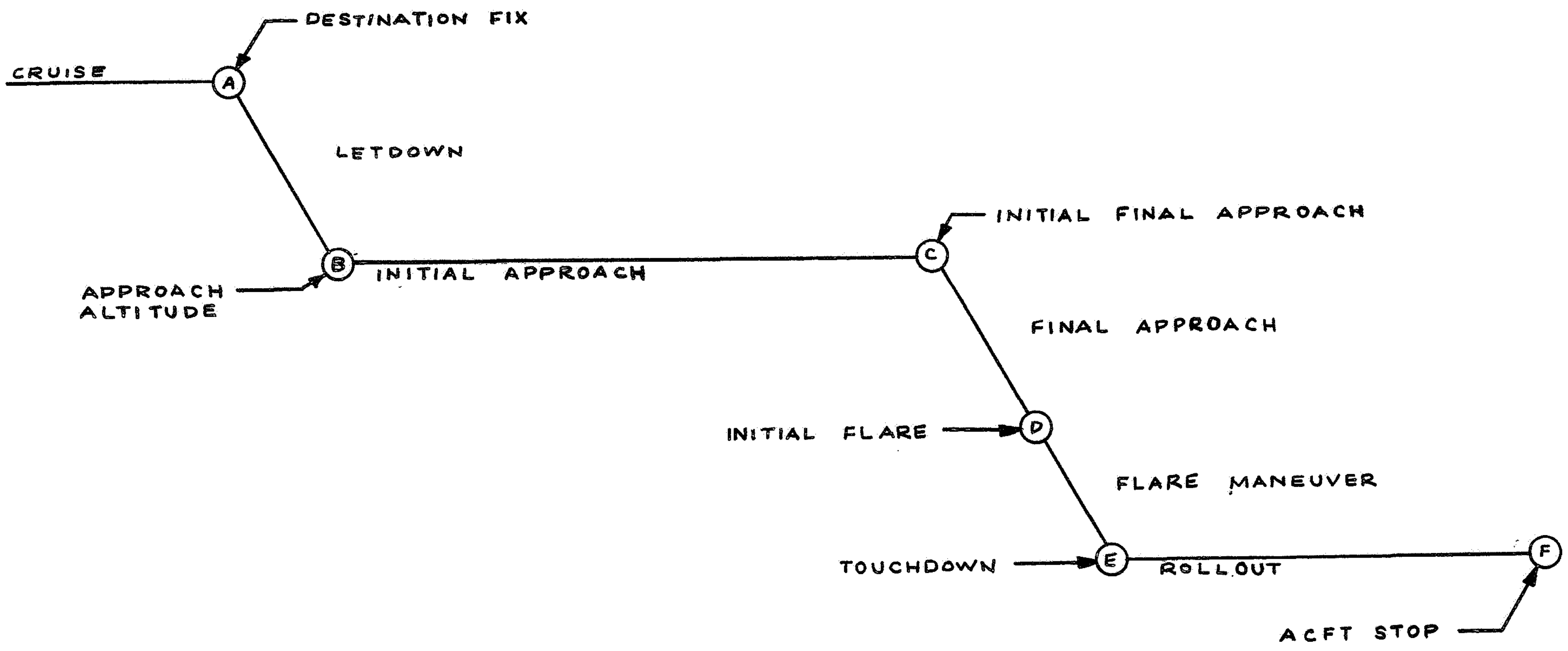

Figure 1. Sequence of events in typical landing situation (not to scale) (from Price, 18).

lined up with the center line of the runway at an appropriate altitude to initiate flare--if a flare is used depends upon the type of aircraft, rate of descent and airspeed.

Flare, Touchdown and Roll-out

The purpose of the flare maneuver is to slow the rate of descent of the aircraft, to reduce the forward speed of the aircraft and to change the attitude of the aircraft so that it can be landed at the appropriate point. Impact onto the runway is called touchdown. Theoretically the airplane ceases to fly at the moment of touchdown. However, the flight does not end here and neither do the pilot's tasks. After touchdown comes the roll-out. When the airplane ceases to fly, directional control is at best marginal. Maintenance of the aircraft direction in a straight line down the center of the runway is very important. Further, the heavier the aircraft and the faster it lands, the more difficult the problem. When the aircraft has slowed to the point where the pilot can maintain control and steer it with the front wheel, the flight is ended.

The Piloting Task.- Let us now consider how the pilot accomplishes these tasks. For this discussion, we will devote our attention to the final approach and subsequent phases of the landing maneuver. See Figure 2. The letdown and the initial approach phases may be accomplished by manipulation of aircraft attitude and power, with reference to indicated airspeed, vertical velocity and altitude. During these phases the aircraft must be trimmed to maintain roll and yaw attitudes for the landing profile.

These are four prerequisites for the final approach:

1. Appropriate angle of attack, and throttle setting;

2. Appropriate altitude;

3. Straight and level flight;

4. Lined up with runway center line.

Given these four conditions, the initial task of the pilot is to select the point to begin the descent toward the runway aiming point. Once he has begun this descent he must adjust the rate of descent until it is appropriate for the given situation. Finally, he must maintain this rate of descent until he reaches the point to begin the flare.

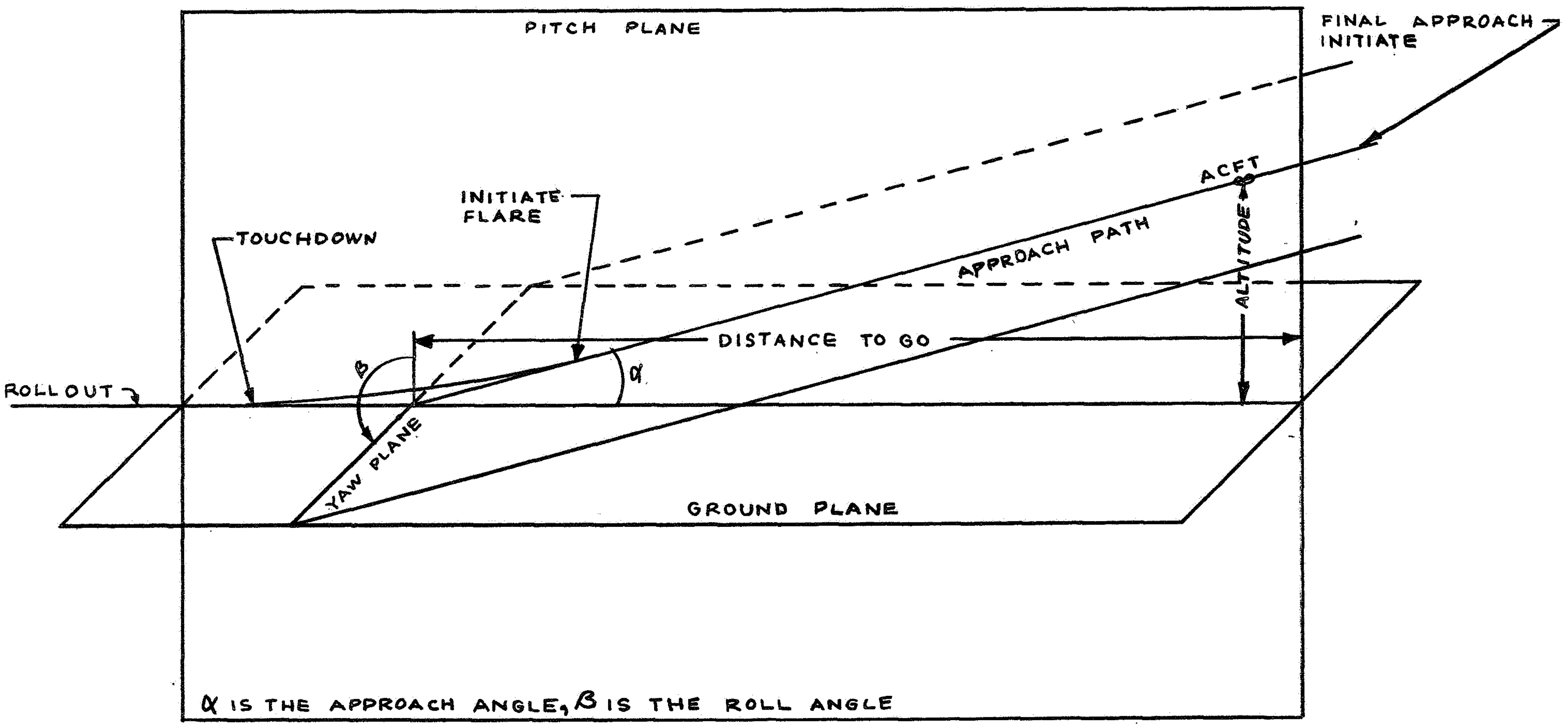

Figure 2. Dimensions in which the pilot must exert control in landing an airplane.

The above description suggests that there are three separate distance judgments which face the pilot.[4] The first of these is the distance from runway threshold to initiate the final approach. It is desirable to initiate the final approach at a point in time such that the normal glide path for that aircraft will bring the aircraft across the runway threshold at the time that flare altitude is reached.

The second distance judgment is the basis for the question "Am I going to make the runway?" This question may be answered in terms of distance to runway, altitude and sink rate and the point on the runway at which the aircraft would impact if the given glide path were maintained.

The third distance judgment is that of determining the distance above the runway for initiation of the flare maneuver.

Given the above information about the nature of the task which the pilot must perform during the final approach phase of the landing maneuver, we may ask what cues the pilot has to aid him in making these distance judgments?

Final Approach

There are three cues which the pilot may use to decide when the aircraft is the proper distance from the runway to initiate the final approach. Listed in order of value to the pilot these are:

Aerial perspective--the change in color of distant objects coupled with the loss of sharp outline and detail (12), e.g., the haziness of more distant objects, can be used as a basis for learning how far away an object is from the observer.

Angular distance from the horizon to the aiming point on the runway (14, 15)--this distance will remain constant as long as the glide slope remains constant. There are two problems: one is to determine the actual aiming point of the aircraft and to bring this into coincidence with the runway threshold; the second is to maintain the coincidence of these two points.

Relative size--the more distant a known object, the smaller it seems (12). Since the size of the runway is

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[4] The reader will recognize that the pilot must make more than three judgments in flying the final approach. We are here discussing only distance judgments.

known, the reduced apparent size is interpreted as distance. The problem is to learn the appropriate apparent size which signals the point at which to initiate the final approach.

To Make The Runway

With respect to the second distance judgment, i.e., making the runway, there are four cues, listed in order of value to the pilot:

Angular distance between the horizon and the aiming point --is dependent upon the fact that the horizon, due to its apparent placement at infinity, seems to be always the same distance away (14, 15). Thus, the angular distance between the aiming point and the horizon will remain constant so long as the glide angle remains constant. If the angular distance between the selected aiming point and the horizon appears to increase, then the aircraft will overshoot the selected aiming point. In this case, the actual aiming point is further down the runway than the selected aiming point. Conversely, if the angular distance between the selected aiming point and the horizon appears to decrease, the actual aiming point is short of the selected aiming point and the aircraft will undershoot. As the aircraft comes closer to the runway, this judgment is enhanced by the behavior of objects in the visual field (15). As an example, if one were landing over trees and the trees seemed to move up toward the runway threshold, then the aircraft would not clear the trees.

Motion perspective--the relative apparent motion of objects as the observer moves, e.g., the apparent movement of hangers and other buildings toward the observer as the aircraft approaches the runway (12). This cue can be used as a basis for learning how far away an object is from the observer. This cue is used in conjunction with perceived rate of sink to estimate the point at which the aircraft would impact, if the given approach path were maintained.

Runway perspective--is the apparent shape or perspective of the runway (14,15). The pilot must learn the appropriate shape of the runway which indicates an appropriate approach path. Then on a given approach, if the runway shape appears long and narrow the pilot would know that the aircraft would overshoot the runway. However, due to the fact that runways differ in length this cue is not as valuable if one is landing away from home. In fact, the operation of this cue can have a detrimental effect if one is landing at a strange airport. As one has more time in the air one gradually incorporates the effects of this cue into one's experiential frame of reference.

Stationary aiming point, the point at which the aircraft is actually aiming is said to be perceived as stationary. Points above the aiming point will appear to move away from the aircraft. Points below the aiming point will appear to move toward and under the aircraft. See Figure 3. A description of this cue (14) follows:

> "If an observer is in motion in a straight line towards a point in a pattern, that point will appear to him to be stationary in the pattern, and the points surrounding it will appear to move radially away from it."

Gibson (12) states that non-pilots, when shown a motion picture of the appearance of the ground from an approaching airplane, regularly enjoy a "compelling experience of moving through space in a specific direction toward the ground. The angle of this movement and its point of aim can be judged by all." Havron has attempted to quantify the operation of this cue (13).

There is another cue which is valuable only at night and then on a lighted field. This will be mentioned in passing, but will be of no value for our present purposes. If one looks at the gap between the first and second runway lights, the gap tends to remain constant if the aircraft maintains the correct glide path. The gap appears to increase if the aircraft is overshooting the aiming point, and to decrease if undershooting. An alternative way of describing this cue is to direct the pilot's attention to the trapezoid formed by the first two pairs of runway lights. If this trapezoid appears to thicken, the aircraft will overshoot. If its thickness remains constant the aircraft is on the correct glide path. If it appears to get thinner, the aircraft will undershoot (14).

The pilot uses these cues to project impact point of the aircraft with respect to the selected runway aiming point. The difference between the intended aiming point and the projected impact point is an indication of the error in the aircraft approach path. The pilot attempts to fly the approach path so that the aiming point and the impact point coincide. The pilot attempts to null the approach error. It is thus seen that the information available to the pilot during the final approach is used very much as the information in a compensatory display (10). A compensatory display presents an indication of the error in the tracking output.

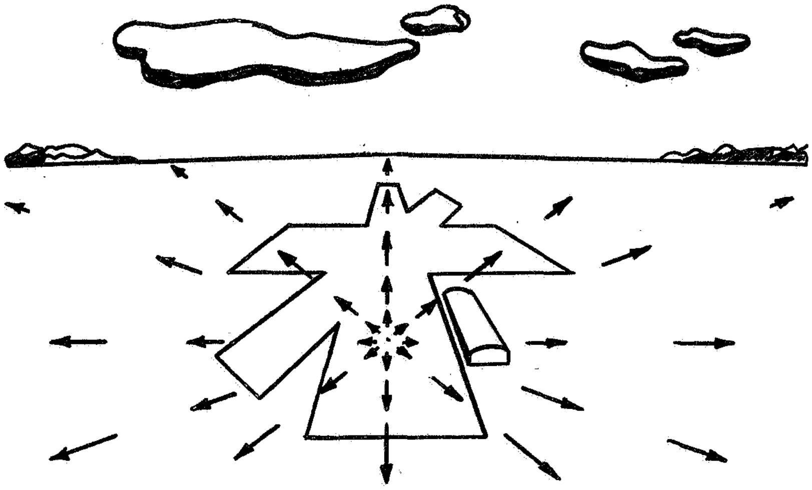


Figure 3. The point at which the aircraft is actually aiming appears stationary. All points around the aiming point seem to radiate out from it. (From Gibson, 12)

A pursuit display, on the other hand, presents both the desired output and the actual output. This analysis suggests that it might be helpful to construe the VFR landing display as a compensatory display, if one remembers also that it is not a simple compensatory display. The point is to abstract away the basic compensatory characteristic as a hueristic device.

In characterizing the VFR landing task as utilizing a compensatory display, we do not wish to imply that such a characterization explains all of the problems associated with landing. The pilots memory of where he has been in an input to the landing task which is not available in the laboratory situation. Thus, any display for landing in reduced visibility must present more than a simple compensatory display.

The rate of procedure down the glide path is a function of the loss of altitude, or sink rate, and ground speed. The former is controlled by the use of power and the latter by aircraft attitude (angle-of-attack) in the case of propeller-driven aircraft. In the case of jet aircraft, speed is controlled by throttle setting. Since there is no propeller wash over the wings, angle-of-attack in conjunction with throttle setting is used to control sink rate. We are here describing the manner in which the pilot flies the aircraft. The appropriate angle-of-attack and throttle setting is, of course, a function of the aerodynamics of the individual aircraft. Final approach ends with the initiation of the flare maneuver.

Flare

The appropriate altitude to begin the flare, if one is required, is likewise a function of the individual aircraft. To judge the point at which to initiate the flare maneuver the pilot must consider:

1. runway alignment;
2. pitch attitude;
3. height above runway;
4. distance to threshold.

Runway alignment is assisted by the existence of the runway center line. Pitch attitude can be estimated by angular distance from the horizon. Distance to threshold was considered above. Height above the runway is a problem in visual judgment of distance. If all of these factors are not right the aircraft may not be flared. The aircraft must go around. We will consider three cues for distance judgment as valuable to the pilot to judge flare height.

Head Movement Parallax or motion parallax--is based on the different views of the runway which one obtains when one scans back and forth ahead of the speed blur (12). Use of this cue is the reason that the student pilot is instructed to scan back and forth in the area about 20 feet ahead of the speed blur. The scanning helps provide more and different data for the judgment through the cue of head movement parallax (motion parallax).

Motion perspective--the gradient in motion in a direction as the aircraft approaches the runway (12). See Figure 4. As the aircraft approaches the runway objects seem to pass beneath it at greater and greater speeds. The problem is that things begin to blur if the aircraft lands very fast. This cue is most useful for pilots operating slower landing aircraft.

Density gradient in the texture of the runway and its surrounds (12). As the aircraft comes closer to the ground, the gradient becomes much steeper. The increase in density generally runs upward in the visual field. The problem for the pilot is to learn the appearance of this gradient at the appropriate time to begin the flare.

Additional cues which the pilot has to assist in judging the appropriate distance from the runway for flare are the sizes of familiar objects and the clarity of their detail.

Information Requirements For Landing

As the aircraft comes closer to the point of actual touchdown, small changes in attitude in any plane become more important. Thus, it becomes increasingly important for the pilot to exercise more compete control of the aircraft the further along on the landing maneuver. As aircraft become larger and cruise at greater speeds, their handling qualities at the relatively slow landing speeds become poorer. This means that the latitude for error correction becomes smaller. The precision with which the landing maneuver must be performed becomes more important.

It should be recognized that the above discussion has assumed an aircraft landing in a calm wind. While this may be the case early in the morning, most aircraft landings are made in some degree of crosswind. The aircraft in flight is

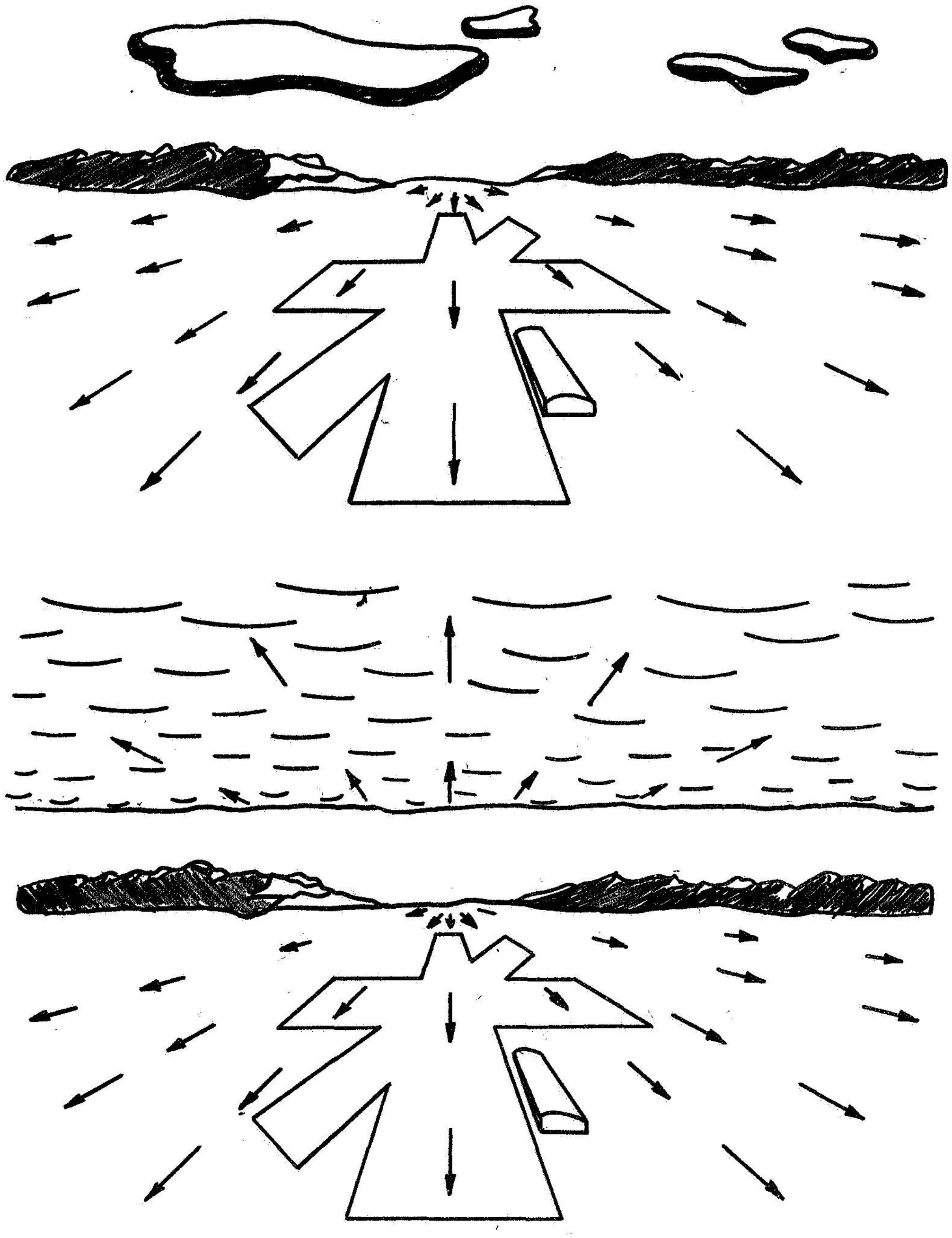


Figure 4. Motion perspective of the field on a clear day (above) and with an overcast (below). (From Gibson, 12)

a part of the air mass. The aircraft does not fly through the air, it flies in the air. Normally the pilot of an aircraft crabs (turns) into the wind to maintain a desired course (ground track). Thus the heading of the aircraft may not be identifical to the course it flies.

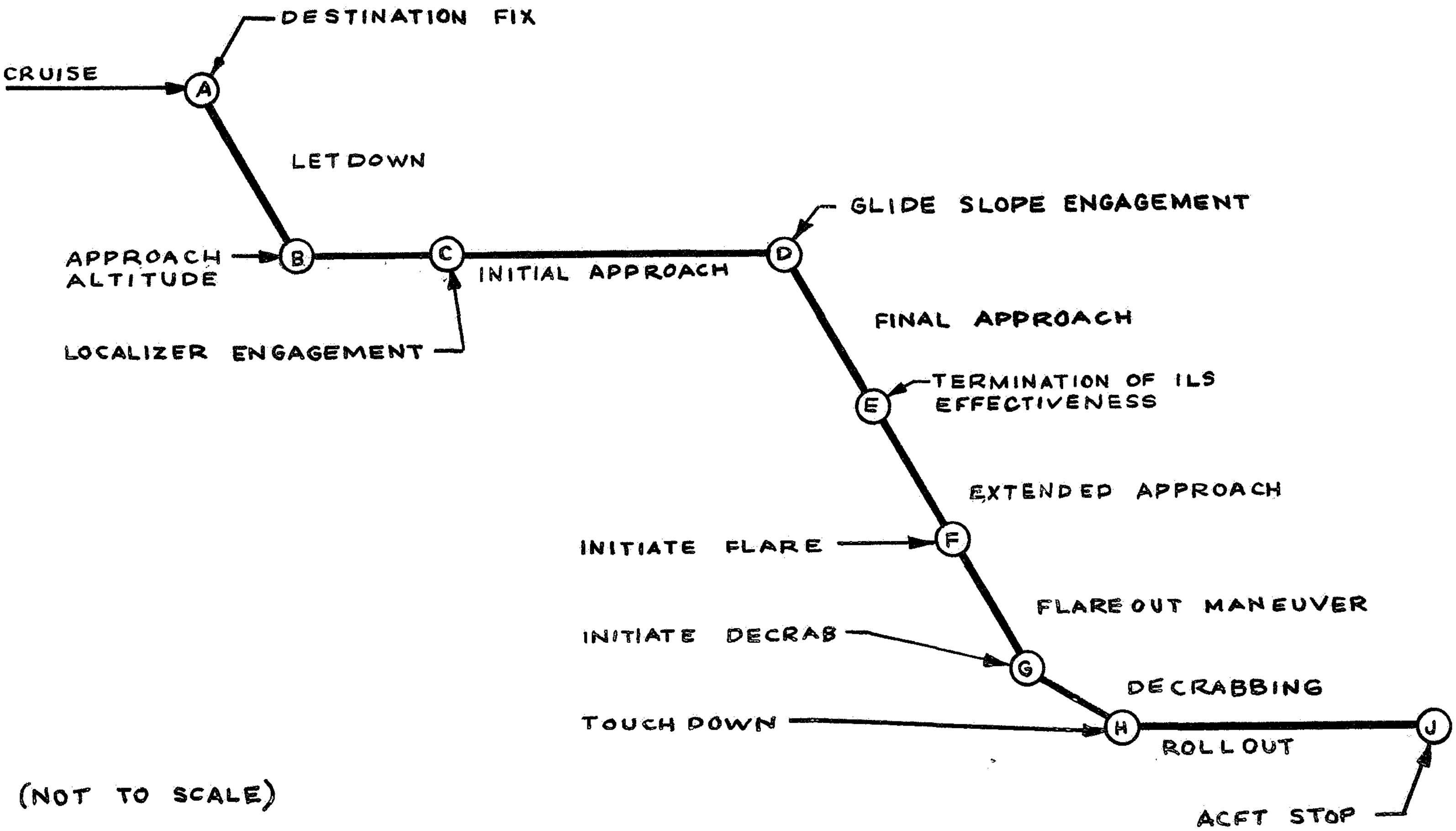
Similarly, the air mass in which the aircraft flies is not static. It is dynamic, continually moving and changing. This is particularly so near the ground. Thus the pilot may have not only to land in a crosswind, but in a gusty crosswind. The possibility of achieving a landing under such conditions depends on the velocity of the gusts. In other situations, local terrain features--small mountains, lakes, rivers, plowed fields, etc.--may give rise to shear winds at low altitudes.

From the above, it may be inferred that the pilot needs information to:

1. Assist initiation of the final approach;
2. Achieve and maintain the appropriate glide angle;
3. Warn of over- or undershooting the aiming point;
4. Maintain the appropriate angle of attack;
5. Maintain the appropriate sink rate;
6. Maintain appropriate roll attitude;
7. Maintain an appropriate course;
8. Indicate the crab angle required to maintain course;
9. Assist initiation of the flare maneuver;
10. Maintain aircraft heading during roll-out.

The IFR Landing Operation

The above discussion assumed VFR flight conditions. The same maneuvers must be accomplished for an IFR landing. The difference is the information which the pilot has available to him to accomplish the maneuvers. Figure 6 shows a typical instrument landing profile. The letdown and the initial approach are the same as under VFR conditions, with the exception that the initial approach may be accomplished with



(NOT TO SCALE)

Figure 5. Typical present day ILS approach and landing. (From Price, 18)

the assistance of radar guidance. However, under IFR conditions the pilot must rely on other sources of information for:

1. Initiation of the final approach;
2. Accomplishing the final approach;
3. Initiation of the flare maneuver;
4. Completing the touchdown and roll-out.

Thus it is seen that 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.

The IFR landing is more complicated due to the fact that the pilot cannot use the usual visual cues. This condition places considerable stress on the pilot which tends to make the task more difficult. The IFR landing is further complicated by the fact that certain aspects of the task, which are accomplished early in the VFR landing, are shifted to the end of the final approach. These are checks and adjustments of pitch attitude, bank attitude and runway alignment. These checks and adjustments contribute to the transition period.

Nature Of The Landing Task

From the analysis presented on pages 17 and 18, flying the final approach may be construed as a tracking task in which the pilot is tracking a ramp input with the aid of a compensatory type display. The approach path which the pilot wishes to fly is the ramp. See Figure 2. The tracking task is complicated by the fact that the pilot must control the aircraft in three dimensions and he must infer the error in the present position of the aircraft from a projection of the future position of the aircraft. This latter has important implications for understanding the period of transition from instrument to contact flying.

Laboratory studies of compensatory tracking tasks provide the following generalizations:

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

i.e., the pilot's ability to control the aircraft on the desired glide path (7).

2. When the control is unaided in relation to the display compensatory tracking is superior to pursuit tracking with a simple input (9).
3. With a shallow ramp input, as in the present case, there is a tendency for the operator to lead the input, i.e., in the present case, to overshoot (6).
4. When the desired output is time invarient, as is the present case, the compensatory tracking task is equally as efficient as the pursuit tracking task (6,9).
5. A compensatory indicator can give a more precise picture of the situation through the utilization of high display gain (4).

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 lead to the conclusion that whatever instrumentation is developed should present a compensatory-type display.

THE ACCEPTANCE STUDY

The purpose of this study was to determine pilot preference for the display of information for landing in reduced visibility. Two types of information display were considered:

1. The situation display which presents an integrated complex of information;

2. The display of individual items of information, e.g., sink rate.

Method

The method used was the technique of paired comparisons. Representative displays of both types--situation and individual displays--were selected. These were arranged in pairs by display type. The subjects were presented with each pair of displays and asked to express a preference for one of the pair. After the preference was stated the subject was asked the reason for the preference. A no-preference response was considered a legitimate response.

After all pairs of displays had been exhausted the subjects were asked two questions designed to elicit information about the cues they used to land the aircraft in VFR and in IFR conditions. Finally, three questions designed to elicit information about required engine performance data were asked. Appendix I contains the data collection sheet and the questions.

Subjects

The subjects were 30 American Airlines line pilots, each of whom were interviewed separately. American Airlines pilots were used because they were not familiar with any of the situation displays in the study. Thus familiarity with a particular situation display could not influence their choice. The average age of the pilots was 46 years. Their age range was 34-58 years. They had been flying for an average of 26 years; the range was 10-38 years. They had an average of 17,520 hours in the air; the range was 3,000-26,800 hours. Of the 30 pilots 29 were qualified in jet aircraft. The average number of hours in jets and the range was, respectively, 2,490 hours and 984-4,140 hours.

Instructions To Subjects

The following instructions were given to the subjects:

"Serendipity Associates is a small human factors research company. We do contract research for various government agencies and for private corporations. We have a contract with NASA to design a research program to develop displays for all-weather landings.

One important aspect of a display for all-weather landings is the attitude of the pilots toward the display and the elements that make up the display. We will therefore be concerned with the degree of acceptance by pilots of different ways of presenting data.

We have selected different examples of each of several types of displays. These displays are mounted in pairs on cards." (The subjects were shown a sample card.) "For each pair we would like you to indicate the display which you prefer and the reason for the preference. It is of course possible that there is no preference between the items of a given pair. In that case, you should so indicate.

Do you have any questions?"

Situation Displays

Four situation displays were chosen:

1. The Collins 329B-7A flight director display;
2. The Spectocom windscreen display;
3. The type A windscreen display of Baxter and Workman(2);
4. The General Electric CRT display.

The Collins display (11) was chosen to represent the conventional panel mounted situation display. It is a standard fly-to director display which, it was estimated (correctly), would be unfamiliar to the subjects of the study.

The Spectocom windscreen display (2) was chosen as one of two windscreen displays because it was rated so low by Baxter and Workman. Further, it was felt that it presented a fairly cluttered-up appearance. The Type A windscreen display (2) was chosen because it was a synthesis of the best characteristics of several displays by Baxter and Workman. Further, it was felt that it presented a relatively clear picture of the landing situation. The General Electric Cathode Ray Tube display was presented because it was felt that a CRT type should be included. We took the picture which was used out of the article by Bradbury (5).

Individual Information Displays

The following individual information displays were selected.

1. Altimeters (3); conventional 3-pointer, with the 10,000-foot pointer modified as a moving index and a vertical moving tape with a fixed index.

2. Airspeed indicators (3); conventional dial, digital readout and a vertical moving tape with a fixed index.

3. Vertical rate of climb or descent (3); conventional with fine graduations, conventional with minimum graduation and vertical tape with a moving index.

4. Turn and bank indicators (2), graduation vs. no graduations.

5. Attitude indicators (climb-dive and roll indicators) (2); displacement bars vs. hinged pointers, both fly-to indicators.

6. Glide slope and localizer indicators (2); hinged fly-to needles vs. a center hinged localizer with a displacement bar for glide slope.

Appendix II presents the displays used.

Reliability And Validity

The altimeters, airspeed and sink rate indicators were chosen to assess the reliability and validity of the results of the study. The method of assessing validity was to compare the preference for certain display methods with recommendations for these same types of displays in the human engineering literature. If the preferences indicated by the pilots coincide with the human engineering recommendations, and if the pilots reasons given for their preference coincide with the human engineering literature's reasons for recommendations, the results of the study would be assumed to have been validated.

Assessment of the reliability (internal consistency) of the results of the study is afforded by the use of the paired comparison technique. On the assumption that consistent preferences follow the transitive law,[5] the preference choices could be used to assess consistency. With three displays, there are two tests for consistency:

1. xPy and yPz, then xPz;
2. xPz and zPy, then zPy.

By successive substitutions of A, B and C for x, y and z all possible combinations may be developed.

The consistency test was applied also to test the results obtained with the four situation displays.

Results

Tables 1 through 14 give the results of the display preference for each of the instrument types presented and the reasons given for each instrument type picked.

Since there were three instrument types for airspeed (Table 1), altitude (Table 3), and rate of climb (Table 5), these tables show the number of subjects who picked each of the types over either of the remaining types. However the actual preference for each subject was determined by the instrument display he picked over <u>both</u> of the other two displays. For example, if subject number I picks A over B, B over C, and A over C, his preference was A since it was picked over both B and over C. This same method was used for the scoring of the situation displays (Table 13) except that there were four types and the type preferred must have been picked over all three of the others. In cases where the subject had a "no preference" choice the subject's preferences were analyzed for consistency and a

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[5] In the present context the transitive law would read "If A is preferred to B and B is preferred to C, then A is preferred to C.

preference was assigned logically.

Table 1 shows the results of the comparisons of the airspeed presentations and Table 2 gives the reasons for their preferences.[6] The conventional clock-type instrument was the first preference of the pilots. $X^2 = 7.52$, $p < .05$.

Table 1. Preference scores for airspeed presentations.

Instrument Type	First Preference	Times Picked Over A	B	C
A. Digital Readout	4	--	7	8
B. Conventional clock-type	16*	23	--	18
C. Vertical (moving) Tape	9	16	11	--
No Preference	1			

*Significant at the .05 level of confidence.

Table 2. Reasons and frequency of reasons for pilot preference of airspeed presentations.

Reason for Preference	f
1ST CHOICE B (conventional clock-type)	
Familiarity (experience)	12
Read angle of pointer	11
Can see trend	8
Easier and quicker to read	4
Relationship to other number: Range	4
2ND CHOICE C (vertical tape)	
Can see trend	5
Easier and quicker reading	4

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[6] In this and the following tables which list reasons for preference we have chosen to present only those reasons with a frequency greater than 3. A complete list of reasons for preference is shown in Appendix III.

Table 2 (continued)

3RD CHOICE _A_ (digital readout)	
Simple, precise	4

Table 3 presents the altimetry preference scores and indicates that the yellow-line altimeter (B) was the first preference of the pilots. $X^2 = 10.69, p<.01$. Table 4 lists the reasons for the choices in Table 3.

Table 3. Preference scores for altitude presentations.

Instrument Type	First Preference	Times Picked Over A	B	C
A. Vertical Moving Tape	7	--	8	10
B. Yellow-line Altimeter	18*	20	--	25
C. Conventional 3-Pointer	5	20	5	--

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*Significant at the .01 level of confidence.

Table 4. Reasons and frequency of reasons for pilot preference of altitude presentations.

Reason for Preference	_f_
1ST CHOICE _B_ (modified conventional clock-type)	
Easy to read	10
Less chance for error	4
An improvement	4
2ND CHOICE _C_ (conventional 3-pointer altimeter)	
Familiarity (experience)	8
Easier to read	4
3RD CHOICE _A_ (vertical tape)	

Scores of the pilot preference of the veritcal speed indicators are presented in Table 5. The reasons for their preferences are presented in Table 6. Pilots preferred the clock-type (A) or (B) significantly over the vertical fixed tape (C). $X^2 = 13.71$, $p<.01$.

Table 5. Preference scores for vertical speed presentations.

Instrument Type	First Preference	Times Picked Over A	B	C
A. Conventional Clock-type	10	--	11	22
B. Modified conventional	13	18	--	23
C. Vertical Fixed Tape	5*	7	6	--
No Preference				

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*Significant at the .01 level of confidence.

Table 6. Reasons and frequency of reasons for pilot preference of vertical speed presentations.

Reason for Preference	f
1ST CHOICE B (graduated standard clock-type)	
Less Interpretation/markings	13
Familiarity	9
2ND CHOICE A (conventional clock-type)	
Simple-No clutter: no need for more markings	13
Familiarity	7
Easy to read	5
3RD CHOICE C (vertical tape)	

Frequency of preference for the two attitude indicators are given in Table 7. There is not a significant difference between the choices of either A or B. Table 8 lists the reasons for the choices.

Table 7. Preference scores for attitude presentations.

Instrument Type	First Preference
A. Displacement bars	14
B. Hinged pointer	11
No Preference	5

Table 8. Reasons and frequency of reasons for pilot preference of attitude presentations.

Reason for Preference	f
1ST CHOICE A (bar movement)	
Like bar-type movement	7
2ND CHOICE B (hinged pointer)	
Easier/quicker to read	4

The preferences for the two turn and bank indicators (Table 9) indicate that B was picked significantly more than A. $X^2 = 12.49, p<.01$. Table 10 gives the reasons for the preferences.

Table 9. Preference scores for turn and bank presentations.

Instrument Type	First Preference
A. Standard	5
B. Graduated	24*
No Preference	1

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*Significant at the .01 level of confidence.

Table 10. Reasons and frequency of reasons for pilot preference of turn and bank presentations.

Reason for Preference	f
1ST CHOICE B (marked conventional)	
Scale markings	16
2ND CHOICE A (unmarked conventional)	

Table 11 shows the results of the comparison of the glide slope and localizer instrument. B was picked significantly more than A. $X^2 = 11.57, p<.01$. Reasons for these choices are given in Table 12.

Table 11. Preference scores for glide slope and localizer deviation presentations.

Instrument Type	First Preference
A. "Fly-to" needles	5
B. Center hinges and displacement bar	23*
No Preference	2

*Significant at the .01 level of confidence.

Table 12. Reasons and frequency of reasons for pilot preference of glide slope and localizer presentation.

Reason for Preference	f
1ST CHOICE C (moving bar-center hinge)	
Don't like hinged pointer	6
2ND CHOICE A (standard blue-yellow hinge type)	

The results of the comparison of the four situation displays are presented in Table 13. The reasons for the choices are presented in Table 14. Although the Type A display was picked more than any of the other three displays, the X^2 was not large enough for significance at the .05 level of confidence. However, comparing the two windshield displays, A (Spectocom) and C (Type A) against the other two, we find that the windshield type was picked significantly more than the other type. $X^2 = 11.16, p<.01$.

Table 13. Preference scores for situation displays.

Instrument Type	First Preference	Times Picked Over A	B	C	D
A. Spectocom	7	--	19	12	16
B. Collins	4	11	--	9	10
C. Type A	11	16	18	--	18
D. General Electric	7	12	18	10	--
No Preference	1				

Table 14. Reasons and frequency of reasons for pilot preference of situation displays.

Reason for Preference	f
1ST CHOICE: C (Type A)	
Windshield	15
Better pictorially	11
Simpler; less interpolation	5
Runway	4
2ND CHOICE:[7] A (Spectocom)	
Simplicity making it easy to read	15
Windshield	11
3RD CHOICE:[7] D (General Electric)	
"Real" pictorial presentation	20
Simplicity/easy to grasp	5

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[7] Tie for second.

Table 14 (continued)

4TH CHOICE: B (Collins)

Familiar: less transition	13
Simpler: more understandable	6

When considering these displays as regards presentation of the situation of the aircraft in relation to the glide slope, the Spectocom was the only one which does not display this information. Displays B, C, or D, which give the situation of the aircraft as regards to glide slope, were picked significantly more than the Spectocom which only has a Command, "Fly-To" director. The $X^2 = 7.76, p<.01$.

Another difference among these displays was the presentation of airspeed information. Displays A, C or D together, all presenting airspeed information, vs. the Collins (B), which does not present airspeed information, were picked significantly more than the Collins. $X^2 = 15.21, p<.01$.

Comparison of the displays as regards altitude information, A and C vs. B and D, resulted in a value of X^2 which was not significant at the .05 level of confidence. It is likely that this result reflects the fact that it is the copilots task to monitor altitude during the final approach, not the task of the person landing the aircraft.

As mentioned previously, all the subjects were asked questions concerning cues they used to land the aircraft under both VFR and IFR conditions. The results of these questions are included in Tables 15, 16, and 17.

Table 15. Responses to question "When making a VFR approach during the daytime do you use the so-called spot of no movement to insure making the runway?"

Response	f
Yes	5
No	20
Don't know	5

Table 16. Responses to question "When making a VFR approach during the daytime what cues do you use to insure making the runway?"

Response	f
Runway perspective	8
X-spot	6
Instruments	7

Table 17. Responses to question "When making an IFR approach during the daytime, what does the pilot attend to during the period of transition from instruments to contact flying?"

Response	f
Checking runway line-up	16

Finally, the pilots were asked three questions concerning the display of engine performance data. The results of which are presented in Tables 18, 19, and 20.

Table 18. Responses to question "During normal operation, which of the engine operation instruments do you find most useful?"

Response	f
Fuel Flow	26
Engine Pressure Ratio (EPR)	11
N_1 Tachometer	6

Table 19. Response to question "Do you use these instruments routinely to infer information about engine thrust?"

Response	f
Yes	25
No	1
Don't know	4

Table 20. Responses to question "If you had a display of per cent of engine thrust, what other engine operation information would you need?"

Response	f
None	10
Exhaust gas temperature (EGT)	8
Fuel Flow	6

Reliability, as the term is here used, means internal consistency reliability. Consistency of the pilots' responses is attested by the fact that out of 450 choices where inconsistency was possible (30 subjects and 15 pairs) only two (2) inconsistencies occurred. Thus the empirical probability of an inconsistency is, for this study, 0.0044. Furthermore, both of the inconsistencies occurred with respect to the situation displays, where there were six choices (4 situation displays, 6 pairs). In no case where there were three choices were there inconsistencies.

Subject number 16 showed one inconsistency when he preferred the Kaiser display to the Spectocom, and the Spectocom display to the Collins, but chose the Collins display over the Kaiser. He felt that the information on the Collins display was more readily grasped.

Subject number 26 preferred the Spectocom display to the Kaiser, and the Kaiser to the Collins, but chose the Collins display over the Spectocom. He felt that the Spectocom director was difficult to understand.

One may conclude from the low occurrence of inconsistencies in pilot judgments, that the data collected are reliable. In other words, there is consistency within pilots. We shall utilize the consistency between pilots to make recommendations about the manner of displaying information.

Validity of the results may be judged by the agreement between pilot choice and human engineering recommendations. The test displays are those for altitude, indicated airspeed and sink rate. The source of human engineering recommendations is (1, pages 94, 95 and 96). This source recommends a moving pointer and a circular dial as superior to a moving scale or a counter for:

1. Qualitative and check reading;
2. Setting in information;
3. Tracking;
4. General use.

The only situation in which our source does not recommend a moving pointer is for quantitative reading, where the counter is recommended.

As regards altitude, the first preference was for the modified circular dial. Second and third choices were the conventional three pointer altimeter and the vertical moving scale, respectively. The reasons given for the preferences are listed in Table 4.

As regards airspeed, the first preference was for the conventional dial with moving pointer. The second and third choices were for the vertical tape and the digital readout, respectively. The reasons given for the preferences are listed in Table 2.

As regards vertical speed, the graduated standard dial presentation was the first choice. The second and third choices were the ungraduated standard dial and the vertical tape, respectively. The reasons given for preferences are listed in Table 6.

In every case, the preference of the pilots corresponded exactly with that of the human engineering recommendations. These are multiple use instruments. They are used for direct reading when going from one altitude to another or one speed to another. They are used also to indicate trends, as when descending on the letdown phase of landing. Finally, there is constant use of these instruments to check the conditions of flight. The pilot checks only for deviations from a desired course.

In terms of the reasons given for selection of a particular instrument, the pilots' reasons do not conform exactly to those of the human factors literature. However, it should be noted that there are no contradictions. What sins there are, are those of omission. For example, the pilots do not mention the importance of trend information as regards the altimeter. It is likely that they do not mention this factor as regards the altimeter because they generally distrust the altimeter--

and further, the altimeter is next to useless on the final approach to landing--the main subject of the study.

In view of the above, we conclude that the data collected as regards altitude, airspeed and sink rate displays is valid. Further, we infer from this that the data as regards situation displays is also valid.

Summary of Results

Situation displays.- The results as regards situation displays allow the generalizations that pilots prefer a display for landing in reduced visibility which:

1. Is presented on the windscreen;
2. Contains information about the position of the aircraft with respect to the glide slope, as well as presenting a picture of the landing situation;
3. Contains information about airspeed.

Individual information.- The results as regards the individual information displays allow the generalizations that pilots prefer displays of altitude, airspeed and sink rate to be presented as circular scales with moving pointers to facilitate quick checks and so that they may note trends.

Results with the glide slope and localizer instruments imply that pilots prefer a displacement bar to needles, when both present a fly-to indication.

Results with all individual information displays implies a preference for a graduated instrument.

Making the runway.- Pilots use a variety of cues to insure making the runway, but the present results indicate that the spot of no movement is not used by the majority of pilots.

Percentage of engine thrust.- The present results indicate that a significant majority of the pilots use one or a combination of present engine instruments to infer data about the percentage of engine thrust which is delivered.

THE DISPLAY

Introduction

The display for landing in reduced visibility should be developed with one overriding consideration in mind. The landing comes at the end of the flight. In all likelihood, the pilots will have flown the aircraft for a period of time ranging from 4 to 8 hours. They will be tired. The aircraft may be low on fuel. The runway, when they get to it, may be wet, icy, fog bound or snow covered. The pilots will be using the display in the worst possible conditions, and it must be developed for use in those kinds of situations.

Information Content

The analysis of the landing task, which was presented in the second section, is the source of the information requirements for the display. The content suggested was information to:

1. Determine when to initiate the final approach;
2. Achieve an appropriate glide angle;
3. Warn of overshooting or undershooting the aiming point (departure from glide angle);
4. Maintain an appropriate angle of attack;
5. Maintain an appropriate sink rate;
6. Maintain an appropriate roll attitude;
7. Maintain an appropriate course;
8. Indicate amount of crab required to maintain course;
9. Determine when to initiate the flare maneuver;
10. Maintain aircraft heading during roll-out.

Criteria For Display Evaluation

The following criteria were derived from the analysis of the landing task, from the pilot opinion study, from previous work (19) and from discussions with flying instructors: The criteria for the evaluation of a display for landing an aircraft in weather are:

1. Information content as indicated above;
2. Presentation of a compensatory display;
3. Presentation of a simple, pictorial indication of the landing situation;
4. Presentation on the windscreen;
5. Utilization of maximum of display gain;
6. Provision for redundant but independent information;
7. Require a minimum of user supplied information;
8. Alignment, and other adjustments prior to use, should be simple to accomplish and should be followed by a simple foolproof checkout procedure;
9. Useful in other phases of the flight than landing;
10. Provide for removal from the display of a malfunctioning element.

Display Elements

The display concept which is presented below derives from the pilot preference study, previous acceptance studies by Serendipity Associates (3,18,19) and from the criteria for displays listed above. The use of a windscreen display conforms to the results of the present study and to (3,19). The runway symbol shape and the aircraft ground symbol shape derive from (3). The use of a crab bar is dictated by the results of the present pilot preference study. The remaining display elements were selected to provide a simple uncluttered appearance and to allow the maximum use of display gain.

The display concept assumes an on-board computer, which is capable of making the various calculations required and which is capable of driving the display. This computer receives information from the ground via radio inputs, from the aircraft itself and perhaps also from the pilot who may insert a card describing characteristics of the airport of intent. The fast-slow airspeed indicator of the display assumes automatic throttle control.

Finally, the display concept assumes an auxiliary source of information about the runway. This is required for the provision of information for cross-checking the operation of the display generation equipment. Some device like microvision (16) is envisioned.

The display consists of the following elements (see Figure 6):

1. Director cross;
2. Fast-slow airspeed indicator;
3. Aircraft ground track symbol;
4. Horizon line with runway heading marker;
5. Runway with aiming point and center line;
6. Crab bar;
7. Radar altitude and flare initiation symbol;
8. Distance-Altitude readout.

The horizon line and the runway symbol are to be gyrostabilized as regards the ground. The remainder of the display elements are referred to the aircraft itself. The horizon line and runway symbol are green in color. The remainder of the display elements are colored red. Figures 7, 7-1 and 7-2 show the appearance of the display for different situations. This sequence illustrates also, that not all of the elements are intended to be on all of the time.

Information for initiation of the final approach is presented by the director cross. This director cross would show deviation from the glide slope and localizer. It would be used on initial approach to align the aircraft with the runway center line. Depending on the strength of the glide slope beam, as the aircraft approached the beam, the director cross would tend to move upward and then down again; warning of approach to the glide slope. When the aircraft intercepted

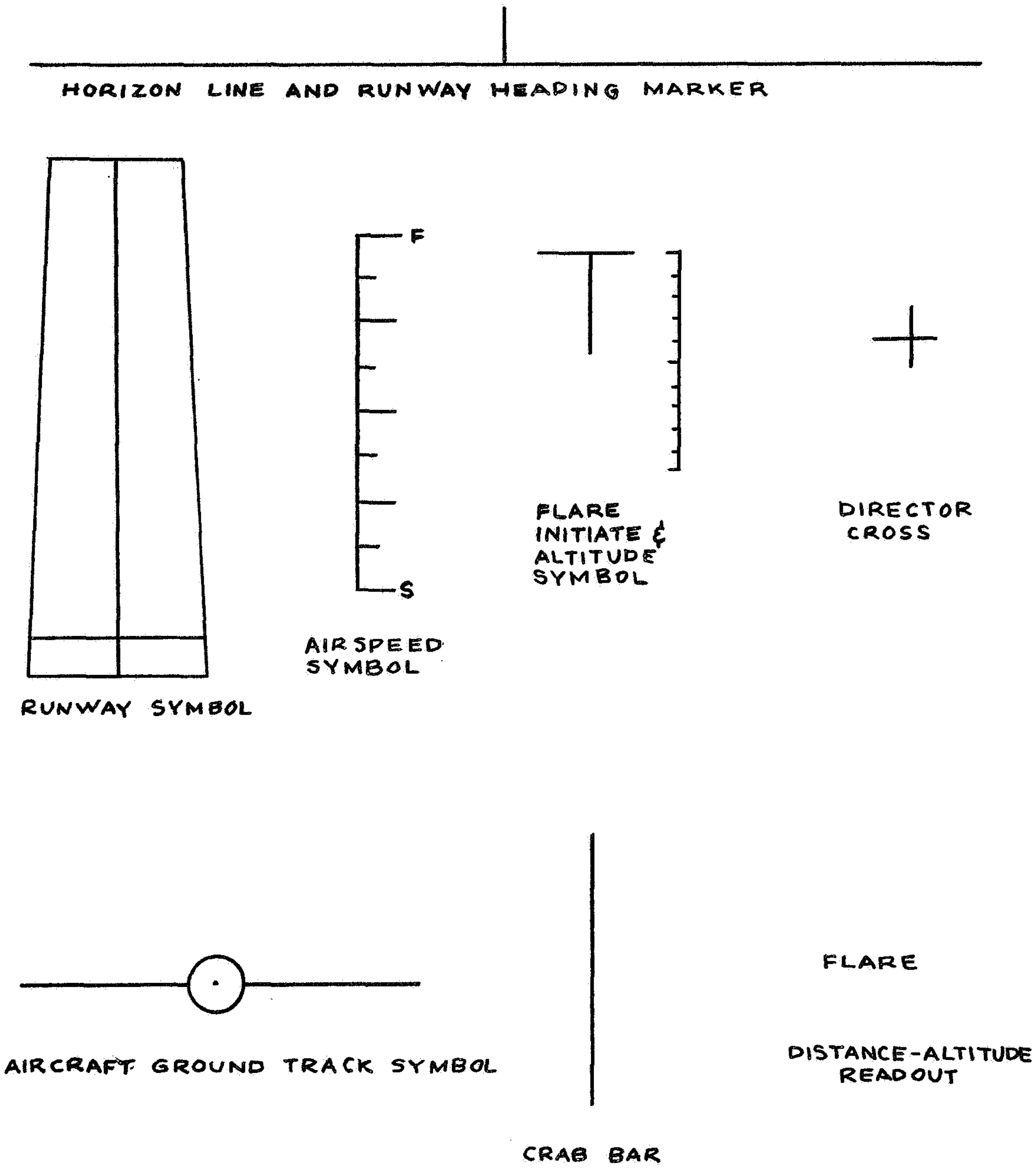

Figure 6. Situation display elements.

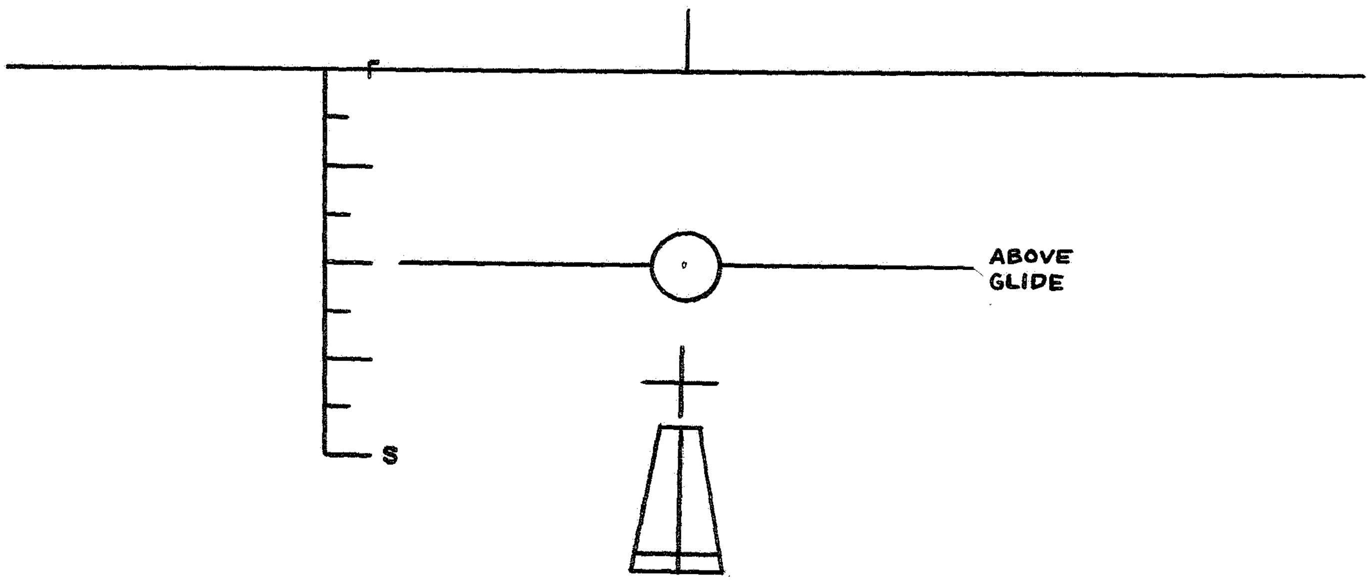

Figure 7. Aircraft has reached the point to initiate the final approach. The director cross is moving down toward the runway aiming point, commanding the pilot to initiate the final approach. Airspeed is right for the given angle of attack. Aircraft is flying straight and level.

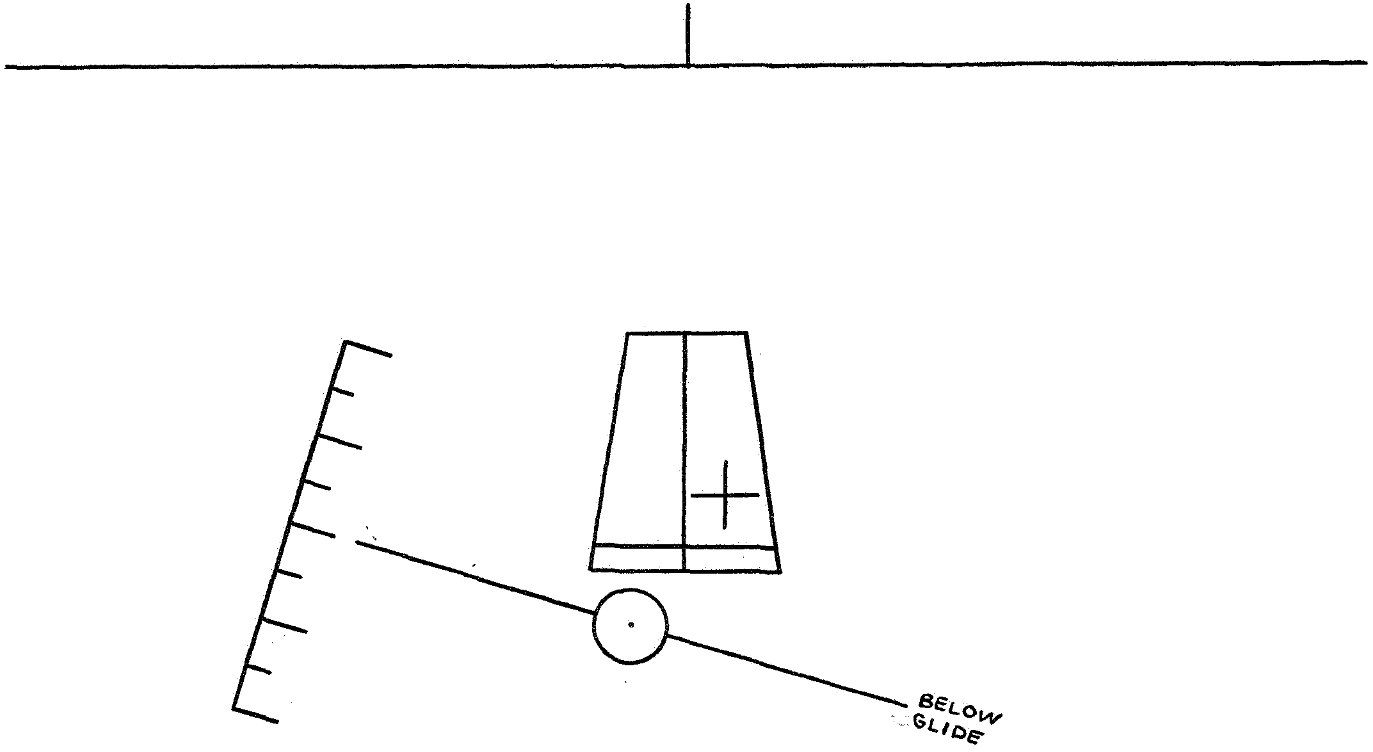

Figure 7-1. The aircraft is below the glide slope and left of the runway centerline. The director cross commands pitch up and a right turn. The aircraft is responding. Speed is correct for this angle of attack.

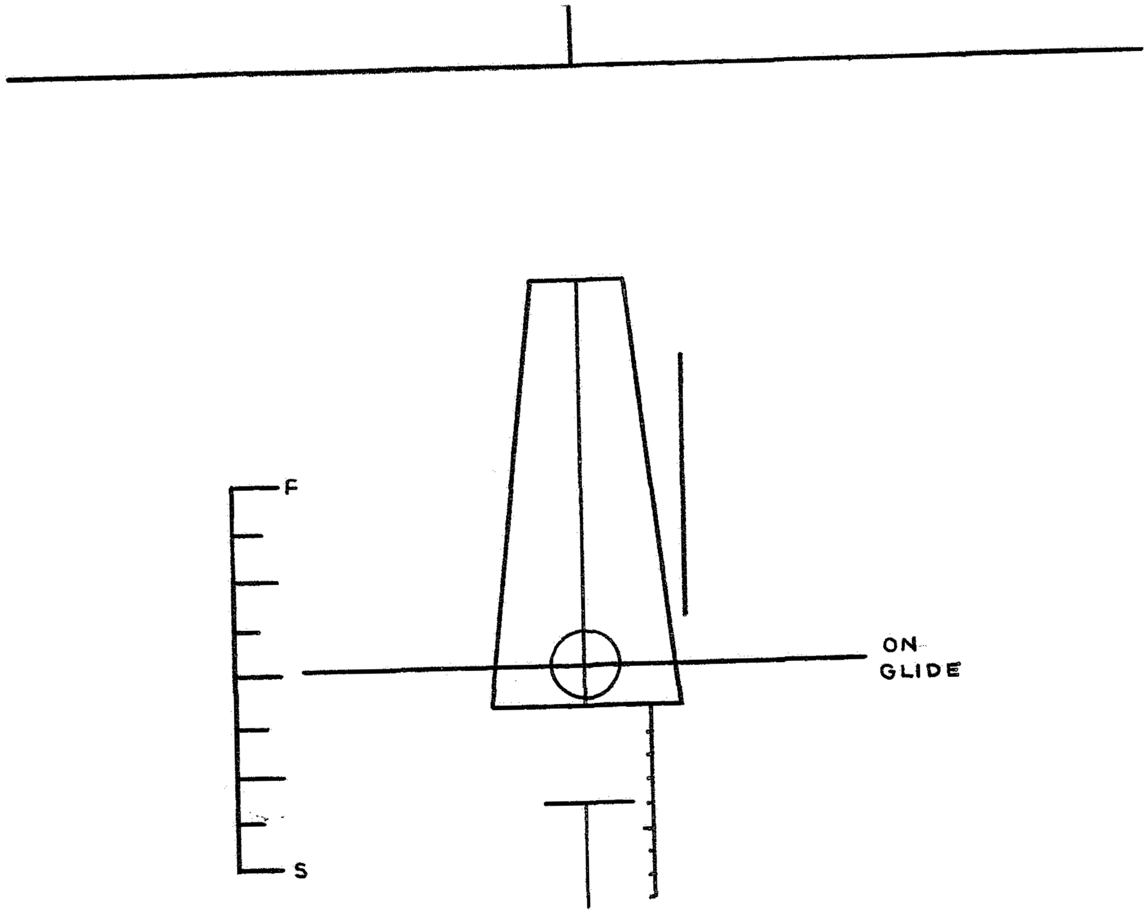

Figure 7-2. The aircraft is on the glide slope and localizer, flying level at an appropriate airspeed for the given angle of attack.

the glide slope, the director cross would begin to move down, indicating that the aircraft was starting to over-fly the field. The pilot would reduce throttle and change the angle of attack of the aircraft to capture the director cross with the aircraft symbol. When the aircraft symbol was fixed over the director cross, the aircraft would have achieved the appropriate glide angle. Maintenance of the aircraft symbol over the director cross would assure maintaining the glide angle. Deviation of the aircraft symbol from the director cross would mean deviation from the glide slope, localizer or both.

Sink rate, or rather inappropriate sink rate, would be signaled by the director cross. If the sink rate were too great, the aircraft would go below the glide slope and the director cross would move up. If the sink rate were too small the aircraft would go above the glide slope and the director cross would move down.

The speed scale appears to the left of the aircraft symbol. The speed scale is a fast-slow indicator. It presents an indication of airspeed which is stabilized with accelerometers and which also is a function of angle of attack. This presentation is simply the safe-flight instrument reoriented. It is placed where it is because this placement allows for a maximum use of display gain. It could be placed alternately at one side of or above the horizon line. However, this would require the pilot to move his eyes up to check airspeed.

Roll attitude would be indicated by the relation between the aircraft symbol and the horizon line. The aircraft symbol is quite wide, thus facilitating the detection of deviation from the horizontal. In addition, display gain would tend to emphasize the magnitude of the roll. Finally, any tendency on the part of the aircraft to roll results in departure of the director cross from the aircraft symbol. Thus if the aircraft rolls to a left wing down attitude, the right wing of the aircraft comes closer to the horizon and the director cross is seen as moving to the right since the aircraft actually turns to the left. In addition to this the pilot would have the displayed information confirmed by the tendency of the aircraft to yaw to the right, since the turn would not be coordinated with rudder.

Aircraft heading would be adjusted to maintain the aircraft course in relation to the runway center line. If the aircraft were on the right course the director cross would be centered in the aircraft symbol, over the runway aiming point. Any misadjustment of the aircraft controls would cause the director cross to move in a direction which would indicate the nature of the maneuver required to correct for that misadjustment. Similarly, the existence of a crosswind would tend to move the aircraft out of alignment and the deviation cross would indicate the nature and degree of the necessary correction. In this case the pilot would hold the heading necessary to maintain the course to the runway. In such a situation, where the aircraft course differed from the aircraft heading the crab bar would be to the side of the runway, showing the actual heading of the aircraft in relation to the runway heading. The director cross would show on course.

Information on which to base initiation of the flare maneuver is displayed below the runway symbol. The scale shows ground-based radar altimetry data which is radioed to the aircraft and put on the display by the computer. The scale is marked off in 10-foot graduations. The display symbol is a "T" which comes up from below the aircraft symbol. This symbol appears just prior to the time for flare initiation. It continues to move up, as the aircraft settles toward the runway. The cross bar of the "T" should touch the aircraft symbol as the main gear of the aircraft touches down.

Elimination of the crab angle would be facilitated by the crab bar. The crab bar would be off to one side of the runway center line, indicating the direction of crab. The task of the pilot in performing the decrab maneuver would be to bring this bar into coincidence with the runway center line as the main gear touched down. It is assumed that the crab bar would be driven by the computer from information supplied by a device like microvision.

The suggested display, with the elements so far described, conforms, or can conform to all of the requirements which were laid down for a display except one-the provision of redundant, but independent, information for cross-check purposes. The five items of most importance for cross-check are:

1. Final approach initiation;
2. Maintenance of the approach glide;
3. Lateral deviation from proper course;
4. Flare initiation;
5. Roll-out.

Two of these items are already taken care of. If the director cross should be inoperative, the matter of lateral deviation from course could be handled if the aircraft ground track symbol and runway were both operative. The crab bar could show deviation from the runway center line for roll-out.

As regards the other three, some addition to the display is required. One of the things that the pilots who participated in this study liked about the Spectocom display was an indication of range to runway. Similarly, in a previous study (3) pilots indicated a desire for information about distance to threshold.

DME distance to threshold and ground-based radar altimetry may be used to supply independent redundant information for the other three functions. Consider first the point for initiation of the final approach. If the aircraft is to fly a given glide angle to the aiming point of the runway of intent, there is, for a given altitude, one distance from the runway at which the final approach should be initiated. DME distance could be fed into and monitored by a computer until that distance was reached. At that time, or slightly before, the computer could trigger a display which instructed the pilot to initiate the final approach. This information could be displayed to the right of the aircraft ground track symbol. As this display appeared the director cross should start to move down toward the runway aiming point.

As regards maintenance of the given glide angle one would use a display based on the ratio of distance to altitude.[8] This ratio is the cotangent of the actual glide angle. See Figure 8. These items of information could be fed directly into the computer on a pre-determined sampling basis. The computer would compute the cotangent of the glide angle which the aircraft was flying. See Figure 9. The desired cotangent would be subtracted from the actual cotangent and the difference compared with an <u>allowable error</u>. If the difference exceeded the absolute magnitude of the allowable error the computer would trigger a display of "ABOVE GLIDE" or "BELOW GLIDE", depending on the sign of the original difference. A positive difference would indicate that the aircraft was below the glide slope. A negative difference would indicate that the aircraft was above the glide slope. If the obtained difference were within the error limit, the display would read "ON GLIDE."

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[8] The original impetus for this idea is due to Captain Carl W. Vietor, American Airlines, Los Angeles.

α = ANGLE OF AIRCRAFT AT A WITH AIMING POINT.

β = GLIDE SLOPE ANGLE.

γ = ANGLE OF AIRCRAFT AT B WITH AIMING POINT

$\alpha < \beta, \therefore \cot \alpha > \cot \beta \cdot \cot \alpha - \cot \beta$ = POSITIVE DEVIATION

$\gamma > \beta, \therefore \cot \gamma < \cot \beta \cdot \cot \gamma - \cot \beta$ = NEGATIVE DEVIATION

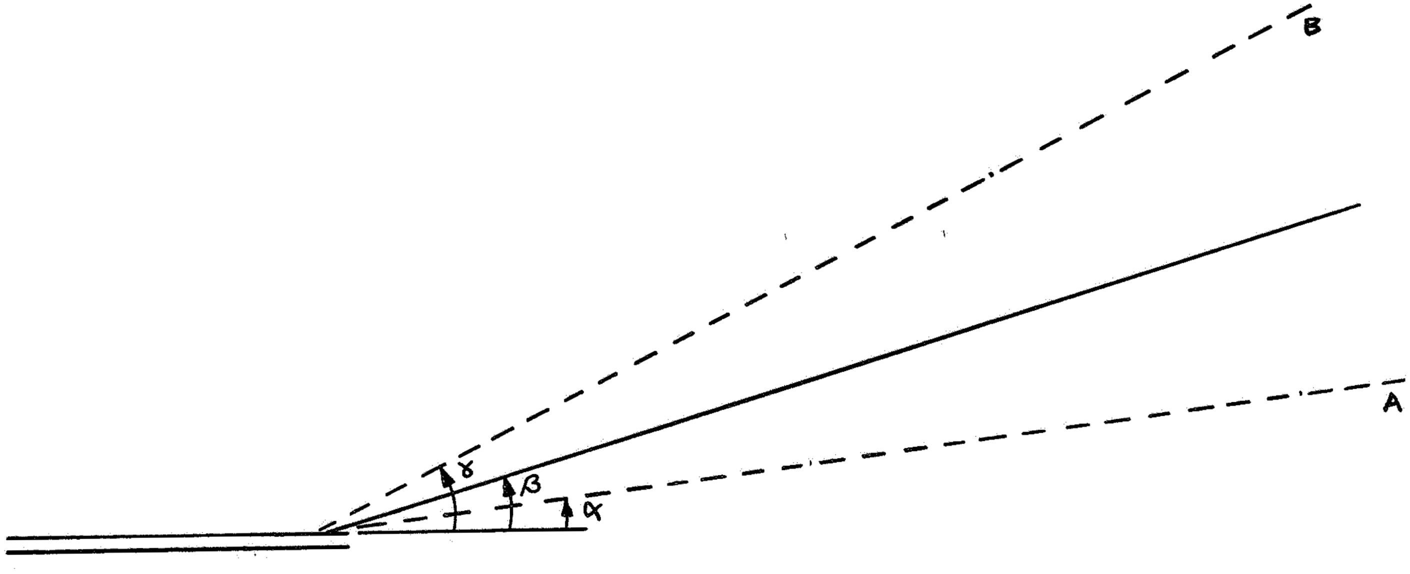

Figure 8. Geometry of the distance/altitude display.

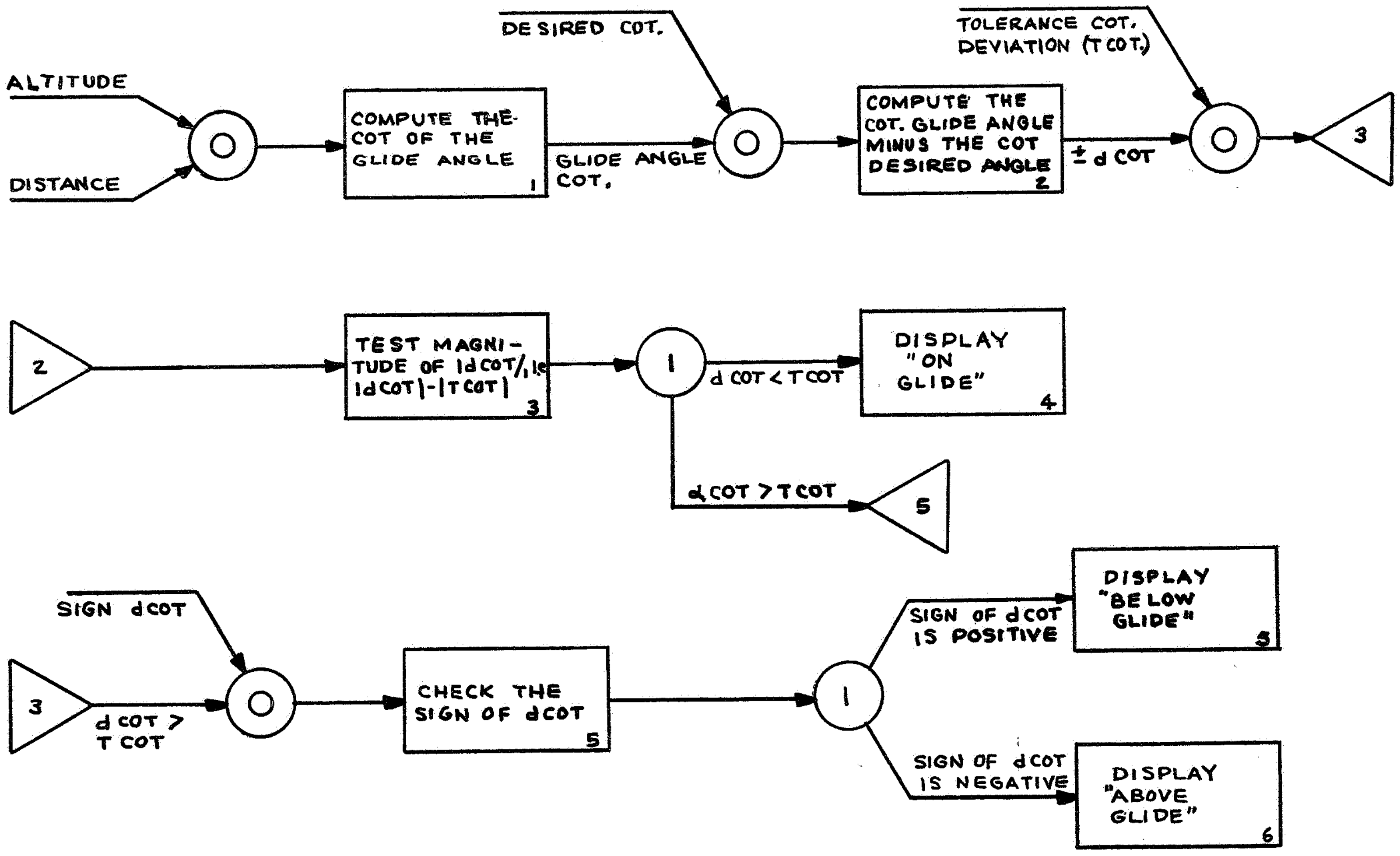

Figure 9. Flow diagram of information generation for approach slope display based on distance/altitude ratio.

◎ DENOTES "AND"

① DENOTES "OR"

Note that if the glide slope information should go out this cotangent deviation could be used to drive the display. However, it should be the responsibility of the pilot to cause the display to be driven by the cotangent deviation. The reason is that the use of the cotangent deviation to drive the deviation cross deprives the pilot of his redundant but independent check. The pilot must be aware that the two displays are based on the same information.

The point to initiate flare would be handled by considering altitude in relation to distance to go. See Figures 10, 10-1 and 10-2. If the altitude and distance were correct, for the given aircraft, as determined by a sequence of computations, the computer would trigger the display "FLARE." If the altitude and distance were not correct the computer would compute the distance (altitude) when the altitude (distance) would be right. It would then refer to aircraft aerodynamic information to determine whether the aircraft could be safely landed. If the aircraft could be safely landed the computer would trigger the display "FLARE" at the appropriate time. If the aircraft could not be safely landed, the computer would trigger the display "GO-AROUND."

While the present display concept was developed for conditions of reduced visibility, specifically for Category II situations, we feel that it is compatible with Category III landing requirements.

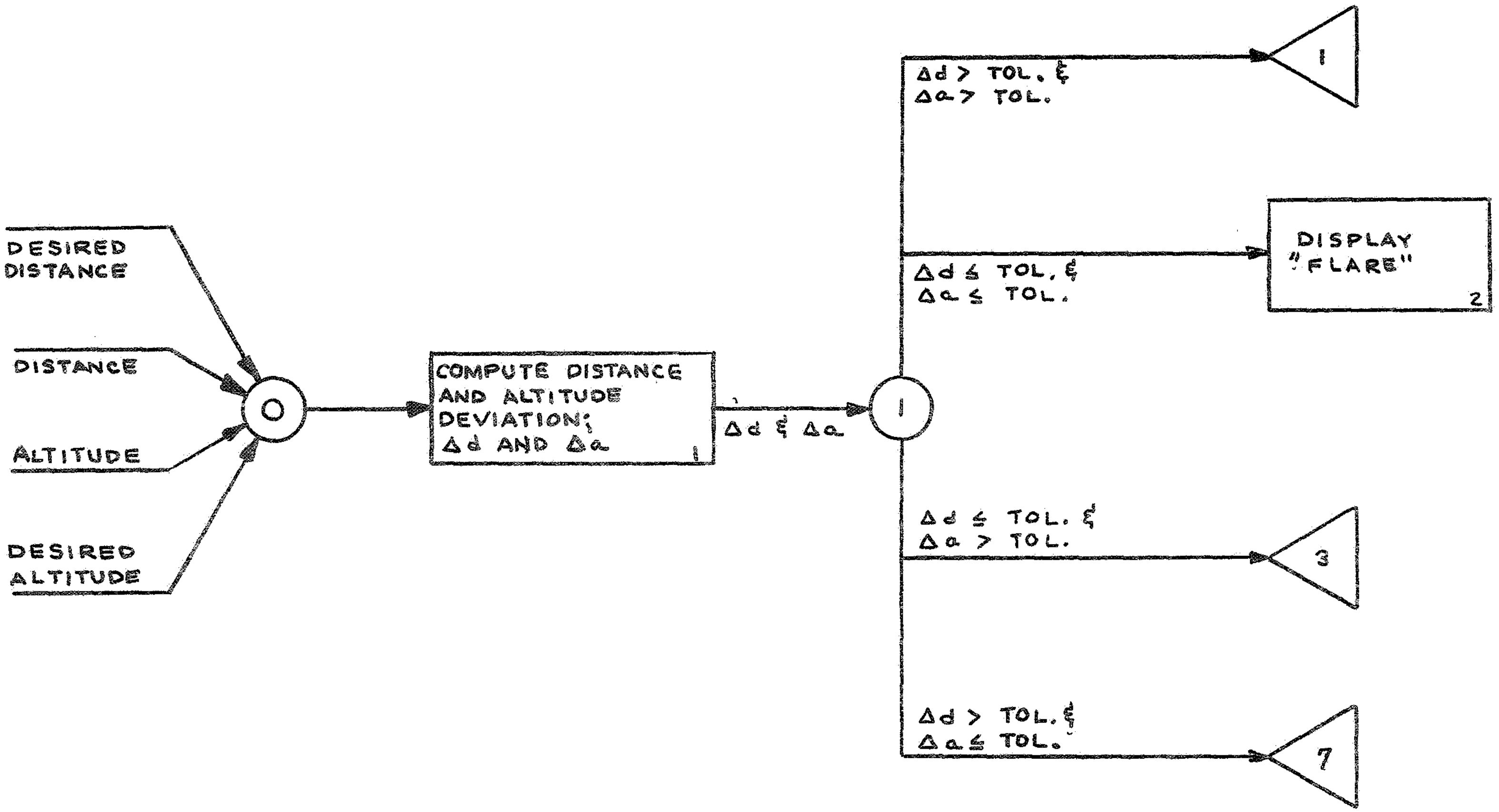

Figure 10. Flow diagram of information generation to indicate "flare" or "go-around."

Ⓞ DENOTES "AND"
Ⓘ DENOTES "OR"

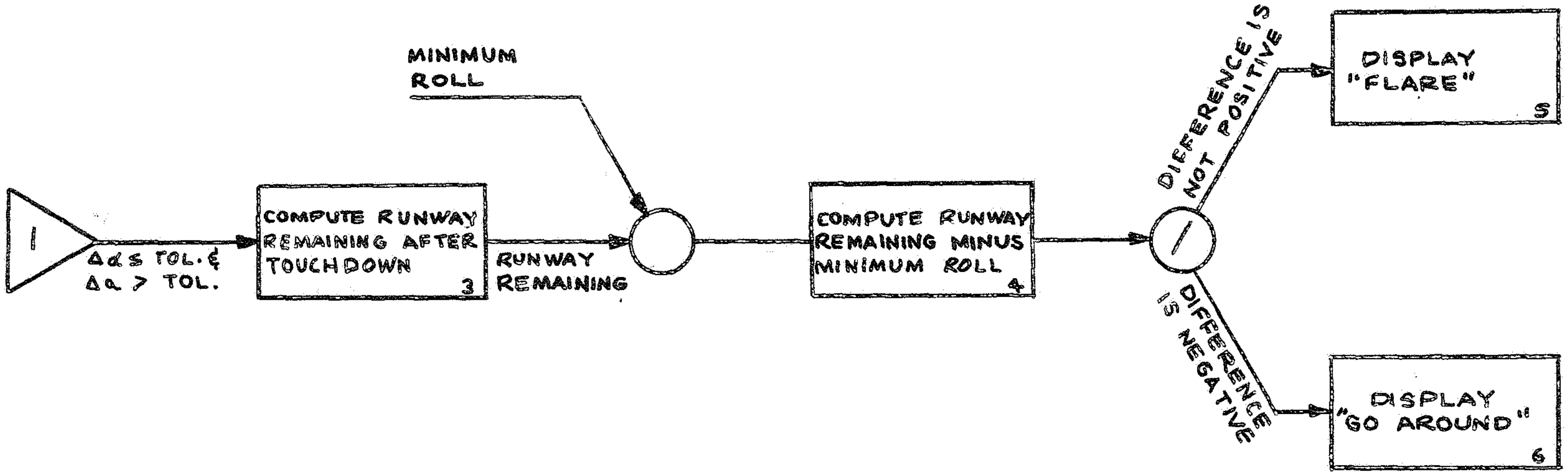

Figure 10-1. Flow diagram of information generation to indicate "flare" or "go-around."

Ⓞ DENOTES "AND"

⊘ DENOTES "OR"

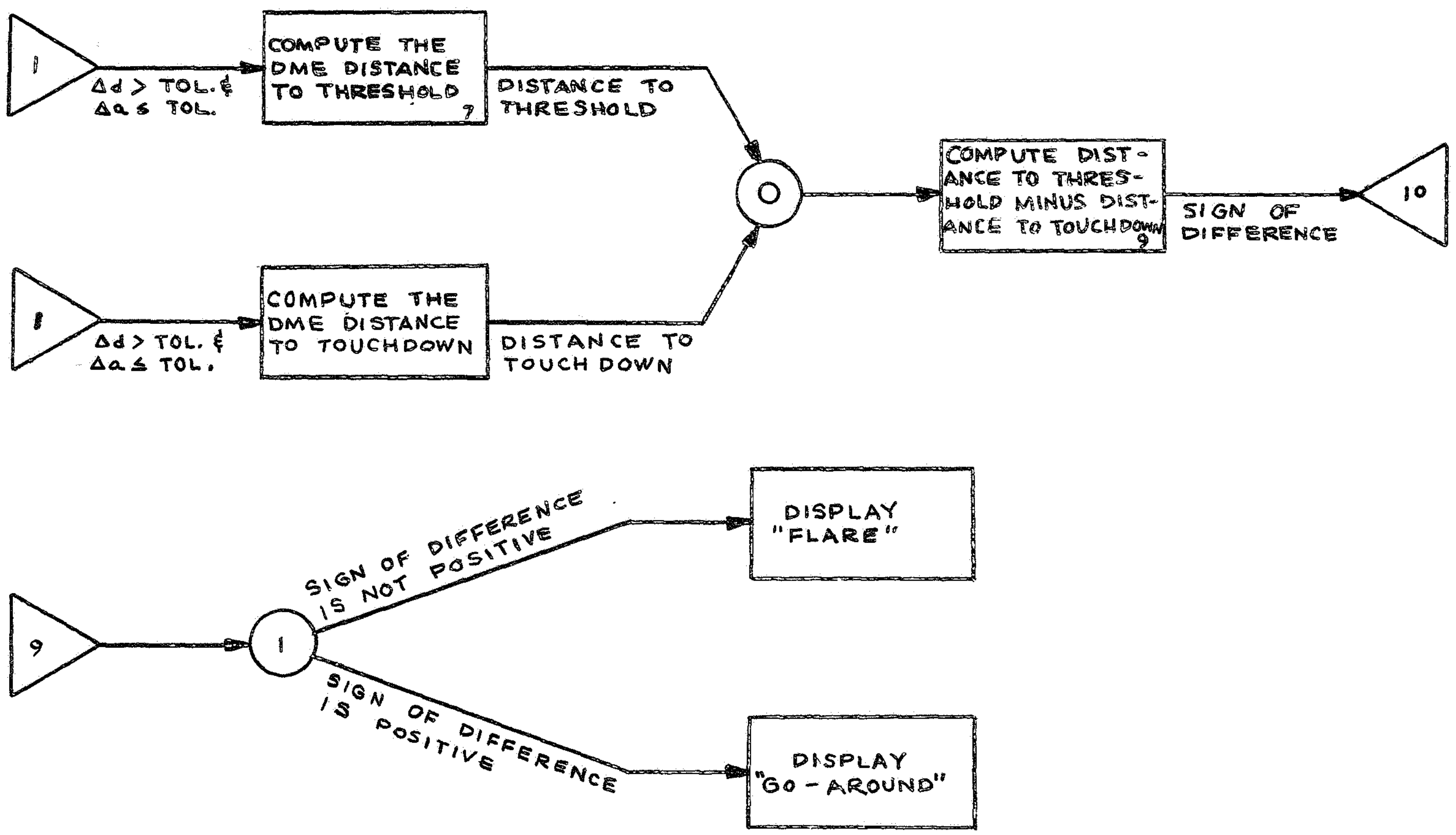

Figure 10-2. Flow diagram of information generation to indicate "flare" or "go-around."

EXPERIMENTAL PROGRAM

Introduction

The purpose of this section is to describe an experimental program for the development of displays for landing aircraft in conditions of reduced ceiling and visibility. The task analysis of the third section provides part of the content for the experimental program. Section I, provides the remainder.

Section I listed seven areas which impinge upon the problem of landing under low minimums:

1. The weather;

2. The aircraft itself--landing techniques;

3. Pilots and piloting technique;

4. Ground facilities and equipment;

5. Cockpit instrumentation;

6. Sociopsychological-legal considerations;

7. Man-machine interface.

The problem of weather should be introduced as a matter of experimental program phasing. The early phases of the program would consider reduced visibility weather in fog, with no wind problems. However, it is recognized that there are weather conditions which reduce visibility to zero which are accompanied by strong winds, i.e., rain or snow. It is therefore desirable to determine the usefulness of the display in crosswinds when visibility is zero. During the latter phases of the program one could introduce crosswind and/or headwinds which would require great pilot skill. At a still later point in the program it may be desirable to introduce shear wind effects.

As regards the aircraft and landing technique, we are concerned with the need for a flare maneuver on landing. It is suggested that aircraft type be introduced early in the program and maintained throughout. Representative aircraft types are the Douglas DC-7, the Convair 880 and the Boeing 707 which would give a range of flare requirements for landing.

Pilots and piloting technique are really two variables. As regards pilots, this is a question of sampling. For the experiments, airline pilots should be used. However, for preliminary runs to prove out procedures and techniques, it will be satisfactory to use research pilots. Piloting techniques should be established for each aircraft chosen and not varied during the experiment. The range of acceptable landing conditions for each aircraft types should be determined from current standard operating procedures. Any trial on which one or more of these ranges was exceeded should not be accepted.

The studies should be conducted with two persons--pilot and copilot--in the cockpit. The division of labor should be patterned after that of the current ILS landing task. The pilot will land the aircraft. He will use the display being tested. The copilot supports the pilot. He monitors all of the flight information presented by the instruments. He informs the pilot of any occurrence which would necessitate aborting the landing. He monitors altitude to assure avoiding obstacles on the way in. He calls out altitude at stated intervals. He watches for the runway and informs the pilot when he has it in sight.

A final consideration, which may be difficult to achieve, is that the pilots who serve in the studies should be tired. They should have flown at least four hours before flying the experimental trials. The use of well-rested pilots will not provide a realistic test of the display adequacy, since well-rested, highly-experienced pilots can probably do an acceptable job under most situations.

Ground facilities and equipment should be assumed to be adequate to provide valid and reliable information for the displays to be tested. If this is done conscientiously, the results of the study can contribute to requirements for ground equipment.

Cockpit instrumentation should be adequate to that required for initiating the final approach and subsequent phases of the landing, in relation to the division of labor between the pilot and copilot. In the early phases of the program malfunctions should not be simulated. In the middle phases malfunctions may be introduced and then one can develop requirements for support instrumentation. However, most of such requirements could most economically be developed through analytical procedures.

Sociopsychological-legal considerations should not enter into this program except as regards the choice of the subject population and the man-machine interface.

The man-machine interface is one of the main reasons for conducting the study, since the display mediates this interface. The assumption should be made that the landing will be accomplished manually, except for throttle control.

Experiments On Rate Aiding

The initial experiments should be designed to explore the relative value of a conventional pictorial or representative display and a rate-aided fly-to director display to facilitate the landing task.

Since the display will be a compensatory type, it is reasonable to think of incorporating simple displacement gain as regards the fast-slow airspeed indicator, the crab bar and the wing dip of the aircraft symbol.

Finally, one should also consider the piloting technique demanded by the propeller vs. the jet-driven aircraft. Anticipatory displays may be much more important for jet aircraft because of the considerable lag in response to increased throttle.

The landing approach to be studied should be a straight-in approach with no vectoring. All decisions about the initiation of phases of the landing would be at pilot discretion in response to displayed information. The trial should be started just prior to capturing the localizer and should continue to the point of flare.

This would give an experiment with the following independent variables:

1. Aircraft type--the Douglas DC-7, the Convair 880, and the Boeing 707.
2. Rate aiding, vertical--d, $d + d'$, $d + d''$, $d + d' + d''$
3. Rate aiding, lateral--di, $di + di'$, $di + di''$, $di + di' + di''$
4. Display gain--1_0, 1_1, 1_2.

Variables 2 and 3 would apply only to the fly-to director. Variable 4 would apply only to the airspeed indication, the crab bar and the aircraft symbol.

This is a factorial experiment with 144 cells in the design matrix. Two complete replications of the design matrix would provide an error term with 96 degrees of freedom. There would be 288 data items for analysis.

Sources of Variance	d.f.	d.f. (cum)
Aircraft	2	2
Vertical rate aiding	3	5
Lateral rate aiding	3	8
Display gain	2	10
AV[9]	6	16
AL	6	22
AD	4	26
VL	9	35
VD	6	41
LD	6	47
AVL	18	65
AVD	12	77
ALD	12	89
VLD	18	107
AVLD	36	143
Error	144	287
Grand mean	1	288

Performance measures to be taken include:

1. Deviation from optimum point for initiating the final approach, distance, altitude and lateral position;
2. Root-mean-square deviation from optimal approach path, vertical and lateral deviation separately;
3. Frequency of aborted trials.

---

[9] AV denotes the interaction between Aircraft and Vertical rate aiding. In the present experiment there are six two-way, four three-way and one four-way interaction. The degrees of freedom for each interaction term is the product of the degrees of freedom of its components.

If the study included the flare and touchdown then one could include:

4. Touchdown distance from threshold;

5. Lateral separation from center line at threshold and at touchdown.

This experiment would provide information about:

1. The value of rate aiding in the zero-zero landing situation;

2. The nature of most efficient rate aiding to maintain both vertical and lateral position on the approach path;

3. The value of display gain;

4. The role of rate aiding and display gain as a function of approach path control for different aircraft;

5. The significance of all interaction terms--which information may be used later to design more efficient and less expensive experiments.

Experiments With Crosswinds

The foregoing has been concerned with studies of displays without winds. However, there are situations in which aircraft must land in an adverse crosswind. Fuel shortages constitute one such situation. With the supersonic transport just over the operational horizon, this situation is likely to occur more frequently.

An important aspect of crosswinds is gusting. It will be required to program steady crosswinds and also crosswinds with various magnitudes of gusting. Wind consideration introduces three new variables into the evaluation of displays:

1. Wind direction relative to landing direction;

2. Wind velocity;

3. Wind gusting.

Wind direction and velocity should be included in the same experimental design. It would also be desirable to include gusting in the same design. This would require that a realistic limit be placed on the wind velocity variable. Each trial should continue through the roll-out phase of landing.

The previous set of studies without wind would have provided information about the best rate aiding and display gain values to use. These experiments would assume optimal values of these factors. This would leave an experiment with four variables:

1. Aircraft type--three--Douglas DC-7, Convair 880, and Boeing 707;
2. Wind direction--six values, 0°, 30°, 60°, 90°, 120°, 150°;
3. Wind velocity--four values;
4. Wind gusting--four values.

This is a factorial experiment with 288 cells in the design matrix. With two complete replications of the design matrix, there would be a total of 576 data items for analysis.

Performance measures which would be collected include:

1. Deviation from optimal point for initiating the final approach, distance, altitude and lateral position;
2. Root-mean-square deviation from optimal approach path, vertical and lateral deviation, separately;
3. Deviation from optimal point for flare initiation, distance from threshold and altitude, separately;
4. Distance from threshold at touchdown;
5. Lateral deviation from center line at touchdown;
6. Root-mean-square deviation from a straight path during roll-out;
7. Requirement for emergency measures to halt roll-out, e.g., emergency use of brakes, etc.,
8. Frequency of aborted trials.

This experiment is rather extensive in scope. The requirement is for 576 acceptable trials. This study can be fractionated into manageable portions by assigning a priority to the variables included. For example, it may be argued that the type of aircraft (landing technique) was a variable which did not need immediate investigation.

With the above assumption one could run two studies. The first would consider only the straight-in approach and the Boeing 707 aircraft. The experimental matrix for this study would include 96 cells. Two replications, to provide an adequate error term, would require 192 trials (landings). The analysis of these data would be:

Source of Variance	d.f.	d.f. (cum)
Wind direction	5	5
Wind velocity	3	8
Wind gusting	3	11
DV	15	26
DG	15	41
VG	9	50
DVG	45	95
Error term	96	191
Grand mean	1	192

The second study could bring in the variable of aircraft (landing technique). For this study two values of each of the wind variables would be chosen, to provide a range of values to insure the action of winds in the experiment. The experiment would have a design matrix with 24 cells. Three replications would give an adequate error term. This would require 72 trials (landings). The analysis would be:

Source of Variance	d.f.	d.f. (cum)
Aircraft	2	2
Direction	1	3
Velocity	1	4
Gusting	1	5
AD	2	7
AV	2	9
AG	2	11
DV	1	12
DG	1	13
VG	1	14
ADV	2	16
ADG	2	18
AVG	2	20
DVG	1	21
ADVG	2	23
Error term	48	71
Grand mean	1	72

Study of the Transition Period

The transition period assumes considerable importance because of the step-wise approach which is being taken to arrive at a Category III weather landing capability, and also because of the socio-psychological problems involved. If we are to go step-wise from a 200 foot and one-half mile criterion to a 100 foot and one-fourth mile criterion and finally to a zero-zero weather capability, the display must facilitate the landing by shortening the transition period. The problem is to develop a technique for measuring the transition period.

Measurement of the transition period requires a re-orientation of attitude toward this phenomena. Instead of considering a time period, consider a threshold for accepting the conditions of the landing as satisfactory. What we wish to create in the laboratory is this threshold of acceptance. If we can do this we may be able to manipulate the transition from instrument to contact flying, during aircraft landing.

Thinking in terms of a threshold of acceptance, we may use the method of limits to determine this threshold. The method of limits requires that one present a regular sequence of graded stimulus situations to the subject and observe his reaction. In the present context the stimulus situation would be composed of a specified:

1. Aircraft (landing technique);
2. Display for landing;
3. Pilot-copilot landing task split;
4. Standard approach pattern;
5. Standard ground facilities.

The stimulus situation would be graded as regards the simulated ceiling, from say 300 feet to zero feet, in 25-foot steps. This would give a range of 13 graded steps. Landings would be flown as for the other experiments. Besides collecting the usual data, one would note whether the pilot elected to go-around on a particular landing. Through use of this method, one could achieve for each aircraft-display-approach pattern-ground facility combination a sequence of go-around or not go-around information, e.g.,

Ceiling	Go-around
300	No
275	No
250	No
225	No
200	No
175	No
150	No
125	Yes
100	No
75	Yes
50	Yes
25	Yes
0	Yes

By establishing a scoring convention one could determine the ceiling below which a go-around would be expected to occur. This ceiling would then be accepted as the threshold for that aircraft-display-approach pattern-ground facility context.

There are several problems associated with the development of the above technique:

1. Establishing a simulation situation to vary the ceiling;

2. Validation of the simulation situation;

3. Determining the reliability (consistency) of the method;

4. Standardization.

Simulating the landing involves the provision of visual, kinesthetic and motion cues of landing in the context of a reduced ceiling. It is suggested that Ames Research Center has all of these already, except the displays and the reduced ceiling context. There exists at Ames a landing simulator which provides visual cues associated with the airport, and kinesthetic and motion cues of flight. The displays would have to be created in any case, so this presents no new problem.

It is suggested that the variable reduced ceiling could be simulated by attaching to the exterior of the cockpit simulator sets of rollers on which was wound a plastic material which was for the most part opague to light and which looked like cloud. At some portion, the cloud appearance would become less opaque and finally become clear. For a standardized approach, adjustment of the amount of opaque material would allow one to vary the ceiling, exactly for purposes of experimentation. With the motion cues provided by the simulator, it is felt that movement of the cloud-like opaque material would provide a realistic landing situation.

Validation of the simulation situation could be done by asking pilots who had experienced the transition in real life situations to fly the simulator. They would then be asked to rate the similarity of their reactions and attitudes in the two situations, as regards:

1. Flying in fog;

2. Realistic transition;

3. Aircraft handling;

4. Loss of laboratory context (overall realism).

Determination of the reliability of the simulation would be the next step after (and if) the method passed the validation test. This could be combined with the standardization runs. Reliability involves determining the consistency with which different pilots and groups of pilots performed in the simulation situation for a given aircraft-display-approach pattern-ground facility context. We are here concerned with the variability of performance of individuals and of the groups.

Standardization is concerned with mean values of performance figures, and the standard error of these means, for pilots with a given experiential background and different landing situations. Given the validity of the method and the reliability and standardization data, one could then proceed to design studies to evaluate displays as regards their usefulness to reduce the threshold of acceptance for landing in reduced minimums.

ABSTRACT

The report presents an analytical and empirical study of the information requirements and the nature of a display for landing in reduced weather minima.

The VFR landing task is analyzed to determine information requirements and to determine the manner in which information is used. It was found useful to construe the information available to the pilot as analogous to a compensatory display.

An acceptance study was made to determine pilot preferences for information display. The results indicate that pilots prefer a windscreen display which presents a pictorial representation of the landing situation and the relationship between the aircraft and the glide slope and localizer.

A display concept is presented which conforms to these information requirements and is based on the pilot preferences determined in this and previous studies. A program of research for evaluating the usefulness of displays is outlined.

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APPENDIX I
DATA COLLECTION FORM

Initial ______________
Date ________________
Time _______

DISPLAY PREFERENCE RECORD FORM

1. Airline ____
2. Your usual equipment ________________________________
3. Your usual route(s) __________________________________
   ____
   (Specify major terminals, e.g., LAX, DCA, etc.)
4. Usual Flight Position: Captain _____ 1st Officer ________
5. Additional Ground Positions: ______________________
   (e.g., Safety Chairman)
6. Approximate Total Airline Flying Hours: Jet ____Prop ____
7. Age __________ 8. Years Pilot Experience ______________
9. Approximate total military flying hours ______________
10. Principal military aircraft type: Transport ____________
    Bomber ______________
    Fighter _____________
11. Approach situation Indicator _________________________
    ____
12. Pair No. __________
    Time __________
    Preference: (A) _____, (B) _____, None _____
    Reason for Preference:

13. Pair No. __________

Preference: (C) _____, (A) _____, None _____

Reason for Preference:

14. Pair No. __________

Preference: (C) _____, (B) _____, None _____

Reason for Preference:

15. Pair No. __________

Preference: (C) _____, (B) _____, None _____

Reason for Preference:

16. Pair No. ____________

Preference: (A) ______, (B) ______, None ______

Reason for Preference:

17. Pair No. ____________

Preference: (A) ______, (C) ______, None ______

Reason for Preference:

18. Pair No. ____________

Preference: (A) ______, (B) ______, None ______

Reason for Preference:

19. Pair No. __________

Preference: (B) _____, (C) _____, None _____

Reason for Preference:

20. Pair No. __________

Preference: (A) _____, (C) _____, None _____

Reason for Preference:

21. Pair No. __________

Preference: (A) _____, (B) _____, None _____

Reason for Preference:

22. Pair No. ____________

Preference: (A) ______, (B) ______, None ______

Reason for Preference:

23. Pair No. ____________

Preference: (B) ______, (C) ______, None ______

Reason for Preference:

24. Pair No. ____________

Preference: (A) ______, (B) ______, None ______

Reason for Preference:

25. Pair No. __________

Preference: (A) _____, (C) _____, None _____

Reason for Preference:

26. Pair No. __________

Preference: (B) _____, (C) _____, None _____

Reason for Preference:

27. Pair No. __________

Preference: (A) _____, (D) _____, None _____

Reason for Preference:

28. Pair No. ________

Preference: (B) ____, (D) ____, None ____

Reason for Preference:

29. Pair No. ________

Preference: (C) ____, (D) ____, None ____

Reason for Preference:

Time ______

Time ________

30. When making a VFR approach during the day time do you use the so-called spot of no movement to insure making the runway: (Yes) _____, (No) _____.

What (other) cues do you use?

31. When making an IFR approach during the day time, what does the pilot attend to during the period of transition from instruments to contact flying?

Time ________

32. During normal operations, which of the engine operation instruments do you find most useful?

33. Do you use these instruments routinely to infer information about engine thrust which is not displayed?

YES ( ). NO ( ).

If yes, how do you infer thrust?

34. If you had a display of per cent of engine thrust, what other engine operation information would you need?

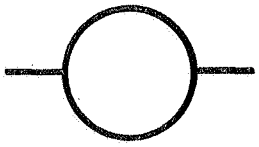
APPENDIX II
THE DISPLAYS USED IN THE ACCEPTANCE STUDY

Situation Displays

A. The Spectocom display.- The Spectocom system produces a display fixed relative to the aircraft, except for the horizon line and the parallel lines below the director. The angular spread of the display is about 7°.

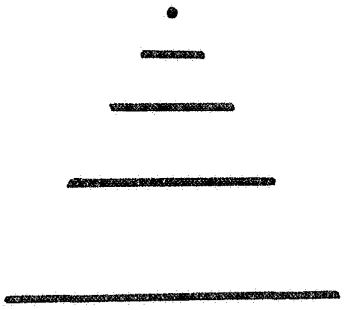
The horizon line, which is a straight transverse line with a break in the center, is gyrostabilized to define a horizontal plane. It and the parallel lines below the director are the only stabilized elements in the display, and it is stabilized only in pitch and roll; its center point always remains in the plane of symmetry of the aircraft (i.e., the xz plane).

The attitude image:



defines a convenient reference line in the aircraft and has wings parallel to the aircraft transverse axis. It is a fixed image in the display and its relationship to the horizon line gives an indication of angle of pitch and roll. The relationship between the attitude image and the aircraft flight path must vary with angle of attack (i.e., with airspeed and weight). However, in the absence of a flight path marker, it is presumed that the attitude image would be related to a reference line which is in close proximity to the flight path at normal approach speeds.

The director image system:



consists of a pyramid of horizontal lines, logarithmically spaced, with a dot at its apex which works in conjunction with the attitude image as a flight director. The pyramid extends or contracts vertically or leans to either side to place the director dot where it is required to be.

A scale of airspeed is provided along the top of the display and a scale of altitude runs vertically up the left hand side. A circular segment around the attitude image gives an indication of range from the runway, the scale being such that a quadrant of the circle represents one nautical mile.

For phases of flight other than the landing approach, the airspeed, altitude and range symbols are switched off and the display operates in exactly the same way as a conventional panel mounted flight director instrument. Having no heading marker or flight path marker, its only advantages over the conventional instrument are its greater size and lack of parallax effects.

B. Collins 329B-7A flight director indicator.- This panel mounted instrument displays ACFT attitude and flight director information in a three-dimensional forward view display.

The aircraft symbol is a fixed reference point.

The command bar is in the shape of a shallow inverted "V" which is matched against the delta-shaped airplane symbol in pitch and roll. The command bar moves up and down to command a change of pitch and moves clockwise and counterclockwise to command a change of roll attitude.

The command bar is servo-driven with separate inputs for pitch and roll. The outputs of the two servos are combined mechanically within the instrument to provide an integrated pitch and roll command on the command bar.

Pitch attitude is indicated by the moving tape relative to the fixed aircraft symbol.

Bank angle is displayed by a pointer read against a fixed scale and by the rotation of the tape with respect to the aircraft symbol. The roll attitude display has 360 degrees of freedom. Both roll and pitch attitude displays are motor-driven servo mechanisms.

The pitch command selector knob provides preselection of a desired pitch attitude for climb or descent. The pitch scale, against which the pitch command knob is read, is calibrated between +15 degrees and -10 degrees of pitch on the expanded scale.

A pitch trim adjustment, located under the pitch command knob, alters the position of the pitch reference line (horizon line) on the tape with respect to the airplane symbol to permit aligning the display during initial installation, if required.

A triangular pointer at the left side of the instrument face displays aircraft deviation from the center of the glide-slope beam. Pointer deflection above the center reference mark indicates that the glide slope is above the aircraft. Two marks on either side of the center reference indicate half- and full-scale deflection. The glide-slope pointer is driven by a linear d-c meter mechanism and, when not in use, is deflected out of view at the top of the scale.

A pointer suggesting the runway in the lower part of the display indicates deviation from the localizer beam. Pointer deflection to the left indicates that the localizer beam is to the left of the aircraft. The localizer display is on an expanded scale to provide increased sensitivity for low approach. The localizer pointer is driven by a linear d-c meter mechanism.

The inclinometer, consisting of a weighted ball in a liquid-filled curved glass tube, provides slip or skid indications.

The detented four-position knob at the lower right of the indicator permits selection of the mode of operation of the Flight Director Computer. Exact operation of each mode is dependent on the Flight Director Computer. General descriptions of the different modes are as follows:

OFF - Flight Director Computer not in use; command bars deflected out of sight. Indicator is used as an attitude reference only.

HDG - Command bars provide lateral guidance to achieve and maintain a compass heading, as selected on the Course Indicator. Vertical guidance is from preselected pitch attitude.

V/L - Command bars provide lateral guidance to capture and track a VOR or localizer radio beam. Vertical guidance same as in HDG mode.

GS - Command bars provide lateral and vertical guidance to capture and track the localizer and glide-slope beams respectively. Glide slope and localizer pointers in view to monitor aircraft deviation from beams.

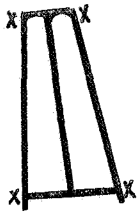
In actual use, this instrument functions as part of a package. This includes also a course selector and a flight computer.

C. The Type A display.- This display for landing in IFR conditions is designed for 1 to 1 compatibility with the outside world and is completely gyro-stabilized and collimated to appear at infinity. The display is produced by a reflection of images on a cathrode ray tube and by reflection of a backlighted engraved reticule. The reticule is used to produce the flight path and airspeed error images.

The horizon line with its track marker:

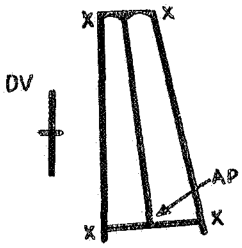
provides a horizontal reference and defines the direction (azimuth) which is ultimately desired to fly. The track marker is set by the pilot to correspond to the runway heading during the approach to landing.

The runway symbol which matches the real runway in position, size and shape.



The runway symbol will have two separate inputs to provide redundancy in the setting of the display. One input will be from runway heading, ILS and DME information and the other will be "microvision" or "Beaconvision" input from radio beacon on the ground adjacent to the runway. On the above runway, the four crosses represent one of the inputs while the runway outline and centerline is the result of the other input.

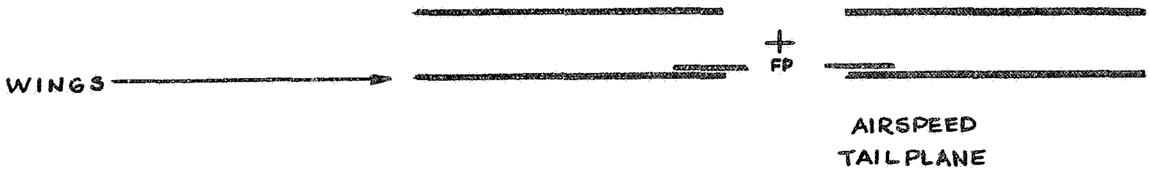
The deviation cross:



by its relationship with the runway aiming point, represents the present position of the aircraft relative to the ILS glidepath.

As the aircraft moves away from the ILS glidepath, the projection of the deviation cross moves away from the runway aiming point in the same direction. It always appears on the display at a point vertically below the track marker (runway heading) at an angle equal to the ILS glideslope angle. The object is to keep this deviation cross on the aiming point of the runway image.

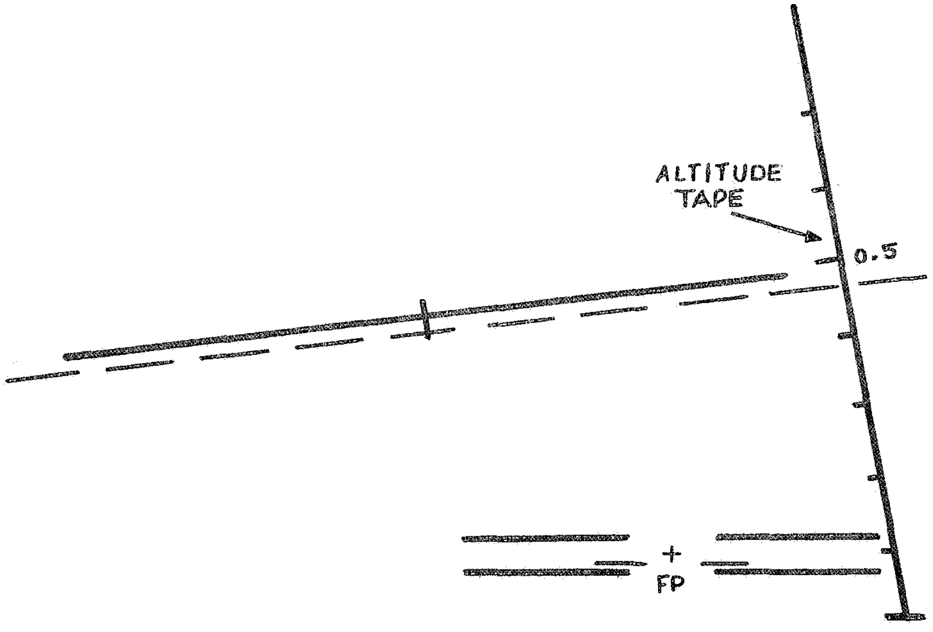
The flight path marker:



indicates the direction of the aircraft velocity vector relative to the ground, giving information as to where the aircraft would impact if allowed to remain in the present configuration and wind condition remaining unchanged. The wings of the FP marker are parallel to the aircraft wings and their position relative to the artificial horizon give roll information.

The flight path marker also gives airspeed information. The small tail plane symbol by its position relative to the aircraft wings gives variations from a desired airspeed set in by the pilot. If the tail plane is below the wings, the speed is too slow and if above the wings, the speed is too fast. The object is to keep the tail plane inside of the aircraft wings (parallel bars). The lateral gap between the inside of the wings is designed to match the aiming bar of the runway symbol at the distance of one nautical mile.

The altitude tape:



is presented along the side of the display and works in conjunction with the horizon line to indicate present altitude. By tracking a certain altitude with the flight path marker as the aircraft climbs or descends, asymptomatic blending to a desired altitude can be achieved.

D. The General Electric vertical display.- The display consists of a moving ground plane that is generated by a digital computer. It has a full six degrees of freedom with roll. Random textures for the ground plane have been developed that provide a good facsimile of the earth's surface texture. Information from the aircraft sensors and other data sources is still utilized, however, it is coded for the pilot in display on a single integrated information channel.

The Flight Path

The flight path as shown here is directional in texture as represented by the "T"s along its axis. Command speed markers are located to the right of the flight path.

Runway

The runway here shown in black represents the unique ground position identifier that can be located at any position in the XY coordinates. These black segments are 60 feet apart, and describe the center line of the runway. The black runway can be either a broad stripe or linearly segmented. Ground texture, texture of the runway and true perspective all serve to tie the runway to the ground plane.

Sky Plane

Sky plane texture is drawn by the same video signal that creates the ground plane. The sky plane is located at an appropriate virtual altitude above the vehicle. It does not respond to translation but will accurately respond to all rotational motion of the vehicle. The sky texture can take the form of clouds, stars, circles, etc. made up of minute blocks which the computer can describe. It is shown here as a plane of arrows in order to give directional information when in high pitch angle, the horizon and ground plane are not visible.

Index Marker and Angle of Attack

The index marker shown by the cross represents the center line of the aircraft. The short horizontal lines describe each 10 degrees of pitch. The circle represents angle of attack with respect to the index marker. As the aircraft climbs the horizon line will drop and the aircraft elevation angle can be read by noting the horizon with respect to the pitch markers. Roll angle can be determined by the center line index. These symbols are described on the face of the display tube as opposed to being located on the ground flank. The angle of attack marker will move as the aircraft moves.

Landing Mode

During landing mode the flight path is located at the intersection of the glide slope and localizer. Wind drift angle is shown by offset of the index marker from the flight path. The runway shown at the termination of the flight path is uniquely located in the X and Y coordinates.

Airspeed

A. Vertical tape airspeed indicator.- This instrument is an indicator displaying calibrated airspeed and command airspeed. Calibrated airspeed is shown by a moving tape, which is positioned with respect to a fixed lubber line. Commanded value of airspeed is shown by moving indicies and by command counter located below the respective displays. A slew switch below the counter, controls the command mechanism.

B. Readout airspeed indicator.- The indicated airspeed is displayed digitally on a simple readout window with a moving tape.

C. Conventional airspeed indicator.- Airspeed is displayed using a standard clock-type instrument. Indicated airspeed (in knots) is read by the position of a single pointer against a fixed circular scale.

Altitude

A. Vertical scale altitude indicator.- This indicator displays vernier and fine altitude, command altitude and barometric setting. Vernier and fine altitude are shown by moving tapes which are positioned with respect to a fixed lubber line. Command altitude is shown by moving indices superimposed over the moving tapes and the command value is displayed digitally by the command counter below the vernier scale.

B. Yellow line altitude indicator.- This instrument is basically a conventional dial type airspeed indicator. It is part of the pitot system and thus the information source is the same as the conventional instrument. The only difference is a modification to the 10,000 foot pointer. This pointer is replaced by a white index mark which is followed by a yellow line, so that the approximate position of the 10,000 foot indicator is immediately visible. The 1,000 foot pointer has been modified as regards shape, so that the white index of the 10,000 foot marker is not obscured. The modification consists in the insertion of an open circle at that portion of the 1,000 foot pointer which might over-lay the 10,000 foot index.

C. Standard 3-pointer altimeter.- Altitude is displayed on a conventional clock-type instrument with a fixed scale and three moving pointers: a short thin pointer, a somewhat larger wide arrow-type pointer, and a long thin pointer. The ten thousand foot pointer is the smallest pointer, and altitude in tens of thousands is obtained from the position along the scale; 1000 foot increments are displayed by the position of the short wide arrow-type pointer; the 100 foot readings are obtained from the position of the long thin pointer on the scale.

Rate of Climb

A. Standard rate of climb indicator.- This is a standard clock-type rate of climb indicator giving thousands of feet where the pointer is read against the circular scale to give climb or descent.

B. The modified standard clock-type rate of climb indicator.- This instrument displays the same range as the standard rate of climb indicator but it includes more graduation marks between zero and one thousand feet and between two and six thousand feet for both climb and descent. Also, this instrument has more numbers indicated on the scale.

C. Vertical fixed-tape, moving-pointer vertical speed indicator.- Vertical speed is read from a moving triangular index against a fixed scale. The index becomes fixed when the vertical rate exceeds 2000 or -3000 feet per minute. The vertical speed tape is then read against the same index and can vary up to 40,000 ft./min.

Attitude

A. Displacement bar, dive-climb and roll indicator.- Two parallel bars, one moving vertically up and down to present dive-climb information, and the other moving horizontally presenting yaw-roll information are read against fixed scales along the side and top of the instrument.

B. Hinged pointer, dive-climb and roll indicator.- Two pointers, one hinged on the side and one on the bottom rotate across fixed scales at the top and side respectively giving roll and climb-dive information.

Turn and Bank

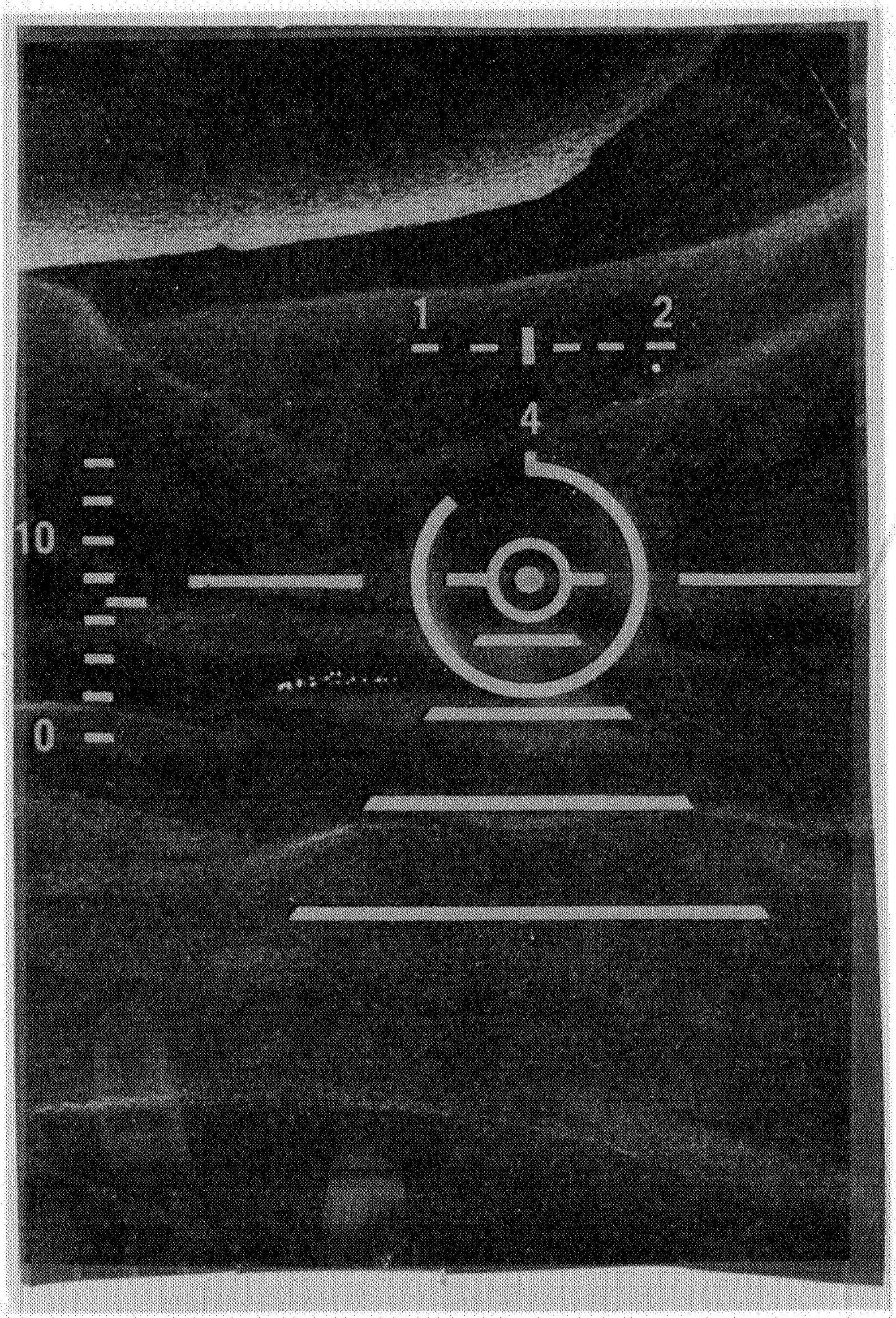
A. Standard turn and bank indicator.- This is a standard ball and pointer type of turn and bank indicated.

B. Modified turn and bank indicator.- The standard turn and bank indicator has been modified by putting markings across the top where the pointer is read.

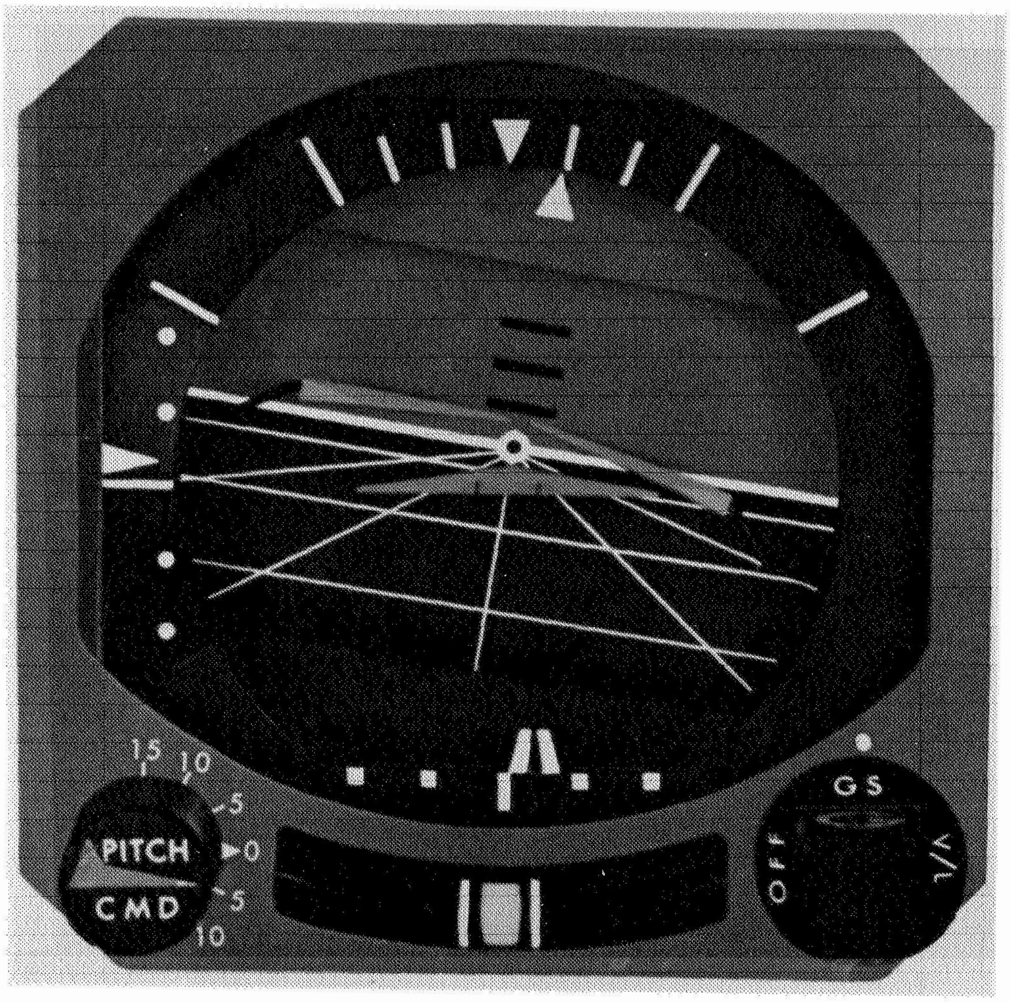
I.L.S. Glide Slope and Localizer Deviation

A. Standard I.L.S. deviation indicator.- This instrument indicates glide slope and localizer deviation by displaying "Fly-To" information. Pointers hinged on the left (G.S.) and the top (localizer) of the display are read as "Fly-To" indicators and in each case the pilot flies to where the needle is pointing to regain the I.L.S. glide slope and/or localizer.

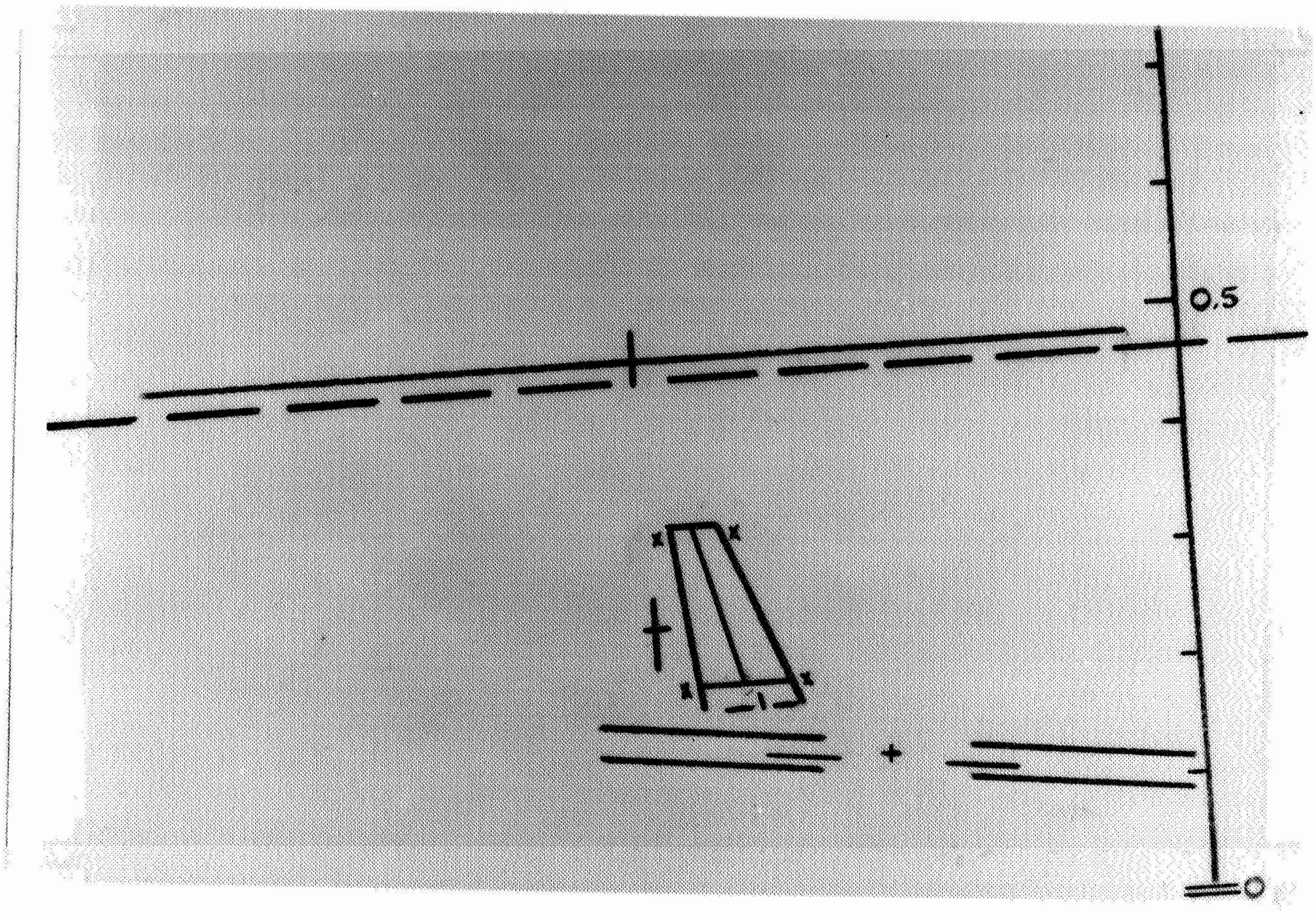
B. Moving bar, center hinge I.L.S. indicator.- Localizer deviation is displayed by a pointer which is hinged in the center of the clock-type instrument, the pointer being read across the top of the instrument. The glide slope deviation is displayed using a horizontal bar which moves vertically up or down to indicate glide slope deviation. Course heading can be set in and read at the top of the instrument and the localizer pointer can also be set into omnirange heading information.



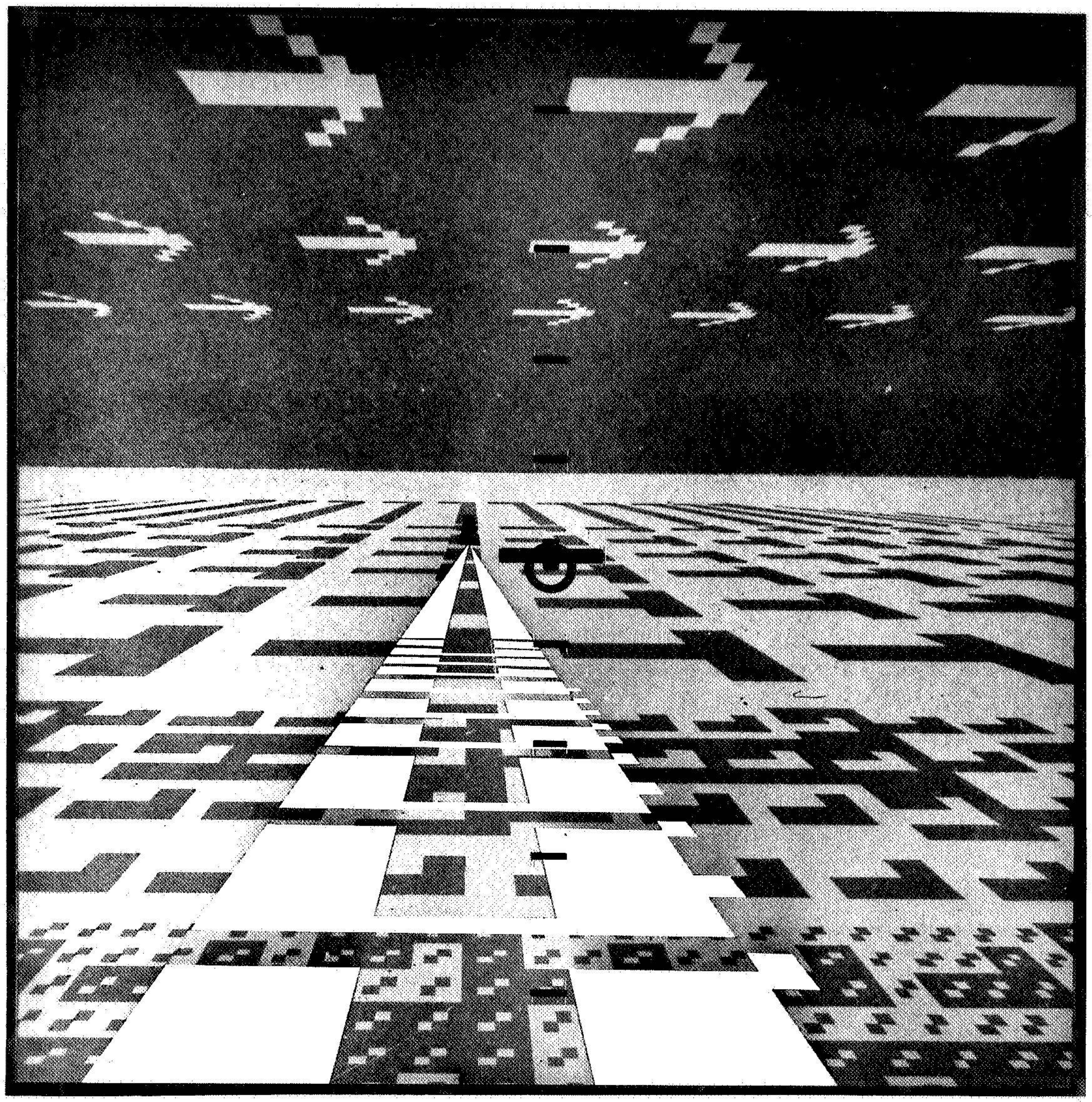
A. The Spectocom display



B. Collins 329B-7A flight director indicator

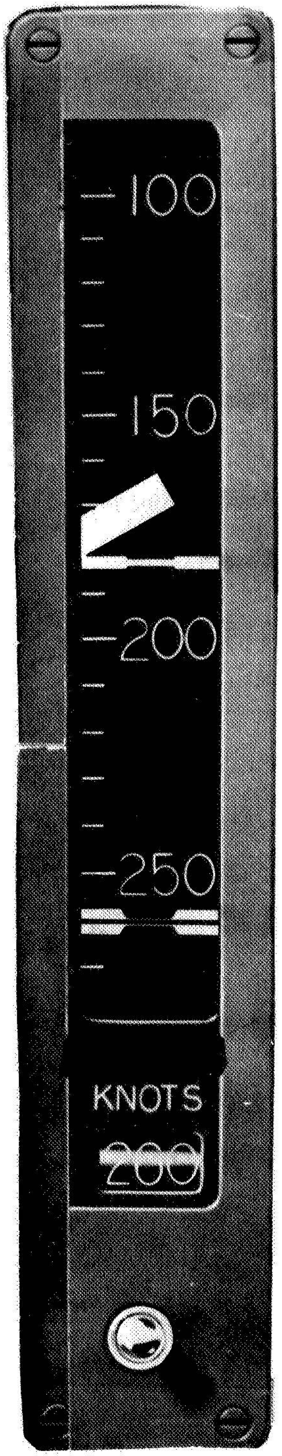


C. The Type A display

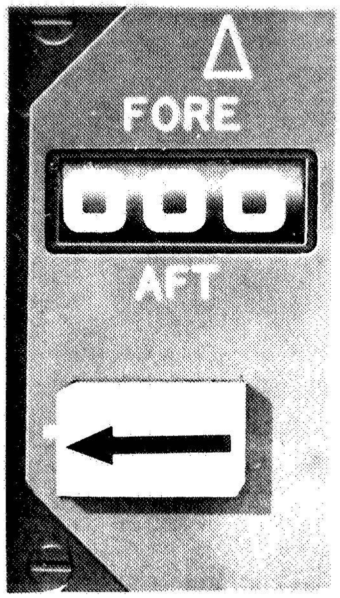


D. The General Electric vertical display

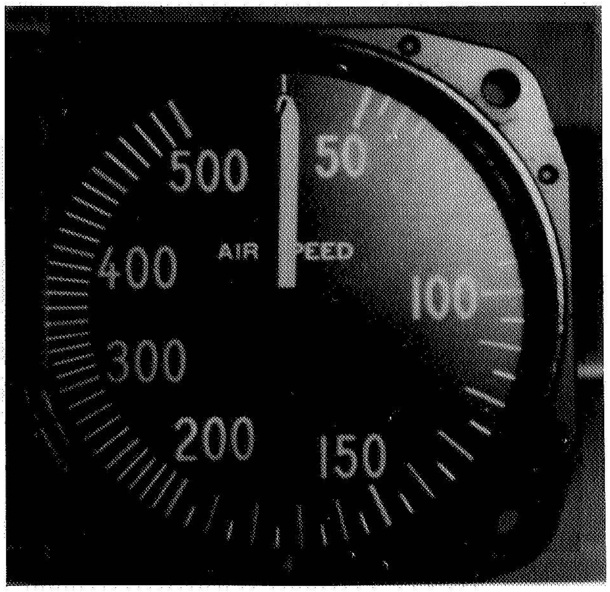
Airspeed



A. Vertical tape airspeed indicator

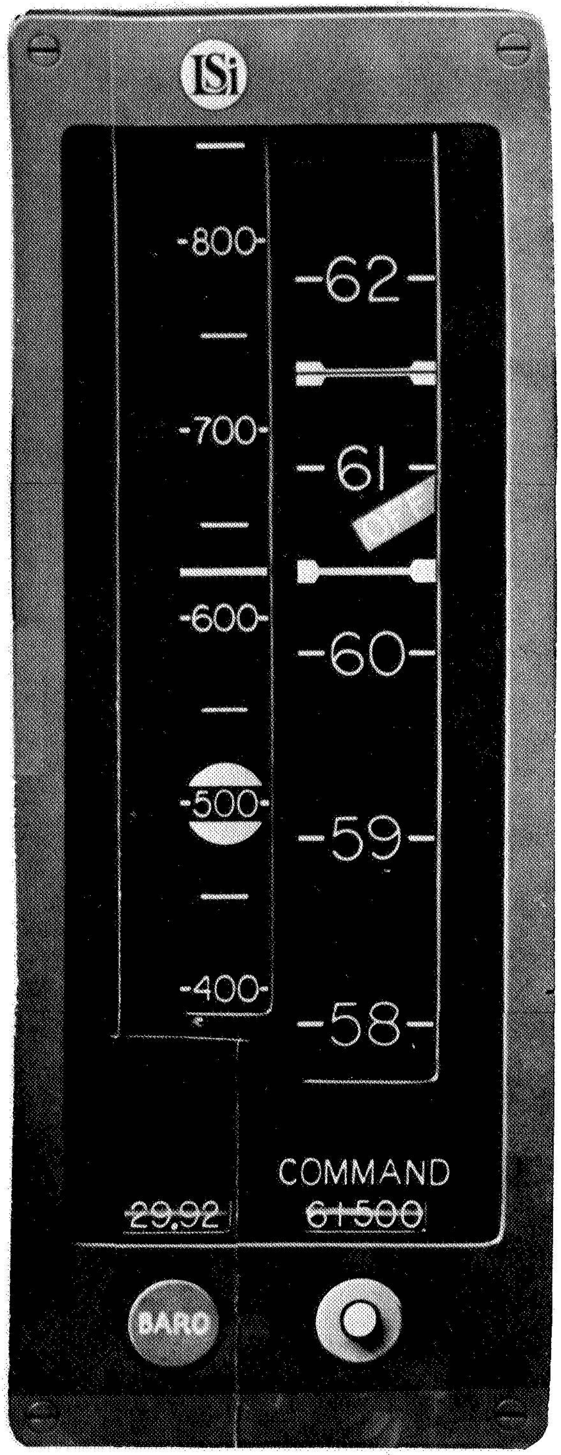


B. Readout airspeed indicator

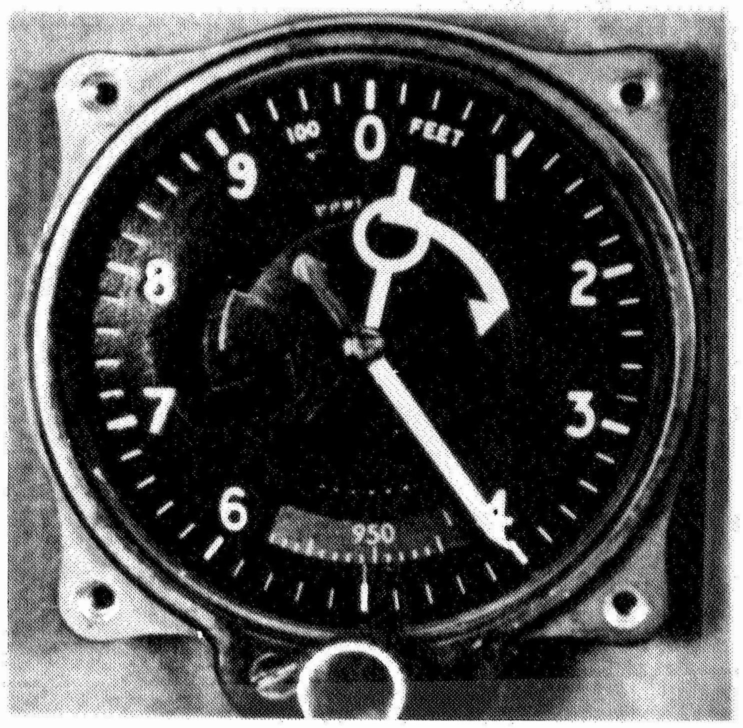


C. Conventional airspeed indicator

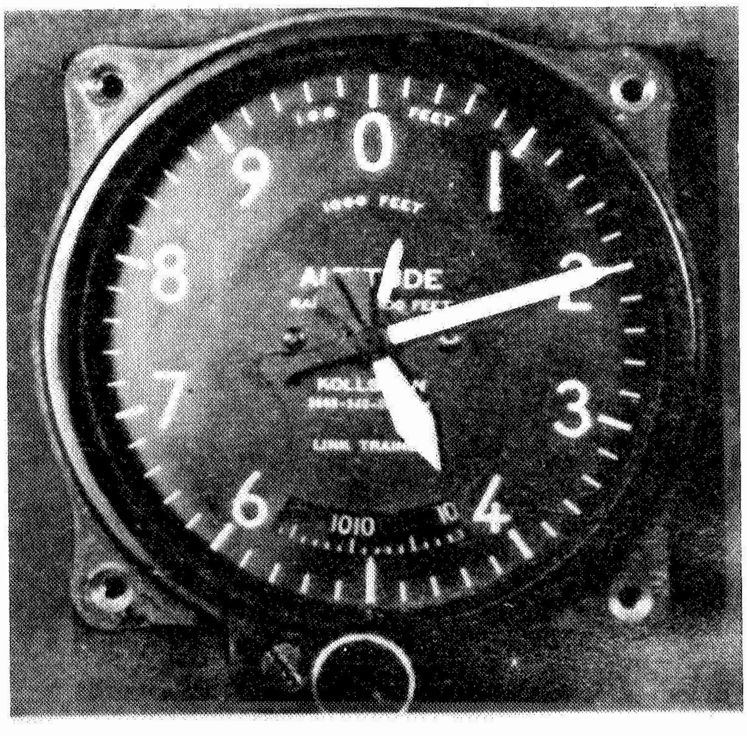
Altitude



A. Vertical scale altitude indicator

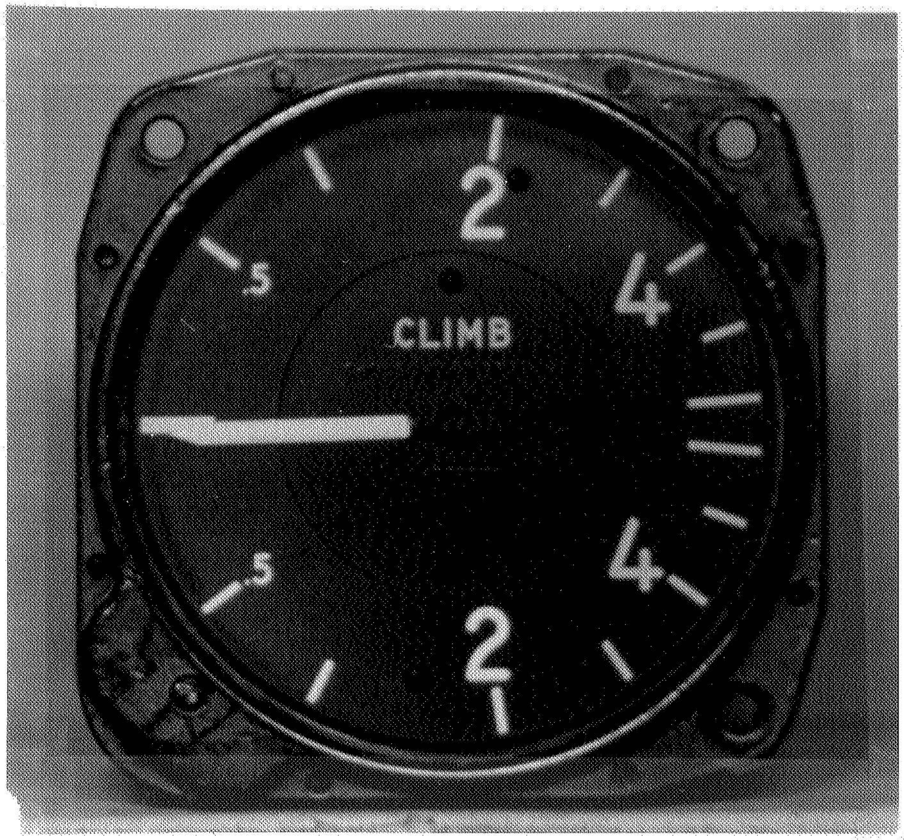


B. Yellow line altitude indicator

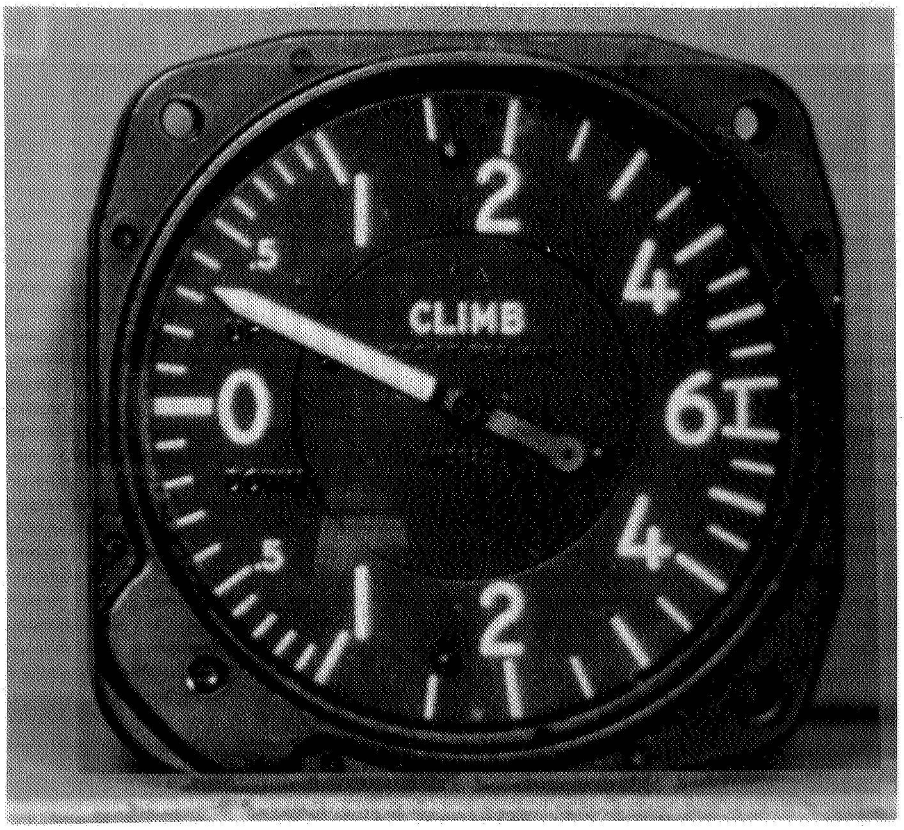


C. Standard 3-pointer altimeter

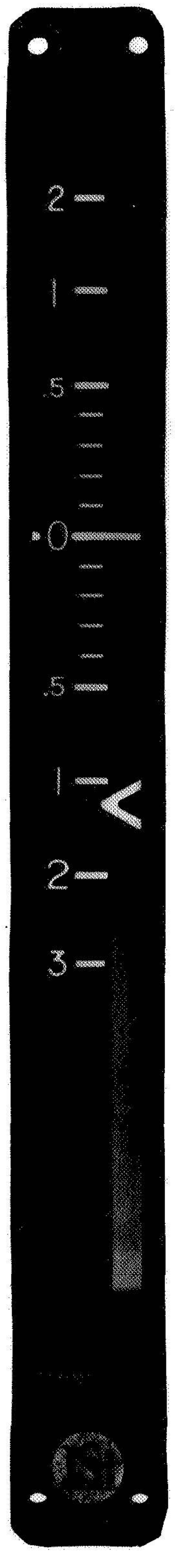
Rate Of Climb



A. Standard rate of climb indicator

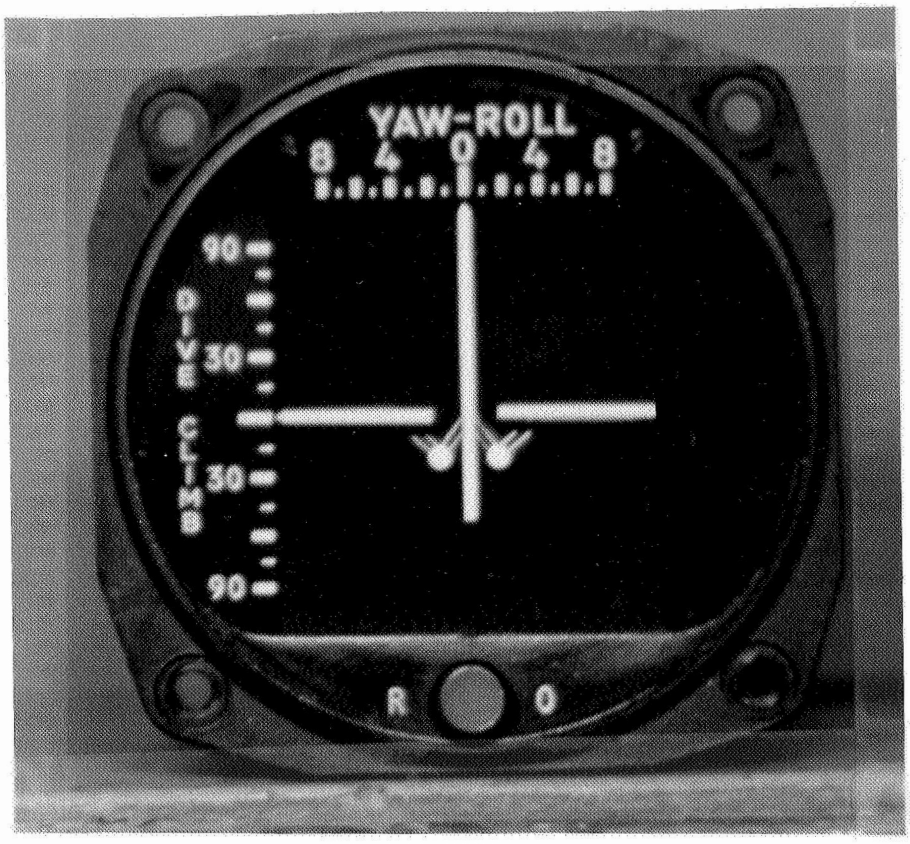


B. Modified rate of climb indicator

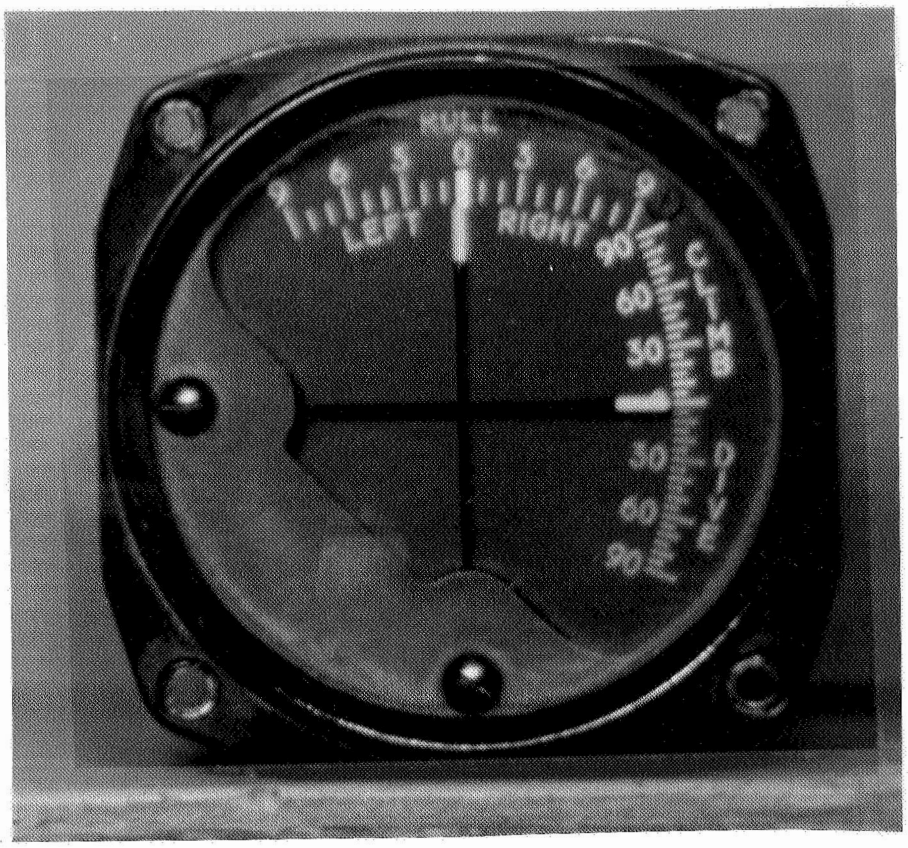


C. Vertical tape rate of climb indicator

Attitude

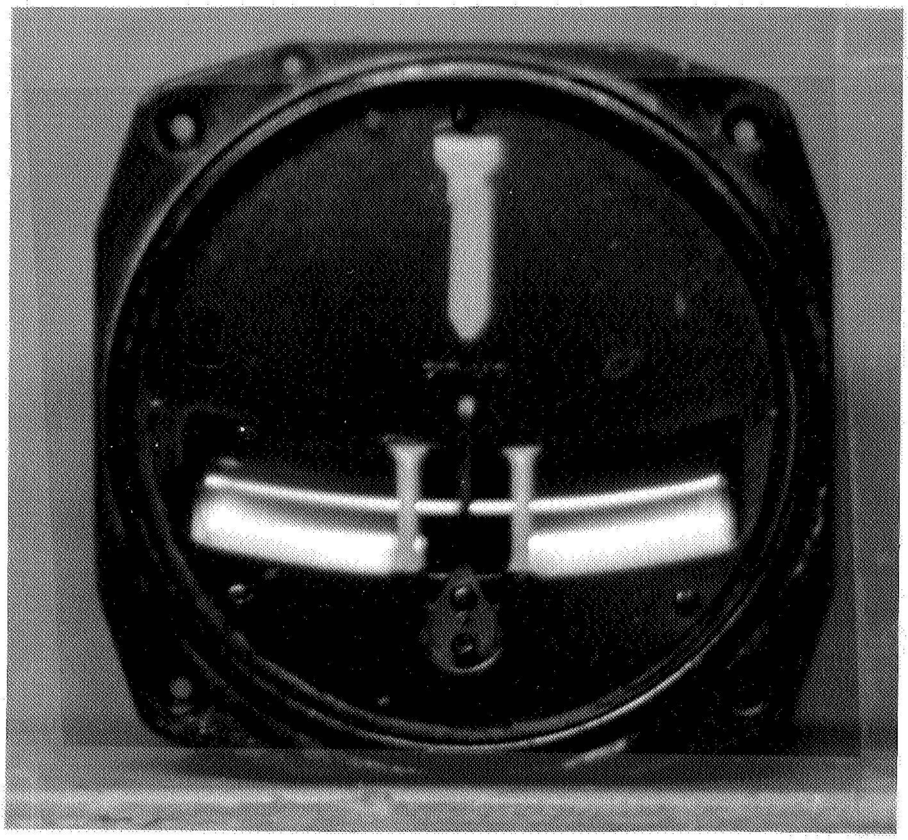


A. Displacement bar altitude indicator

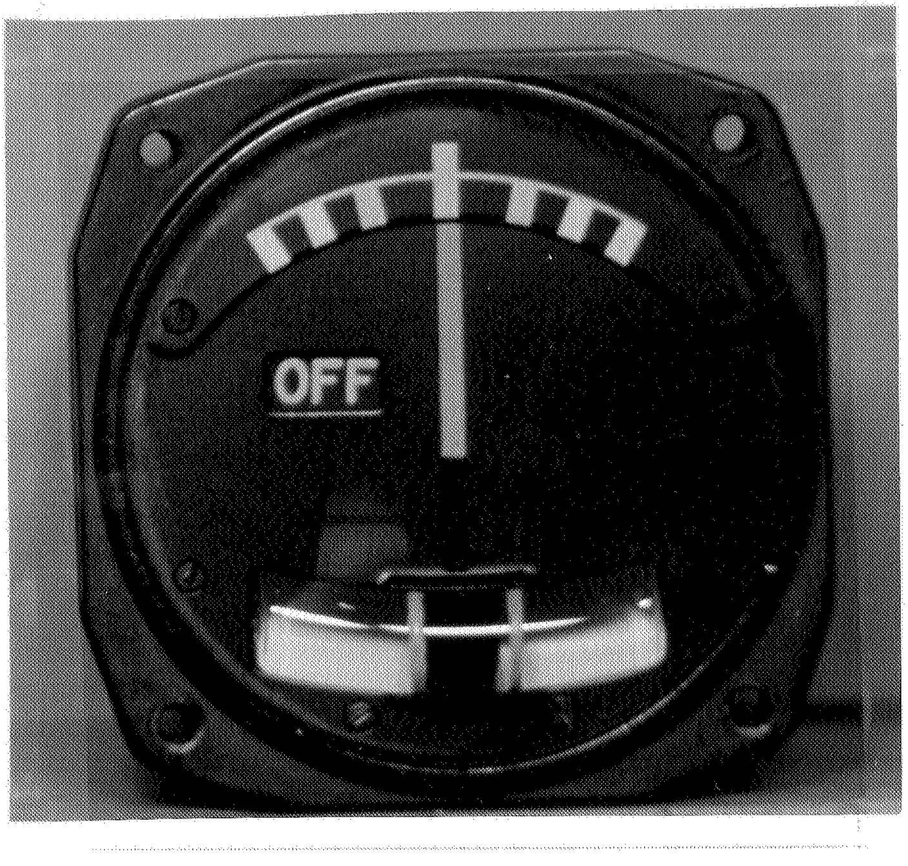


B. Hinged pointer altitude indicator

Turn And Bank

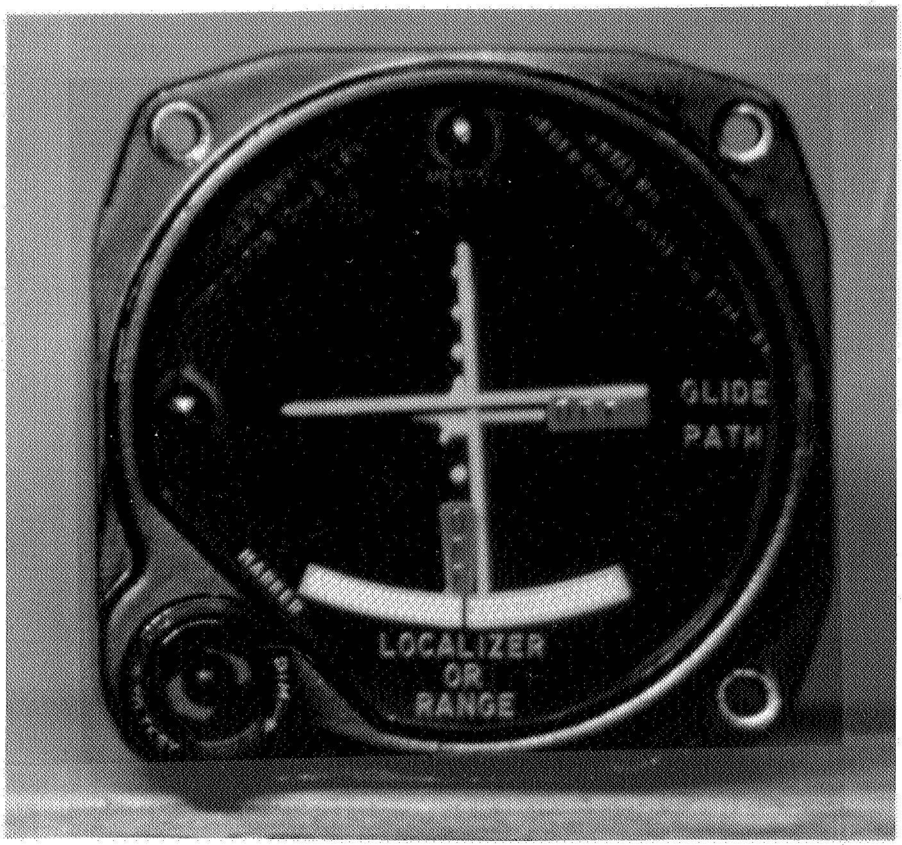


A. Standard turn and bank indicator

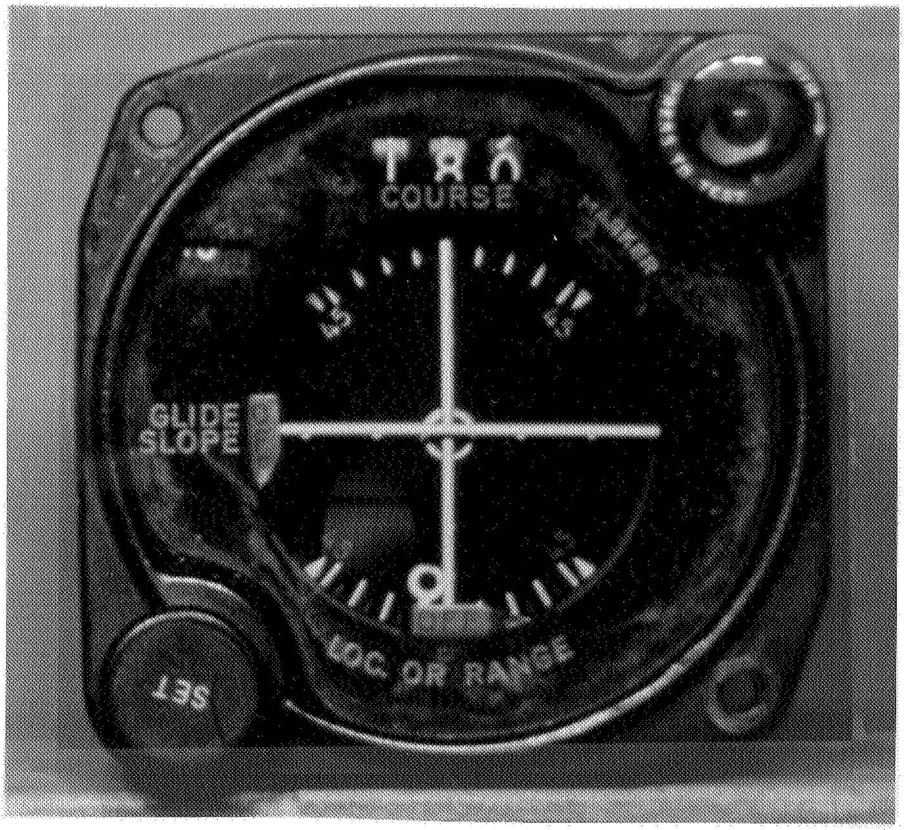


B. Modified turn and bank indicator

ILS Glide Slope And Localizer Deviation



A. Standard ILS deviation indicator



B. Moving bar, center hinge ILS indicator

APPENDIX III
PILOTS'REASONS FOR DISPLAY PREFERENCES

Table 1. Type and frequency of reasons for pilot preference of airspeed presentations.

Reason for Preference	f	Reasons for Non-Preference	f
1ST CHOICE: B (conventional clock-type)			
Familiarity (experience)	12	It is a long way from adequate	1
Read angle of pointer	11		
Can see trend	8		
Easier and quicker to read	4		
Relationship to other number: Range	4		
2ND CHOICE: C (vertical tape)			
Can see trend	5	Easy to misread	3
Easier and quicker reading	4	Don't like it	1
Can see range	3		
Have cross reference (command)	3		
Bigger natural numbers	3		
Better pictorially	2		
Familiar	1		
3RD CHOICE: A (digital readout)			
Simple, precise	4	Too much flopping around	2
Easy to read	3	No way to mark minimums	2
		Could misread if not larger	1
		Want to see trend	1

Table 2. Type and frequency of reasons given for pilot preference of altitude presentations.

Reasons for Preference	f	Reasons for Non-Preference	f
1ST CHOICE: B (modified conventional clock-type)			
Easy to read	10	Yellow bad under light	1
Less chance for error	4	Numbers should be bigger	1
An improvement	4		
Prefer circular type	2		
Familiarity	2		
Like the yellow-line	2		
Lesser of two evils	1		
2ND CHOICE: C (conventional 3-pointer altimeter)			
Familiarity (experience)	8	Hard to read/read correctly	7
Easier to read	4	Don't like 10K marker	1
Prefer circular type	2	Outdated	1
Better comparison: all in one area	2		
Easy to check	1		
Need for low work	1		
Prefer needle	1		
3RD CHOICE: A (vertical tape)			
More pictorial	2	Confusing: hard to read with clutter	9
Easier to check	1		
Simple	1		
Simpler to interpolate	1		
More impressive psychologically	1		
All displayed in one area	1		
Can't misread	1		

Table 3. Type and frequency of reasons for pilot preference of vertical speed indicators.

Reasons for Preference	f	Reasons for Non-Preference	f
1ST CHOICE: B (graduated standard clock-type)			
Less interpretation/ markings	13	B leaves lot to be desired	1
Familiarity	9		
Read angle of needle-quick glance	3		
Simpler	3		
Easy to read	2		
Clock-type	2		
Sufficient	2		
Better comparison	2		
More numbers	1		
For low work	1		
2ND CHOICE: A (conventional clock-type)			
Simple-No clutter: no need for more markings	13	Leaves lot to be desired	1
Familiarity	7		
Easy to read	5		
See at quick glance	2		
More information	1		
Better picture	1		
3RD CHOICE: C (vertical tape)			
Easy to read	2		
You can see if you're going down or up	2		
Markings for accuracy	2		

Table 4. Type and frequency of reasons for pilot preference of attitude presentation.

Reasons for Preference	f	Reasons for Non-Preference	f
1ST CHOICE: A (moving bar)			
Like bar-type movement	7	Confusing	1
Easy to read	2		
Familiarity (experience)	1		
Pictorially better	1		
More of attitude condition	1		
2ND CHOICE: B (hinged pointer)			
Easier/quicker to read	4	Confusing	1
Like hinged pointer	2		
Display of "dive-climb" better	2		
Simpler	1		
Familiarity	1		

Table 5. Type and frequency of reasons for pilot preference of turn and bank presentations.

Reasons for Preference	f	Reasons for Non-Preference	f
1ST CHOICE: B (modified)			
Scale markings	16		
Better and stronger display	1		
2ND CHOICE: A (conventional)			
Adequate - compute needle width	2		
Familiar	1		
Resist change	1		
Simple - don't need more markings	1		

Table 6. Type and frequency of reasons for pilot preference of glide slope and localizer presentation.

Reasons for Preference	f	Reasons for Non-Preference	f
1ST CHOICE: C (moving bar)			
Don't like hinged pointer	6	Can't read localizer	2
Cleaner picture	3	Too much clutter	1
Course heading	3		
Omnirange	2		
More information	1		
Familiar	1		
Easier to read	1		
Lesser of two evils	1		
2ND CHOICE: A (standard hinged pointer)			
Like moving pointer hinge	1	Blue-yellow always was confusing	1

Table 7. Type and frequency of reasons for pilot preference of situation displays.

Reason for Preference	f	Reasons for Non-Preference	f
1ST CHOICE: C (Type A)			
Windshield	15	Too confusing and complicated	9
Better pictorially	11		
Simpler; less interpolation	5		
Runway	4		
Easy to read	2		
More information	2		
Idea of display better	1		
Best of most complex	1		
2ND CHOICE:[7] A (Spectocom)			
Simplicity making it easy to read	15	Don't like it	2
Windshield	11		
Integrated	3		
Like idea of presentation	3		
Director-steer to it	2		
Target	1		
3RD CHOICE:[7] D (G.E. CRT)			
"Real" pictorial presentation	20	Too complicated and not understandable	7
Simplicity/easy to grasp	5	Don't like "crab"	4
		Doesn't give numbers	1
Gives airspeed	1	Don't like cathode ray tube	1
4TH CHOICE: B (Collins)			
Familiar: less transition	13	Don't like it	3
Simpler: more understandable	6	Too busy and complicated	2
Attitude indication better	2	Gives only reference line to object	1
More pictorial	2	Glidepath opposite my present director equipment	1
Adequate for present equipment	1		

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[7] Tie for second.

Table 8. Responses to question "When making a VFR approach during the daytime do you use the so-called spot of no movement to insure making the runway?"

Response	f
Yes	5
No	20
Don't know	5

Table 9. Responses to question "When making a VFR approach during the daytime what cues do you use to insure making the runway?"

Response	f
Runway perspective	5
X-spot	3
I.L.S.	3
Instruments	3
Overall picture	3
Depth perception	2
Spot along runway	2
1000 ft. marker	1
Sink	1
Don't know	2

Table 10. Responses and frequency of responses to the question "When making an IFR approach during the daytime, what does the pilot attend to during the period of transition from instruments to contact flying?"

Response	f
Checking runway line-up	10
Look for approach lights	3
Check runway line-up and check sink	2
Check runway line-up and check altitude	2
Check runway line-up and check airspeed	2
Getting mental picture of what instruments tell you in order to have an idea of what to expect	2
Look for spot on runway and check altitude	1
Look for spot on runway and check sink	1
Adjust glide path	1
Adjust for drift (crosswind)	1
Look for distance marker	1
Check sink, airspeed and attitude	1
Check runway line-up and final check of instruments	1

Table 11. Responses and frequency of responses to the question "During normal operation, which of the engine operation instruments do you find most useful?"

Response	f
Fuel flow	10
Engine Pressure Ratio (EPR) and fuel flow	8
Fuel flow and N_1 tachometer	5
Engine Pressure Ratio (EPR)	2
Exhaust Gas Temperature (EGT) and fuel flow	2
Exhaust Pressure Ratio and fuel flow and N_1 and N_2 Tachometers	1
Torque Indicator (BMEP)	1

Table 12. Response to question "Do you use these instruments (Table 18) routinely to infer information about engine thrust?"

Response	f
Yes	25
No	1
Don't know	4

Table 13. Answers and frequency of answers to the question "If you had a display of per cent of engine thrust, what other engine operation would you need?"

Response	f
None	10
Exhaust Gas Temperature (EGT)	7
Fuel flow	4
Fuel flow and Exhaust Gas Temperature	2
Fuel flow and Engine Pressure Ratio	1
All but Engine Pressure Ratio	1
It's just another way of doing it	1
We have it - N	