LEVEL II

FLIGHT TESTS OF THE HEAD-UP DISPLAY (HUD) IN DC-9-20 SHIP 382, NOVEMBER 1968 - JANUARY 1969

by

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FOREWORD

The work described in this report was carried out as part of an Independent Research and Development program on the contribution of the Head-Up Display to an All-Weather Approach and Landing System.

The section of this report dealing with control gains was presented to the Sixth Annual Conference on Manual Control, sponsored by the Air Force Institute of Technology, at the Wright-Patterson Air Force Base, Ohio, in April 1970. The experimental test flying was carried out by H. H. Knickerbocker in conjunction with W. S. Smith, who also acted as subject in simulated flight tests.

Aknowledgment and appreciation are extended to Conductron (Missouri), Elliott Flight Automation, and Sperry (Phoenix) for support in the experimental program.

This report has been reviewed and is approved.

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ABSTRACT

The investigation starts by discussing the symbol format of the Head-Up Display (HUD) in terms of principles of selection, organization, and design, and their effect on performance. It then deals with optical and mechanical problems of installing an operational system in a commercial jet transport. Two possible installations are evaluated by flight test, with a preference for an overhead mounting, because of freedom from internal reflections of the sun and minimal interference with cockpit layout. In these tests, two commercially available, short cathode ray tube systems are used successfully, except for minor effects of tube design, waveform generation, noise elimination, and bank resolution. Small format changes, involving digital height, raw ILS, and master warning elements, are used to extend the scope and effectiveness of the display without sacrificing previously established properties.

A method is given for optimizing control gains which is based on objective and subjective measures of performance, in real and simulated flight. Results obtained with one subject are found applicable to a larger group of subsequent users, allowing optimum control conditions to be agreed upon. Tracking accuracy is almost always within Category II limits, learning is rapid, and visual judgment is much improved, as in the military application.

Comparison of a manual approach with HUD and an automatic approach shows equivalence in tracking, and disorientation probability, but inequality in the availability of information. This deficiency could be removed by monitoring an automatic system with HUD, though the further problem of maintaining flying skill would only be solved by continuing to use manual methods. The results of the investigation are applicable in current jet transports, especially in supporting, or in replacing, automatic flight systems. Work remains to be done in further extending the use and scope of the system, particularly in its application to velocity vector information.

KEYWORDS

Head-up display, symbol design rules, optical and mechanical installation parameters, flight test, CRT system, aberrations, fatigue, errors, noise, display gains, pilot performance, real and simulated flight, new symbols, ILS approach, Category II, learning, collision avoidance, crosswind approach, disorientation, night flying, comparison of manual and automatic approach.

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1. INTRODUCTION AND SCOPE

This report is concerned with developments in head-up presentation affecting its application to civil aviation. Former studies were made chiefly in military aircraft and were concerned with basic features distinguishing this type of system from a conventional flight instrument system.[1] It was shown, largely by the selection and design of symbols, how to provide the pilot with an information system which he could use accurately and easily, while looking where he was going. The resulting symbol format is described and explained in the next section, and is used with little alteration in the present study.

Following the former basic investigations, flight tests were more recently carried out in a modern jet transport.[2] It was immediately recognized that there would be much greater difficulty in finding installation space than in military aircraft and no attempt was made to solve the problem at that time; the display equipment was simply attached to the glareshield by a crude and temporary mounting. The flight tests were intended, instead, to determine whether the advantages of this type of information system and symbol format could be transferred from military to civil use. The tests, which were essentially of a preliminary nature, confirmed that pilots could use the system without previous experience, with sufficient accuracy for full manual touchdowns, and with the forward view obscured by crossed polaroid screens It was not possible to apply the results to all pilots and operating conditions, but there were grounds for believing that a more rigorous investigation might allow conclusions of a general nature to be drawn. It was also abundantly clear that an installation was required which would allow the head-up display system to operate efficiently, yet which would require no major change of cockpit layout, or otherwise impair normal operating procedures. The present flight tests are therefore directed towards an extended study of human factors, and an evaluation of solutions to the installation problem.

After dealing with the symbol format and how it is related to results which may be achieved with the system, the report considers the equipment to be installed. Since earlier tests, the equipment has changed principally through the use of a smaller cathode ray tube, introduced by Conductron (Missouri). The system is still difficult to install, however, and optical, mechanical, and operational problems arise. These are considered with a view to ensuring adequate visual qualities and integrity of information, in a variety of flight conditions and in the presence of mechanical and electrical noise.

The report considers two possible solutions to the installation problem which are evaluated qualitatively, mainly on the basis of pilots' flight test reports. After calibrating the system, optical and visual qualities of the collimator and cathode ray tube are studied. The format is then considered in terms of errors affecting the transfer of information, a process which may also be influenced by features particular to individual symbols and by more general graphical qualities of the format.

The next part of the work paves the way for subsequent studies of human factors and is essentially a gain survey, thus breaking new ground in the field of head-up presentation. Attention is directed towards time-dependent aspects of presentation: how symbols move and change in shape, as determined by gains applied in control loops operating on the input data. Whereas earlier tests were made with gains arrived at by ad hoc methods, the present investigation is more systematic, with a view to deriving numerical relationships applicable to a range of users. The assumption is made that it may be advantageous to examine the display and pilot system by methods used in optimizing an autopilot, for both systems operate on signals originating in aircraft sensors; the object is to fit display dynamics to the man. Gains are surveyed in real flight and in the laboratory, by simulation, for the purpose of developing a general method of adjusting display gains before flight tests begin. The experimental method embraces both objective measurement of tracking performance and subjective estimation of handling quality, for a small population of pilots.

The final part of the experimental work is a series of demonstration flights, making use of the gain survey to provide operating conditions which may also best suit a larger population of users. This opens the way for comparing human and automatic tracking performance for accuracy, variability and freedom from disorientation, with special relevance to the operation of aircraft in all-weather approaches. As in earlier work, the human factor studies are extended to cover learning effects, among visiting pilots, and the dual observation of display and forward view. The demonstration flights are also devoted to methods of using the display system by night and in several flight modes.

The chief questions to be answered are whether an acceptable installation of current display equipment is possible in the jet transport of today; whether this equipment operates in an entirely satisfactory manner, and whether gains can be found which allow most pilots to perform with a high standard of accuracy. Another question is whether characteristics of the system other than accuracy can find general application in civil aviation; that is, whether the system can be learned easily by airline pilots and used, by dual observation, to eliminate the transition from instrument to visual flight. Finally, a question suggested by the experimental results is whether a display system of this type can assume a significant role in the all-weather approach.

2. SYMBOL FORMAT

Principles of Organization

The purpose of the system is to present information, chiefly concerning the flight path, while allowing direct observation of the forward view along that path. It is, of course, necessary to select information appropriate to this purpose, which will be represented by suitable symbols. Also, it is desirable to avoid anything making it difficult for the user to get at the meaning of the display format, or obtain access to the information represented therein. At the same time, it is desirable to avoid anything making it difficult for the user to move freely between display and forward view. These are the general rules governing the choice of information and the principles of organization and design which follow. The methods of deploying these principles and their areas of influence are summarized in Table I.

Format Position. The display format is located in the pilot's forward line of sight at a very large distance. This choice of position tends to eliminate physical acts of refocusing and redirecting the eyes, and has been shown by experiment to increase the efficiency with which both display and forward view can be viewed, by eliminating attention gaps on the order of 3 seconds.[3] It is thus an important factor in eliminating the transition between visual and instrument flight modes.

The position of the display is also important in eliminating space myopia, or short-sightedness in an empty visual field. This condition occurs in total darkness, in fog, or in a uniform sky, where the eyes can focus on nothing and, as Whiteside has shown by experiment, a pilot is unable to focus on points more than one to two meters away.[4] The effect is to delay the moment of first sighting an emergent object, such as the runway, thus leaving less time to understand what is eventually seen and increasing chances of confusion and disorientation.

The visual focus of a man using a collimated display, generated in the manner of Fig. 1, is already adjusted to observe objects at a large distance. He is, as it were, pre-focused for detecting objects emerging in the external visual field, at the earliest possible moment. Pilots have given evidence showing improved visual acquisition in an empty field; for example, they can pick up runway lights sooner.[5] (This result is contrary to the supposition that the system's reflector plate would reduce forward visibility.)

The influence of the position principle is thus twofold. It helps eliminate the transition and it also prevents space myopia.

Framework of Interpretation. The display format is given the same interpretative framework as the forward view, for symbols understood by rules similar to those applied in the forward view. For example, a symbol fixed in the display format represents an item fixed in airplane

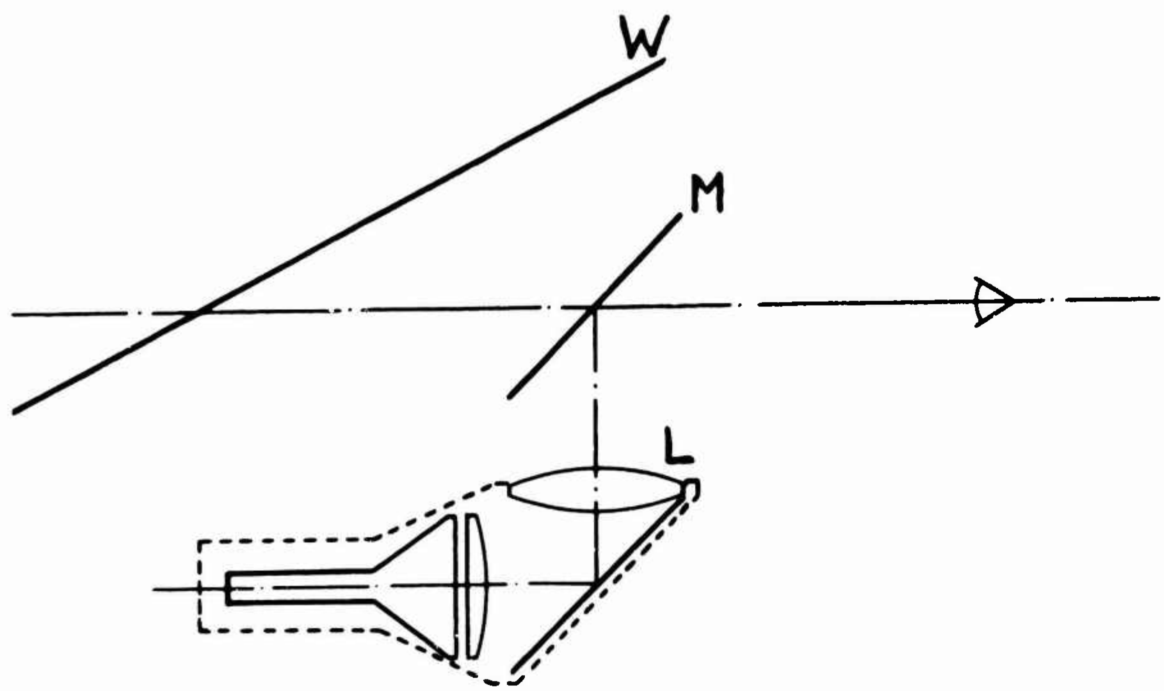

FIGURE 1 **REFLECTING COLLIMATOR.** Display superimposed on forward view through windshield, W, by partial mirror, M, and imaged at infinity by lens, L.

TABLE I. ORGANIZATIONAL PRINCIPLES USED IN SELECTING INFORMATION, AND IN IMPROVING ACCESS, INTERPRETATION, AND MOVEMENT BETWEEN FIELDS

Principle	Deployment	Area of Influence
Format Position	Reduction of physical workload	Instrument/visual transition. Space myopia.
Framework conformity	Reduction of interpretative workload for conformable symbols.	Learning. Tracking. Instrument/visual transition.
Simplicity	Limitation of information channels. Use of basic, unique visual forms.	Uncluttered, critical use of both fields. Identification.
Zoning	Selection of symbols amenable to restricted movement.	Interference. Velocity prominence. Size prominence.
Symbol position	Priority according to frequency of use. Limited use of conventional position.	Visual load, external scan. Identification.
Continuity	Rejection of symbols prone to excursion. Occultation.	Failure annunciation.
Integrity	Rejection of symbols prone to form and position errors.	

axes, such as horizontal fuselage datum, and a moving symbol represents something moving with respect to the airframe, with the same direction of movement as in the forward view. It has been found by experiment that this type of conformity, for display and forward view, allows the skills already learned in visual flight to be used in the display, [6] which can thus be learned and used very easily.

It is evident, moreover, that when display items are presented in the same framework as the forward view, they are also presented in a common display framework. For example, heading information, which is customarily presented in aircraft axes, can be more efficiently shown in earth axes, along with the artificial horizon, according to the scheme of Fig. 2. The pilot then has more immediate access to the meaning of the symbols presented in this common geographical framework, and this type of unification has been shown experimentally to improve tracking accuracy. [7]

The concept of a single interpretative scheme cannot be applied indiscriminately to all symbols, because this does not always improve interpretation. For example, height is not usefully shown by a display element having pictorial relationship with the forward view, because height information can scarcely be extracted from the forward view, so the same method of interpretation would be equally ineffective in each field.

Conformity, whenever its use is warranted, lessens mental effort due to differences of interpretation between display and forward view. The user is then no longer required to change from a visual field of abstract, multiple instrument dials, each with its own frame of reference, to an external visual field in which information is available as a pictorial, single scheme in earth axes, as indicated in Fig. 3. Reduction of the interpretative workload, together with the reduction in physical workload due to using a common position for display and forward view, allows the user to move freely between both visual fields.

It follows that the transition between instrument and visual flight modes, which otherwise can interrupt the flow of information, need no longer be the most anxious part of an instrument approach. Nor need instrument and visual flight be thought of as mutually exclusive processes. Extensive experiments have shown to what degree the transition can be eliminated[3, 8] and further evidence on this issue is provided in the present report. The improvement in information flow occurring when the pilot's display is thus superimposed on the forward view is illustrated schematically in Fig. 4, where cross marks represent visual acquisitions from the instrument field and circles represent acquisitions from the forward view. Each type of acquisition is arbitrarily taken as occupying an equal length of time, and these intervals are smaller[9] than the time needed for the transition. The flow of information from superimposed fields is then more continuous than from separated fields.

An adverse effect due to framework occurs in head-up presentation when the user is confronted with an additional, unwanted reference frame

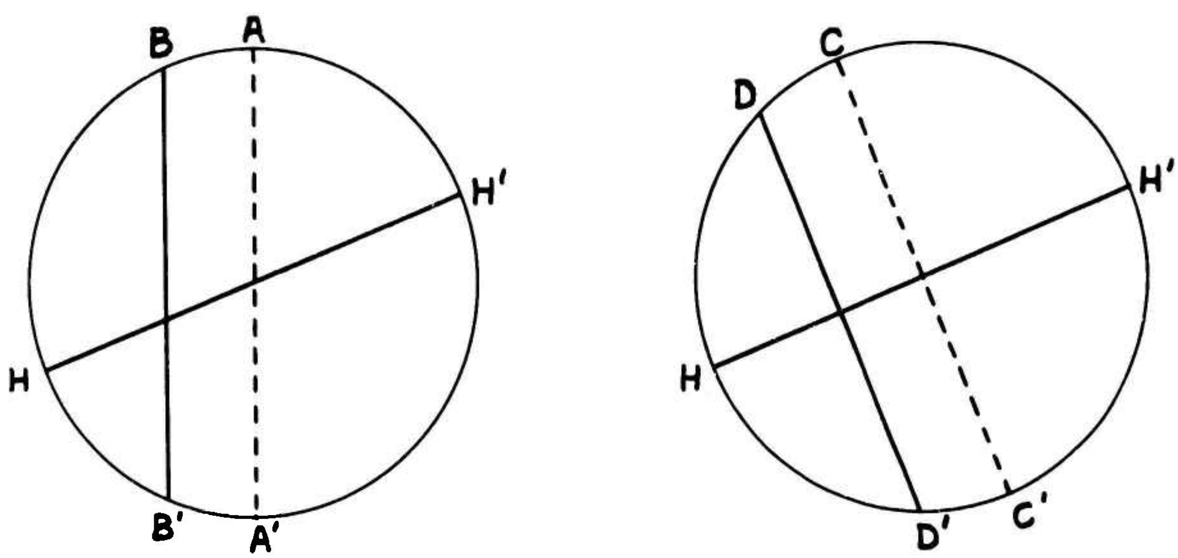

FIGURE 2 DISPLAYS WITH MIXED AND SINGLE AXES. Displacement from AA' to BB' shows heading in aircraft axes. Displacement from CC' to DD' along horizon HH' shows heading in earth axes.

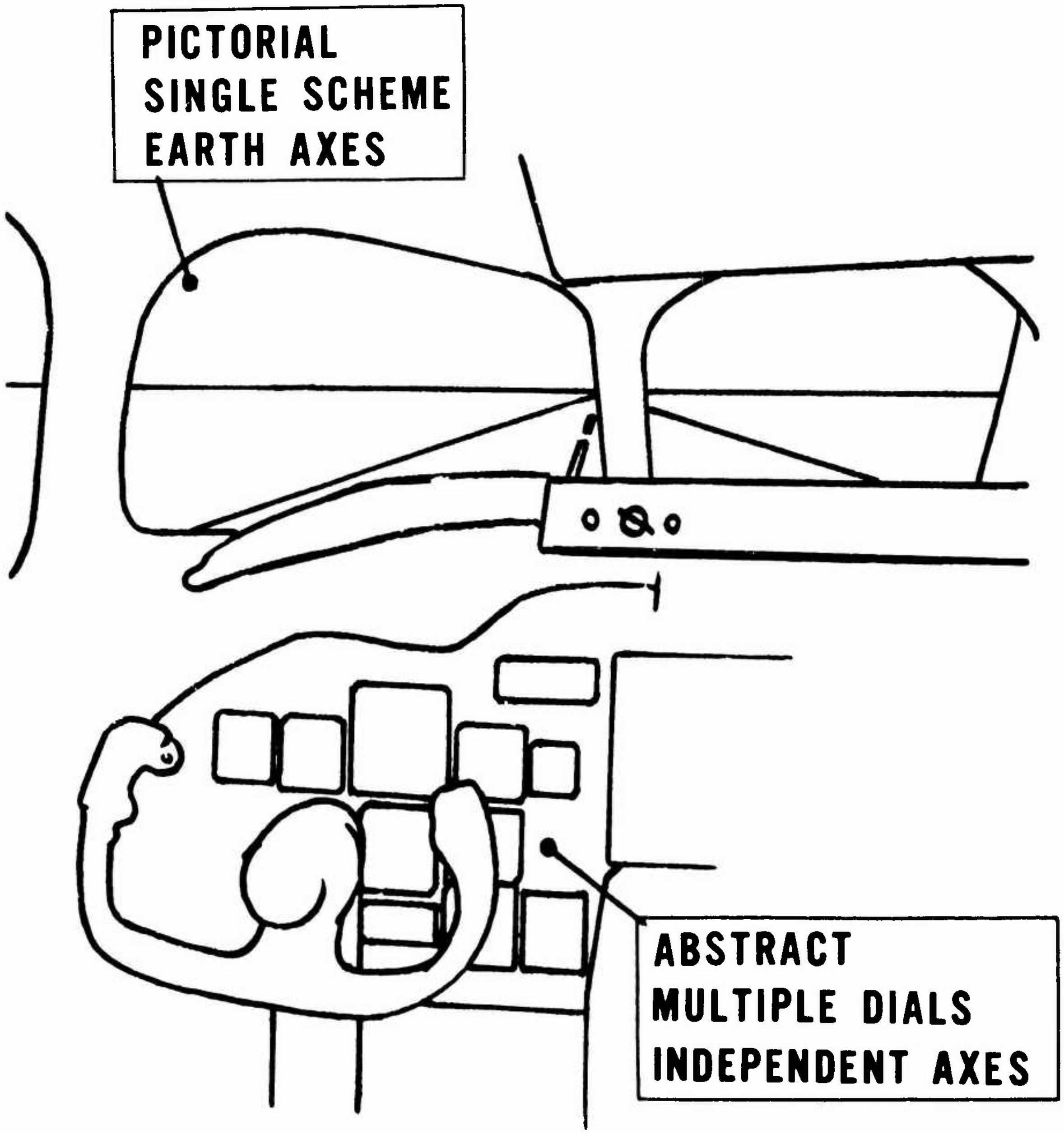

FIGURE 3 DIFFERENCE OF INTERPRETATIVE METHOD FOR INSTRUMENT PANEL AND FORWARD VIEW

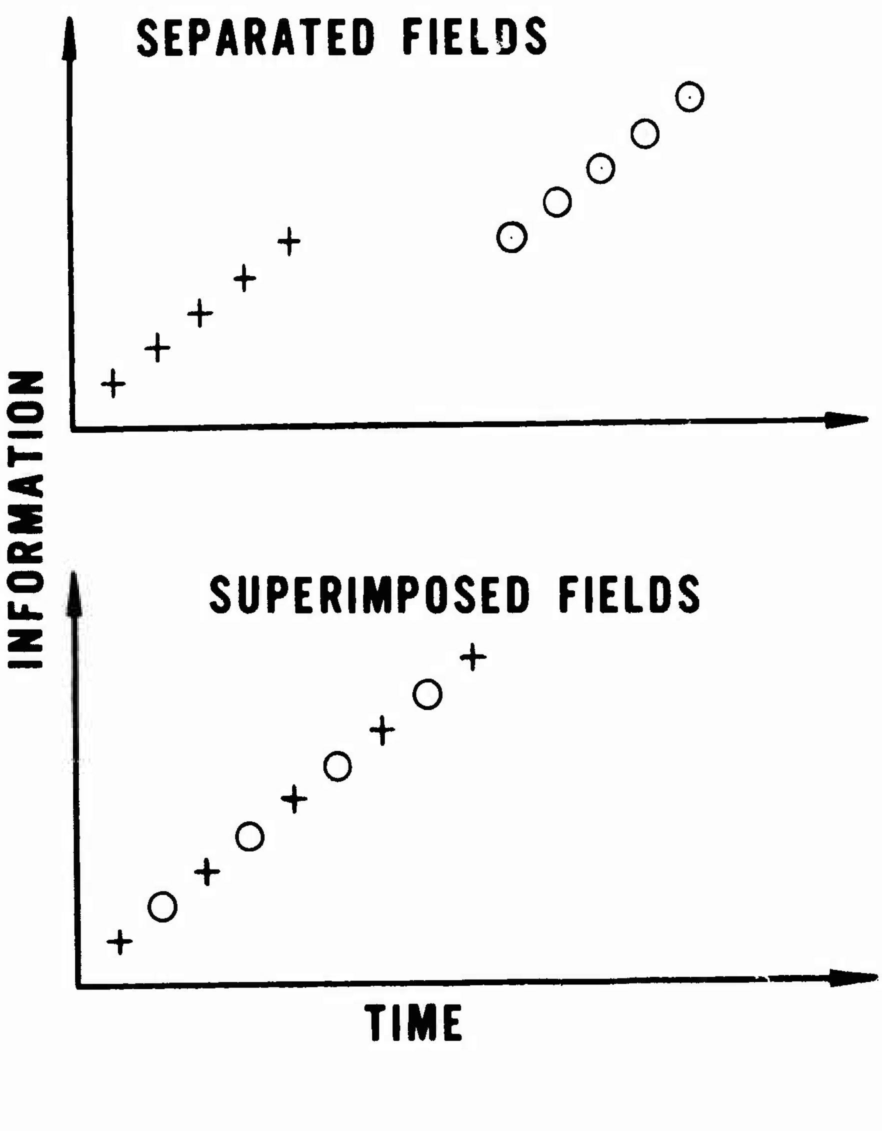

FIGURE 4 INFORMATION GAINED FROM SEPARATED AND SUPERIMPOSED VISUAL FIELDS
Acquisitions from instrument (+) and external (0) fields shown as discrete events associated with individual fixations.

interposed between his own frame of aircraft axes and the forward view, in earth axes. This effect may be induced by setting up a display grid which moves with respect to the aircraft framework at a speed different from the apparent speed of the ground. Pilots using this arrangement have experienced disorientation and the effect is perhaps similar to the nauseating effect of descending an openwork iron fire escape, through which the distant ground can be seen. This effect is avoided by using a single frame for conformable symbols.

To sum up, the influence of the framework principle can be used with advantage in three areas. It can be used to promote rapid learning and low workload. It can be used to improve tracking accuracy. It can also be used to help in the process of eliminating the transition.

The single framework, or conformity principle is applied in the display format to attitude and director symbols, in the following manner. The artificial horizon remains parallel with the visible horizon at all times. The flight director index is moved either along the horizon, for heading commands, or at right angles to the horizon, for vertical commands. All other symbols occupy positions which remain fixed in the format. These features are indicated in Fig. 5 and are elaborated during the subsequent description of symbols.

Simplicity. The display format is planned for simplicity of content by the elimination of unnecessary information, and for graphical simplicity by the design of individual symbols. Simplicity is desirable on the general ground that things should not be made complicated except out of necessity (Occam's Razor: entia non sunt multiplicanda praeter necessitatem). More specifically, simplicity is desirable to avoid wasting time in rejecting redundant data, and in extracting the meaning of ornate symbols, which may also clutter the forward view. Such time losses may be important in the approach, when both display and forward view have high information rates. As a more technical consideration, simplicity is useful in reducing the total line length used in each writing cycle, which helps in maintaining the brilliance of electronic displays.

Simplification of the format has come about through exposure to a large user population, a process tending to eliminate all but essentials. Only the bare necessities for instrument flight are provided. It has been verified experimentally that the forward view can be scanned critically (which may be a useful way to define clutter) if the number of information channels is limited, the format comprising only attitude, command, height and speed information. [10, 8] The format of Fig. 5 shows a similar limitation of content but peripheral ILS scales have been added, and further observations on this issue are made in the present report. Simplicity has also been sought for individual symbols by choosing elementary geometric forms; or by reducing more complex forms to a functional minimum. What is sought is just sufficient power of association with the information represented, and just sufficiently unique identification, assuming each symbol to be used only once.

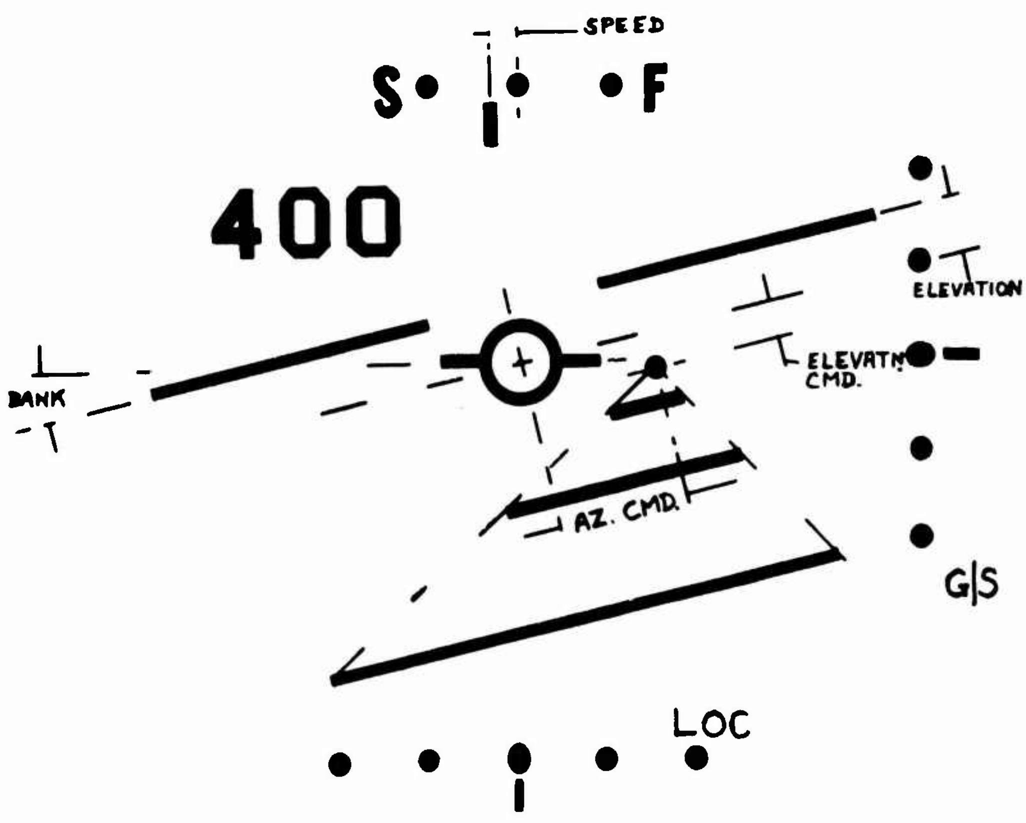

FIGURE 5 DISPLAY FORMAT

Zoning. The display format is divided into zones which restrict movement of the symbols. The object is to avoid interference of symbols and unwanted prominence due to excessive symbol movement or excessive symbol size. These effects may influence the flow of information from the display, for reasons to be discussed, and they may also be expected to induce cluttering of the forward view.

When symbols occupy the same position in the format they interfere with each other in their function of representing information, since it may no longer be clear what is represented by the conjoint graphical form. Symbols representing real world objects are prone to this effect, in a superimposed display, because they wander freely through the format as the aircraft axis changes direction. However, the artificial horizon is not truly a real world symbol and therefore can be prevented from interfering with other symbols by scaling down its movement in elevation, which is operationally acceptable.[11] Neither is the flight director a real-world symbol, and it can easily be confined to a zone because it need only move in the same direction as a corresponding command in the real world, for the sake of conformity; it need not move through any particular real-world angle. All that is required is to scale and limit director displacements, and the scaling can be chosen to suit the operator, as will be shown. Speed and height symbols can obviously be zoned without difficulty when they assume abstract form.

Symbols moving in the format with large angular speeds attract more attention than slower-moving symbols. This is particularly true of real-world symbols,[12] which move through the restricted area of the display with greater apparent speed than the corresponding real world objects move through the larger area of the windshield panel (blue-tailed fly effect). Horizon and director symbols can be controlled, however, because the scaling and limiting used to reduce interference will also reduce prominence due to speed. For similar reasons, the problem need not arise with symbolic speed and height displays.

The prominence of symbols also varies with their size, larger symbols being more prominent than smaller symbols because they can be seen while looking in a larger number of directions. Since the size of a symbol is limited by the area it may occupy, zonal area can be used to control the visual prominence of an enclosed symbol. The basis for allocating area is that the most important symbols are given precedence, and these are judged to be the flight director and artificial horizon symbols. Speed and height components occupy smaller zones, because they are used less continuously. The zoning arrangements used to minimize effects of interference and undue prominence are shown schematically in Fig. 6.

Symbol Position. The position of symbol zones is used as an aid in acquiring information. The most frequently used material is situated centrally, to even out the workload of visual excursions to the areas of lesser importance. Director and attitude symbols thus occupy the central zone, an arrangement also promoting conformity with the forward view,

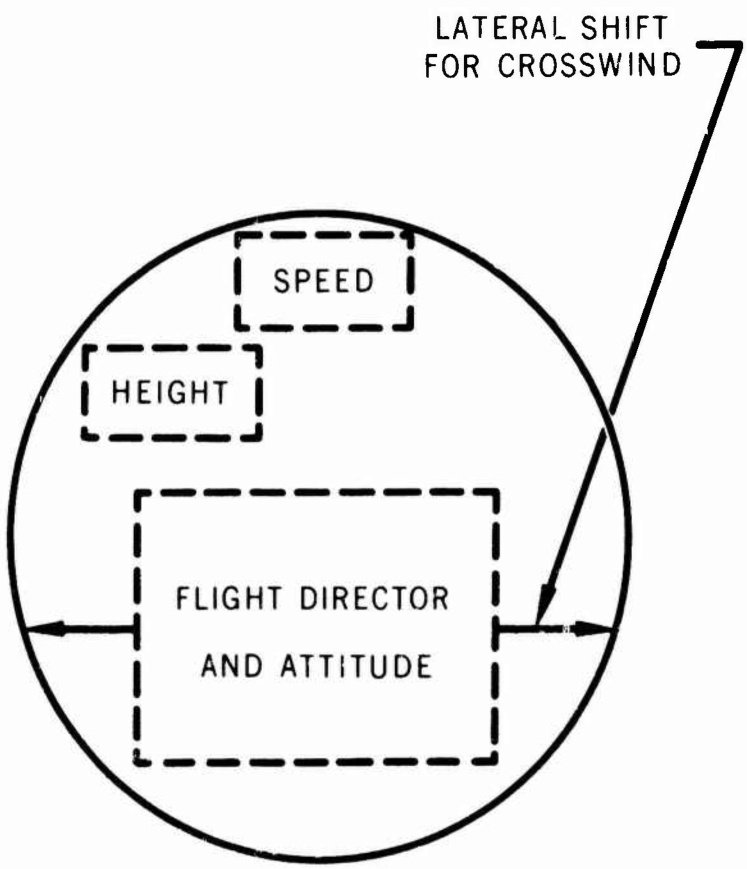

FIGURE 6 ZONING ARRANGEMENTS IN DISPLAY FORMAT
(Not to scale)

while supporting symbols, including the subsequently added ILS scales, are given peripheral positions as shown in Fig. 5.

Further use could be made of symbol position to suggest the meaning of supporting elements of the display format. For example, the height component could be presented in the top right corner, and speed could be shown as a vertical scale at the side of the format, in conventional positions. It is more convenient, however, to present height, especially radar height, on the left of center when shown as a numerical display, since the numerals vital to the last stages of an approach are then closer to the center of the format. For this reason, radar altitude is presented in the upper left quadrant, while the upper right quadrant may otherwise be used for barometric altitude. It is also convenient to keep at least one side of the format free of symbols such as a speed scale, to allow slewing the display, in the event of needing to offset crab angle. The format, or its central zone, can then be slewed towards the unoccupied side, and if a symbol in the occupied side (such as an ILS scale) can be shown equally well on either side, bilateral slewing is possible, as indicated in Fig. 6.

Symbol position is also used to promote scanning in the forward view. When all symbols are close together the user has no stimulus to scan outlying areas and it has been found desirable for this reason to show supporting information in off-axis positions. (13)

Continuity. The flow of information is maintained by the continued presence in the format of symbols representing valid information. Continuity could be interrupted in two ways: by the excursion of symbols beyond the limits of the format (or beyond the optical limits of the equipment) and by the deliberate removal of symbols from view by blanking, or occultation.

Interruption by excursion is prevalent with real-world symbols, which may disappear when the aircraft rotates through more than the semi-diameter of the display field. Since the display field can be as little as 10°, real world symbols only remain visible during a tightly controlled attitude regime and may disappear, for example, while following a bent beam, as indicated in Fig. 7.* On the other hand, the symbols of Fig. 5 are not subject to this form of interruption.

Deliberate removal, by blanking out a symbol, prevents the user acquiring information which is no longer valid. For he can hardly gain data from a symbol no longer visible. Blanking is therefore used as a means of failure warning, for symbols which otherwise preserve continuity of information.

Integrity. The integrity of displayed information is affected not only by the validity of source data but also by the presence of visual noise, which may be seen as changes in the form and position of symbols. Experience has shown that noise cannot be eliminated entirely from electronic symbol

* Here it is assumed that the position of the symbol is defined by an earth stabilized reference system. The alternate case where it is defined by the beam is discussed later.

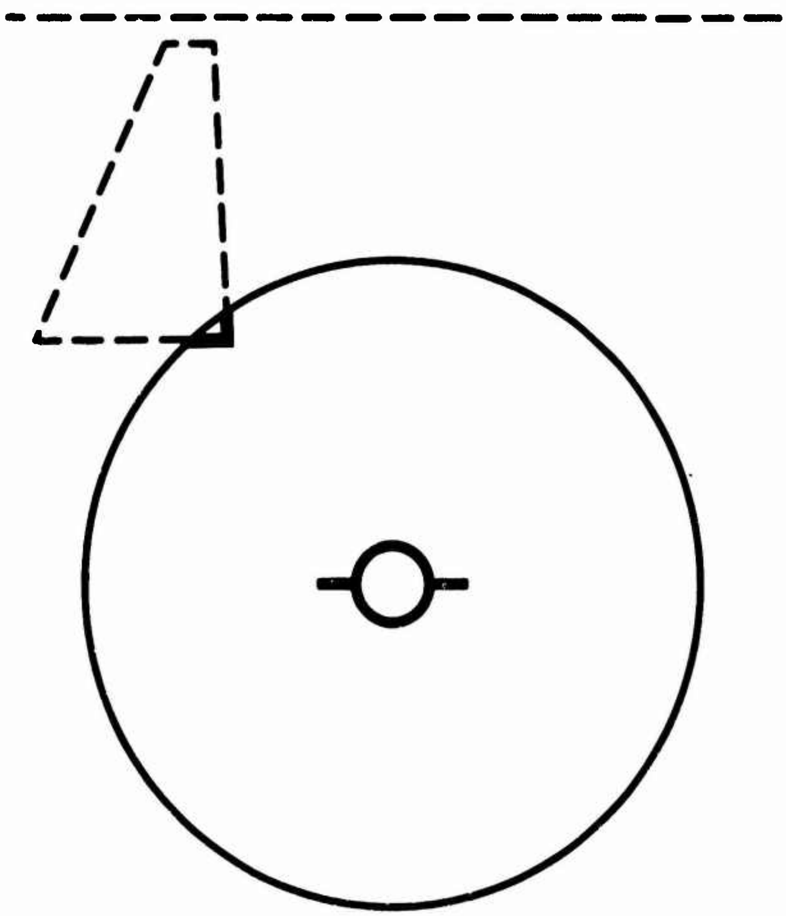

FIGURE 7 EXCURSION OF EARTH-STABILIZED RUNWAY SYMBOL IN BEAM BEND

generation, or from presentation systems incorporating an optical lever. The format is therefore designed to exclude symbols sensitive to noise

A real-world symbol, such as an artificial runway, conveys information mainly by its form and position in the display field (representing position and attitude of the airplane, respectively). It follows that errors of form and position falsify most of the information conveyed by this class of symbol. But symbols which are not pictorial convey meaning almost entirely without being visual analogs of a real-world situation, and thus may suffer considerable form and position errors without loss of integrity (14) The choice of attitude, command, height and speed symbols thus protects the integrity of presented information.

Symbols

Selection. Symbols representing attitude, command, height, and speed information are selected for head-up presentation because they are amenable to zoning, and are suitable for reasons of continuity and integrity. They also provide the basic necessities of instrument flight because they define attitude, together with position and velocity in relation to the approach path. (For an accurately flown approach, lateral and normal velocity components are negligible and height may be regarded as equivalent to range.) Real world symbols are excluded from the format because they cannot be zoned, and are deficient in continuity and integrity. The selected symbols have simple forms which, together with the positions they occupy, are consistent with principles presented in this section. They are shown diagrammatically in Fig. 5 and, as seen by reflecting collimation against a dark ground, in Fig. 8. The following notes describe their purpose, shape, position, movement, or change of shape, and means of identification within the display format. Similar information is given in Table II.

Aircraft Reference. The aircraft symbol acts as datum for the artificial horizon. It also provides a reference for nulling the index of the flight director symbol. It has the shape of a circle, which is also the shape of the flight director index (or the index may be reduced to a single point). A circular shape is chosen as allowing the similarly shaped director index to be moved into it from all directions with equal ease.

The aircraft symbol remains stationary at the center of the format and is thus also stationary with respect to the airframe, so that it is automatically identified, according to the conformity principle. It is also identified by lateral extensions representing wings, which serve as the datum for estimating bank angle.

Flight Director. This symbol shows the direction towards which to steer, and suggests the amount of control action required. In the null condition it shows that correct action is being taken. The nature of that action is, of course, shown by the horizon symbol. In other words, command, or flight director information is supported by status, or attitude information.

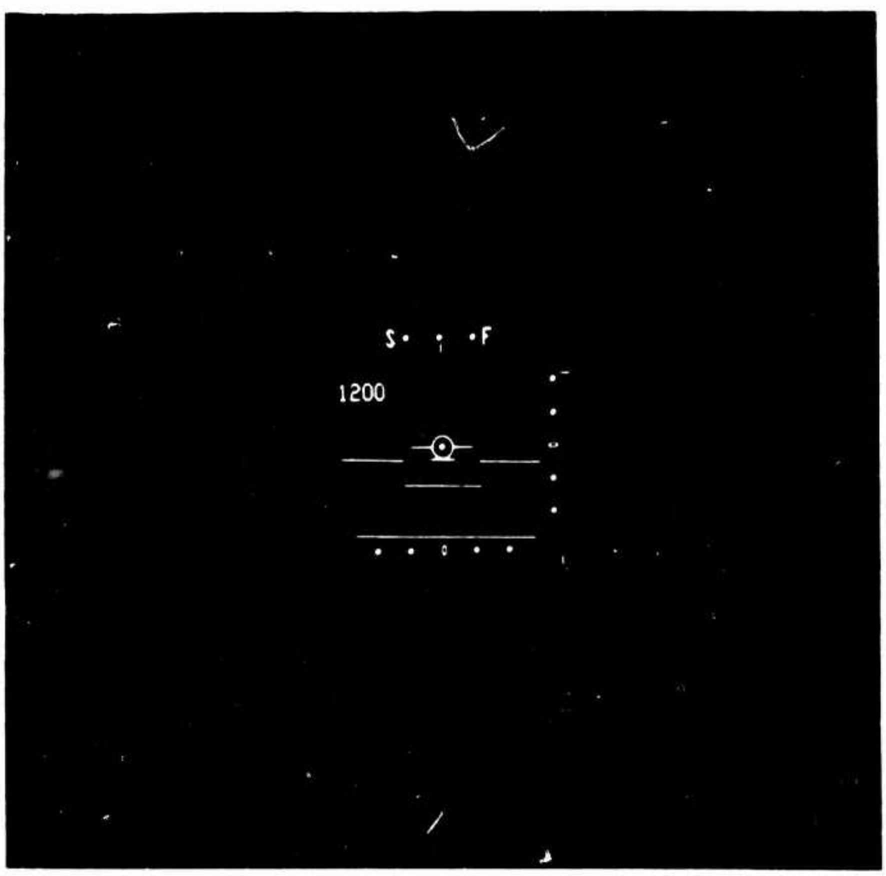

FIGURE 8   DISPLAY FORMAT COLLIMATED ON DARK GROUND

TABLE II. CHARACTERISTICS OF SYMBOLS CHOSEN TO ACCORD WITH ORGANIZATIONAL PRINCIPLES

Symbol	Function	Form	Position	Movement	Means of Identification	Notes
Aircraft Reference	Serve as datum for horizon & director	Circle	Central	None (in format)	Immobility	Equally effective for all director displacements
Flight Director	Show direction & amount of steering action	Perspective crossbars	Distributed over central zone: bank resolved	Fly-to; earth axes; elastic	Mobility	Anti-hypnotic; easily located
Artificial Horizon	Show attitude	Interrupted line	In central zone; bank resolved	One-to-one in bank; scaled in elevation	Movement and form	Avoiding horizon dip problem
Speed	Show speed error, command, or angle of attack	3-dot scale and letters S, F	Peripheral, top center	Only within symbol	Form	Position allows slewing
Height	Show sampled radar height	Digital read-out	Peripheral, top left	None	Form	Position aids access to low digits

The symbol takes the form of a single point (or small circle) and a stack of three parallel lines of diminishing length. The lines are parallel with the horizon symbol, and they lie within an imaginary triangle standing on the lowest line and culminating in the single point, which is the flight director index. The index is the essential part of the symbol. Its position in relation to the aircraft symbol shows the steering direction. Its angular separation from this circle suggests the amount of control action to be taken. By itself, however, the point index may easily be lost against the changing background of flight, and it may become concealed by interference with the aircraft symbol. Moreover, the act of placing the circle on the dot, though efficient, is attention-holding or even hypnotic (a situation common to flight directors). The stack of supporting lines is therefore added to lead to the position of the dot, and to allow the index to be nulled without continually watching it, thus reducing any hypnotic tendency. In addition, bank angle is shown by the direction of these lines, a feature which is useful at large values of pitch attitude. The director symbol is thus distributed over the format for rapid pick-up, reduced interference, and reduced hypnotic effect.

The director index roams the central zone, while the user attempts to "fly" the fixed reference circle towards it. The base line of the stack remains at a fixed distance from the circule, for all bank angles, and this distance can conveniently be made equal to .707 R, where R is the format radius. The dot moves along the horizon, for heading changes, and at right angles to the horizon for vertical commands. Director movements are thus in earth axes, and this framework is emphasized by the direction of the stack lines. As the dot moves, the invisible triangular envelope becomes distorted.

The symbol is identified by the fact that it moves in relation to the aircraft, thus showing a direction in the external world, by the conformity principle, and towards which the aircraft should be steered. It may be thought of as showing a path from "here to there", where "here" means "within the aircraft", and "there" means "outside and beyond", this interpretation being heightened by the perspective form. The symbol does not, of course, represent a runway.

Artificial Horizon. In conjunction with the aircraft reference circle, this symbol shows aircraft attitude. It takes the form of a straight line, which is the simplest shape suggesting division of the upper and lower hemispheres. The horizon line is interrupted at its center to avoid interference with the aircraft symbol.

The horizon symbol also roams the central zone, remaining parallel with the visible horizon. It rarely coincides with the visible horizon, however, because of the reduced scale of elevation (pitch scaling), because of the angle of dip of the visible horizon (which can be shown to vary with height) and because variations of visibility, and variations of terrain, may obviously affect the apparent position of the horizon. The symbol is identified by its linear form, and by its remaining parallel with the visual horizon (and with the head-down artificial horizon).

Speed. The speed symbol shows departures from a datum speed, or it may show command speed derived from angle of attack. The symbol is used in regimes where this type of information is of more immediate application than the numerical value of the aircraft's forward speed. It takes the form of three fixed dots and a movable marker line, which are used as a simple form of scale and pointer. The symbol occupies and remains stationary in the upper center of the format, so that the scale is horizontal, in aircraft axes, this arrangement being prefered to the conventional vertical disposition at one side, because it allows the format to be slewed during a cross-wind approach, as previously discussed. The marker moves to the left when speed is low and to the right when speed is high. The symbol is identified by being the only scale, and by the letters S and F, which have been introduced to denote slow and fast directions.

Height. This symbol shows radar height intervals traversed during climb or descent, which can be sampled at a rate varying with height. For example, close intervals are expected to provide useful information during the flare but not at greater altitudes, and the sampling rate may therefore be increased as the runway is approached. The symbol is used during approach and takeoff where vertical speeds tend to be constant, so that the user can build up a rhythmic method of acquiring height information. In these modes, the numerical value of the height is taken to be more important than an analog value. The height symbol is therefore in the form of a numerical read-out. It remains stationary in an upper left zone, the upper right being reserved for the eventual presentation of barometric altitude, for reasons previously discussed under Symbol Position. The symbol is identified as the only numerical element of the format.

To sum up, collimated presentation of the symbol format constitutes the Head-Up Display (HUD) as used in the present investigation. It has been shown to accord with principles of selection, organization and design, promoting visual interchange with the external world and efficient access to relevant information. The experimental program is therefore expected to confirm corresponding properties of accurate tracking, rapid learning, and continuous transition, which have already been established in the military application, and which it would obviously be desirable to repeat in the field of civil aviation, if a suitable installation could be engineered.

3. INSTALLATION

The main difficulty of installing the Head-Up Display is, of course, in finding room for a comparatively large piece of equipment in a region of the instrument panel where most of the space is already occupied. Little difficulty arises in military aircraft, where cockpits are often designed around the optical system of a reflecting gunsight, and it is only necessary to find a little more room for the slightly larger reflecting collimator of HUD. But no such situation exists in civil aircraft, where the corresponding panel space is quite densely populated with primary flight instruments. Invasion of this area would cause a major change in panel design and, apart from the cost, could scarcely fail to influence conventional instrument flight procedure.

The difficulty was avoided in preliminary flight tests(2) by strapping the reflecting collimator directly onto the upper surface of the glareshield, without affecting the instrument panel. The arrangement is shown in Fig. 9 for DC-9-30 Ship 48, where the resulting penalty is very evident. Although the system operated with satisfactory optical efficiency, there was an appreciable loss of visibility through the center windshield panel, and face clearance was less than enough. What has now to be determined is whether a less cumbersome arrangement can be achieved without loss of optical efficiency. It has to be asked, What are the basic optical needs for the system? What are the mechanical problems of providing adequate body clearances for the pilot, and of achieving a necessary freedom from vibration? Also, What conventional visual requirements have to be maintained? It will be seen that some installations offer partial solutions to the overall problem, but a complete solution is desirable if HUD is to be used in regular airline service.

Optical Problems

Orientation of Reflector and Collimator. The basic optical problem is to install the reflecting collimator so that the display format is seen in the forward line of sight, as discussed under Format Position. For this to be possible, the exit pupil (or last optical aperture) must be imaged to lie in the forward line of sight, and the collimator axis must be directed so that its emergent beam travels in the direction of eye datum. These conditions are satisfied when the orientation of collimator and reflector satisfies a simple relationship based on the laws of reflection.

The relationship is illustrated in Fig. 10 where lens A and reflector M_1M_2 are arranged to present a collimated image of object K in the forward line of sight through eye datum E. When the lens is at A and its axis directed towards a point O on the forward sight line EO, the lens aperture may be imaged at A' and its axis transferred to A'K', where A' and K' lie on EOK'. This, of course, occurs when M_1M_2 bisects the angle A'OA. If the lens is moved to B, with its axis still directed towards O, the aperture may be imaged at B' and the axis transferred to B'J', where B' and J' also lie along the line EOK'. The reflecting surface has now to be placed in a position M_3M_4 which again bisects the angle through which the collimator axis is transferred, BOB'. It is easy to show that the rotation of the reflector is half the rotation of the collimator, or $AOB = 2M_1OM_3$.

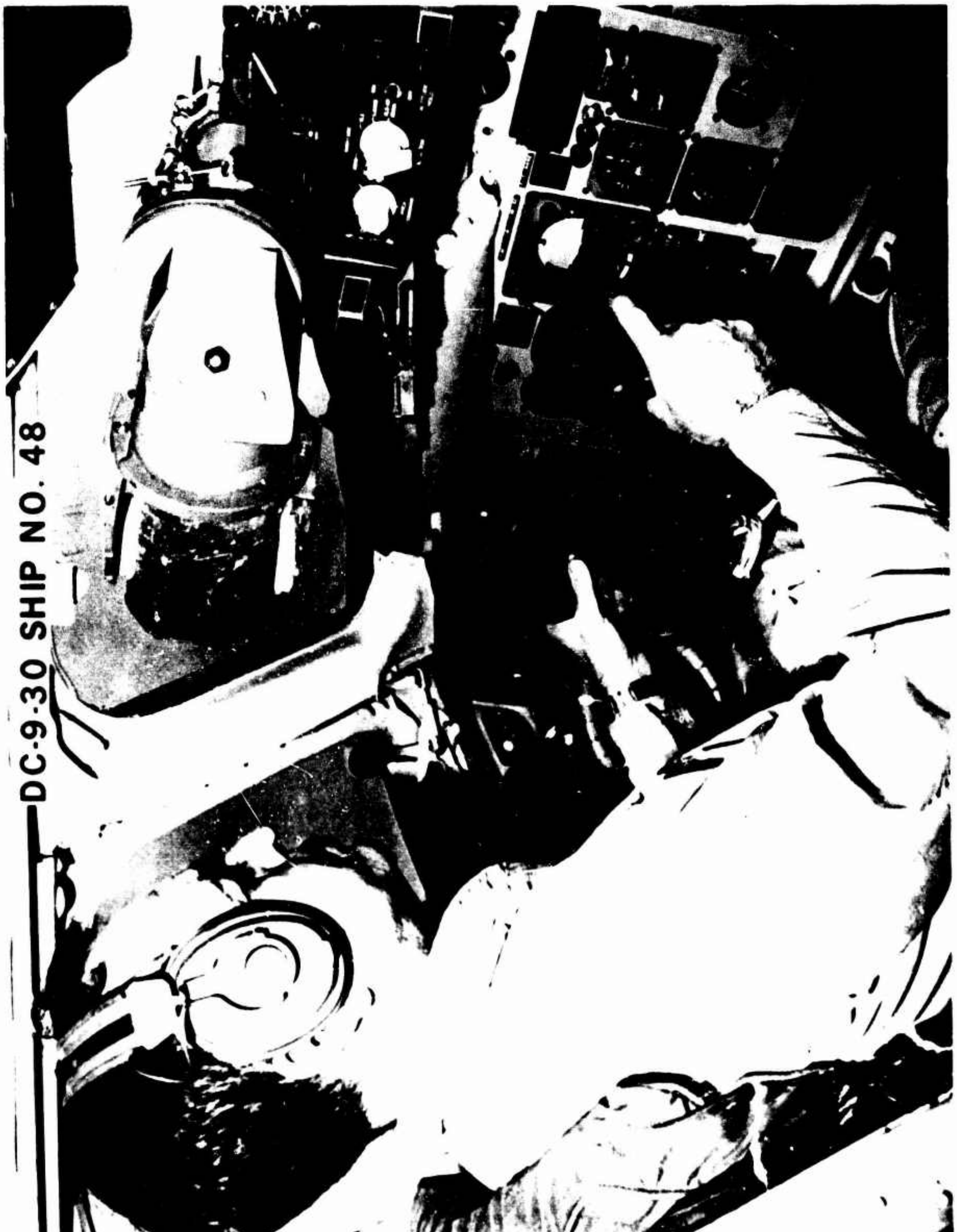

FIGURE 9 EXPERIMENTAL INSTALLATION OF REFLECTING COLLIMATOR IN DC-9-30

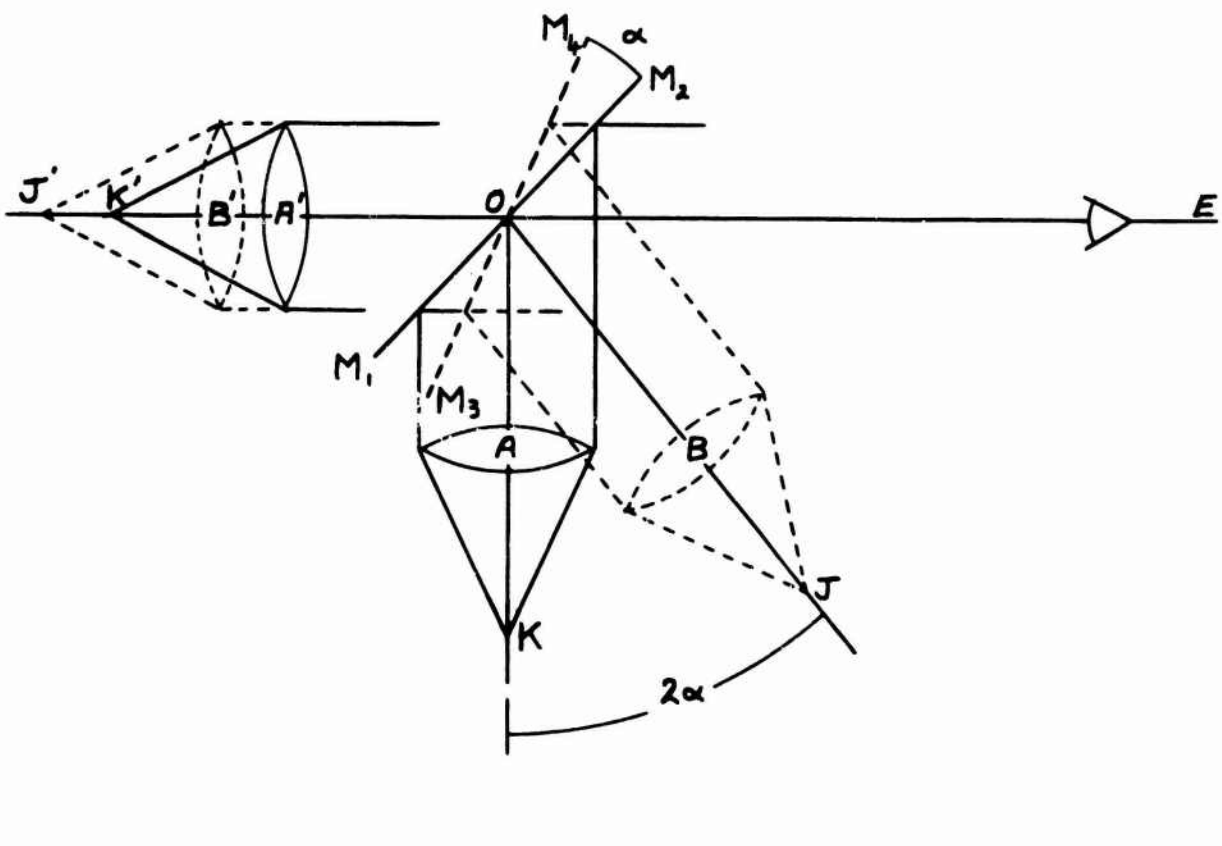

FIGURE 10 ORIENTATION OF REFLECTOR AND COLLIMATOR

In satisfying this relationship, it is necessary to start by placing the reflector in the forward sight line, at a distance limited by face clearance and windshield position. Orientation of the reflector is then governed by the position of the collimator, which can be chosen within fairly wide limits but which must always allow the axis to be directed towards the reflector. It is sometimes helpful to fold the optical path with an auxiliary mirror, but the basic optical relationship nevertheless amounts to an unfortunately rigid constraint, especially if the collimator is bulky, and this is sometimes felt in making small adjustments to the system.

Volume of Collimator Barrel. Dimensions of the collimator housing, or barrel, are very largely determined by optical considerations, and a problem arises because good viewing conditions are generally to be obtained by enlarging the collimator, thus requiring more installation space. The barrel needs to be wide enough to house an optical aperture providing adequate head freedom; for a given symbol only remains visible as long as an eye remains within the pupil diameter, as shown in Fig. 11. Also, the barrel must be long enough to house a cathode ray tube of sufficient picture quality, and to accommodate a focal length sufficient to avoid high aperture ratio.

Experience in previous investigations [1,2,5] has shown that the optical aperture needs to be at least four inches in diameter if the user is to be comfortable. Also, by keeping the focal length as large as the aperture, it has generally been possible to achieve good optical quality without undue complexity of design. Finally, the smallest acceptable cathode ray tube length is about seven inches, in the present state of the art. The collimator barrel will thus be nearly five inches in diameter and about twelve inches in length; that is, about the size of an attitude indicator. Clearly, space cannot be found for equipment of this size in a densely populated instrument panel, except by major rearrangement of currently installed equipment, or by the obviously unacceptable expedient of allowing panel instruments to become obscured.

Instantaneous Field. As an indirect consequence of barrel size, there is a problem in providing sufficient instantaneous field in the restricted space available in an airplane cockpit. The instantaneous field is the visual area in which symbols can be seen from a fixed eye position. For a viewing distance D and a collimator aperture 2A, the instantaneous field is $2 \tan^{-1} A/D$, since an object subtending this angle in the focal plane will just be visible, while rays from a point further from the optical axis cannot reach the eye position, as shown in Fig. 12. The problem arises when it is necessary to increase the viewing distance, since aperture should then be increased to maintain the instantaneous field, with consequent increase of installation space.

In military aircraft, there is no problem in installing a reflecting collimator in the center of the instrument panel. The simple arrangement of Fig. 1 is then possible, with the help of an auxiliary mirror built into the collimator barrel, and the viewing distance may be as little as 20 inches for a 4 inch aperture system, if the face clearance is assumed to be 16 inches. These values give an instantaneous field of nearly 11.5°, which was typical of systems found satisfactory in earlier work[1,5]. A central position is less acceptable in civil aircraft because it causes excessive rearrangement of the conventional instrument panel, but an adjacent position might be

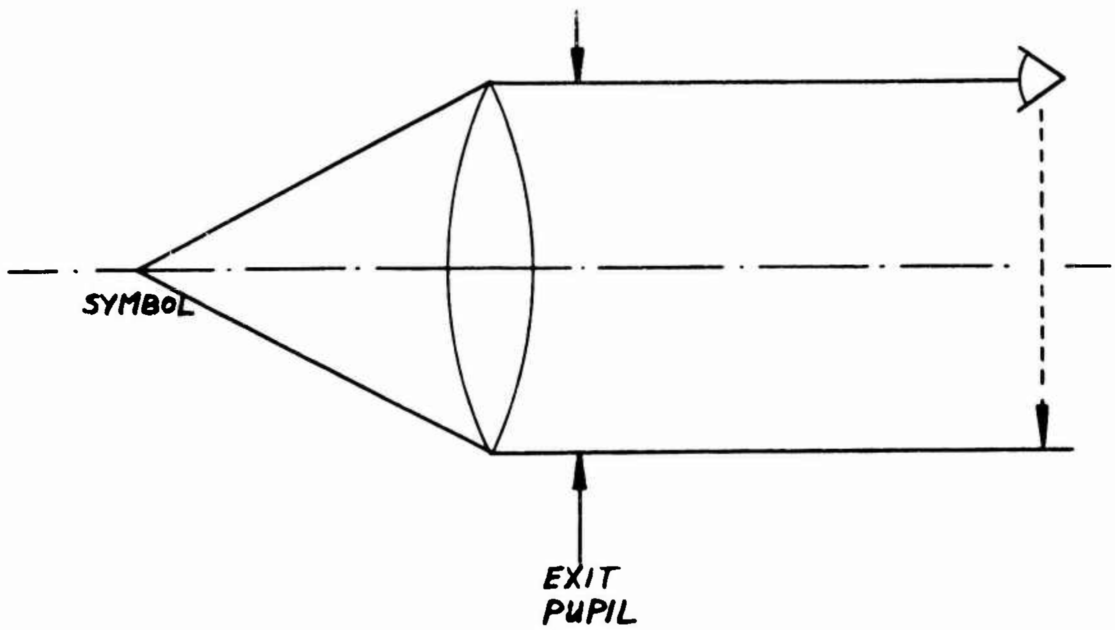

FIGURE 11 COLLIMATOR APERTURE AND HEAD FREEDOM

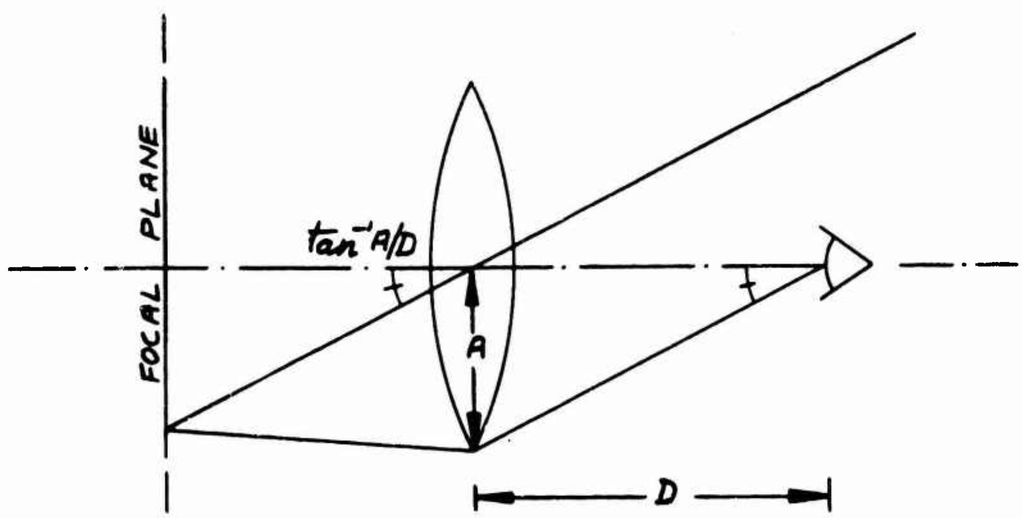

FIGURE 12 INSTANTANEOUS FIELD OF COLLIMATOR

acceptable if the consequent increase in viewing distance were not too great. In the DC-9 cockpit, it is found that the viewing distance with a 4 inch system can be held to 22 inches for a position just outside the instrument panel, and it is to be determined whether the resulting 10.25° field is sufficient.

Obstruction of Forward View. An obvious visual requirement is that the pilot's external view should not be obstructed by any part of the system. Now according to Figure 10, the reflector must be located in the forward sight line if the exit pupil is to be imaged in the same direction. It follows that care should be taken in designing this unit to avoid features likely to obstruct the forward view; for example, it is desirable to use the lightest of reflective coatings and to reduce the visibility of edges and supports. No major difficulty is encountered in satisfying this requirement, as will be shown.

On the other hand, if the collimator barrel is allowed to intrude upon the forward view, the pilots' external visibility will be reduced because of its opacity and size. The barrel is therefore to be excluded entirely from the volume swept out from eye datum through the edges of all forward-facing windshield panels; and since it cannot readily be installed in the instrument panel, space needs to be found in the narrow region between the top of the panel and the glareshield, or even further afield. The nature of this problem can be judged from Fig. 13, which shows the limited space available in the DC-9 cockpit.

Mechanical Problems

Hand Clearance. A small viewing distance has been seen to be desirable in maintaining the instantaneous field; it has also been seen that the exit pupil will only be correctly placed if the reflector is in the forward sight line. It follows that at least part of the installed equipment may be close to the pilot, and it is therefore necessary to make sure that body clearances are sufficient for safe operation. For example, the pilot's hands will only be free to move safely if the equipment is excluded from a space enclosing the control wheel, augmented by a knuckle clearance of, say, 1.5 inches, for all fore-and-aft positions of the control column.

The effect of this restriction is to intensity the problem, already discussed, of installing the barrel in the narrow region between panel and glareshield, for the wheel clearance envelope may interfere with this region, as can be judged from Fig. 13. Unless the wheel configuration can be changed, the barrel has to be moved sideways into a position such as the one shown in Fig. 14 for the First Officer's station in the DC-9; this is above the instrument panel, below the glareshield, and beyond the hand clearance envelope. Further detail is given in Fig. 15, where the clearance can be judged after allowing for foreshortening due to camera position. The penalty in choosing this position is to displace caution and warning indicators, and to conceal the "bow-tie" warning and failure indicator, which can be seen in Fig. 14 above the left hand grip of the control wheel. The viewing distance is found to be 22 inches for this glareshield installation of the reflecting collimator.

FIGURE 13 RELATION OF INSTRUMENT PANEL TO GLARESHIELD IN DC-9-20

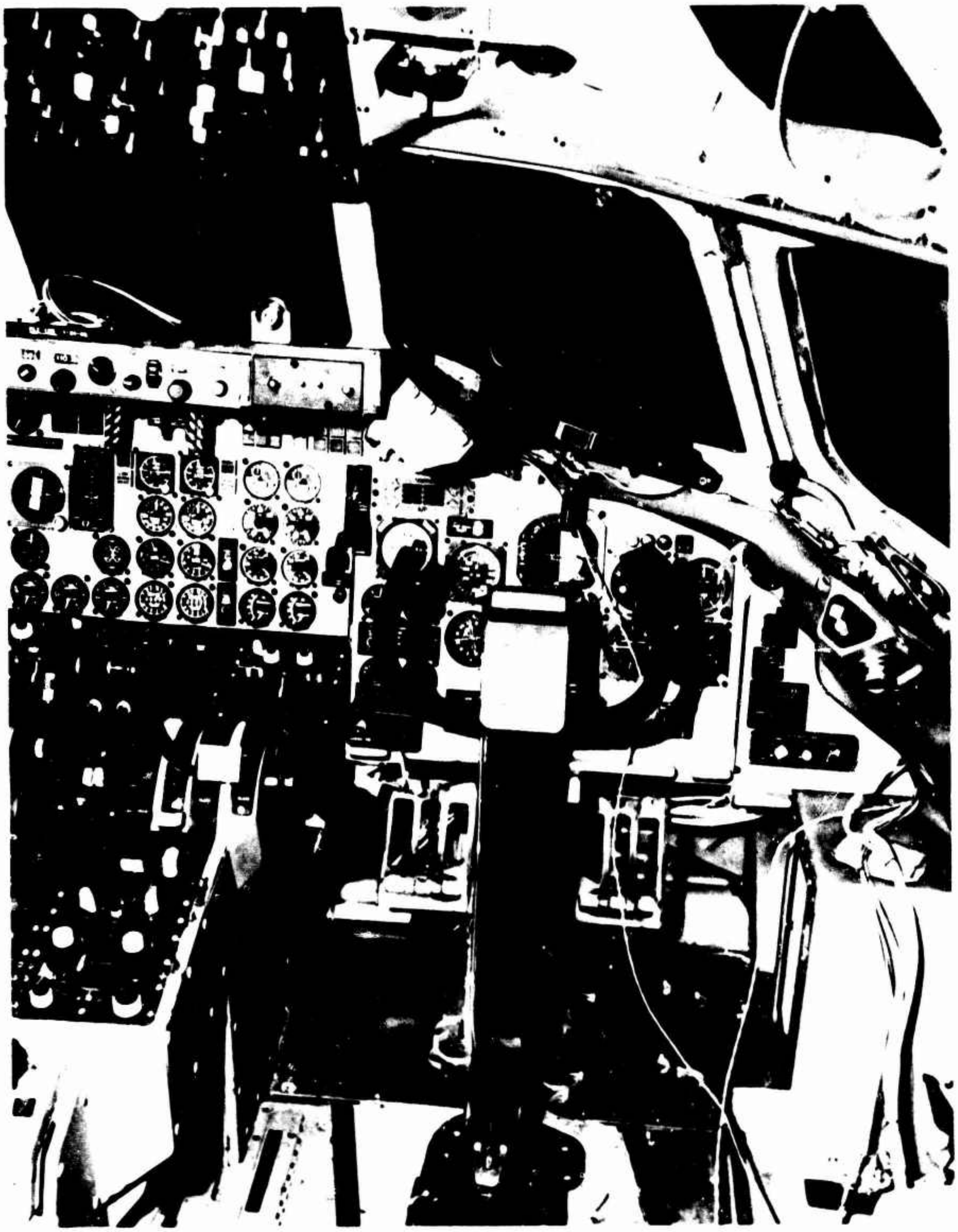

FIGURE 14 FIRST OFFICER'S GLARESHIELD INSTALLATION

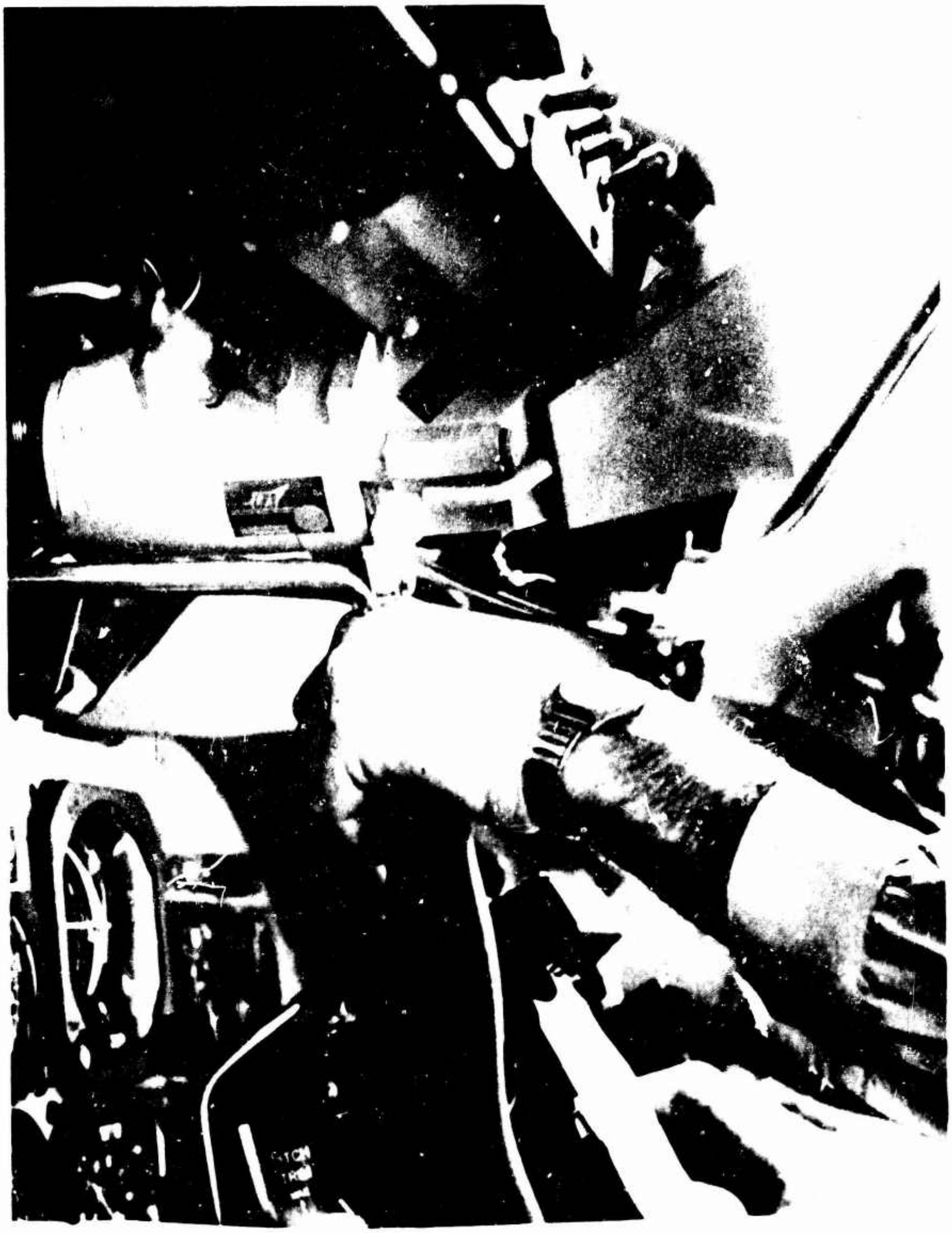

FIGURE 15 HAND CLEARANCE FOR GLARESHIELD INSTALLATION

Face Clearance. Another body clearance to be provided is for the pilot's face. It has to be decided, for example, whether equipment can be mounted closer to his face than the edge of the glareshield, or whether anything nearer might be struck, when seated normally and wearing a restraining harness, or would constitute an additional hazard in an emergency. It seems difficult to make a case for bringing equipment closer than the glareshield, for which the position has probably been decided by similar considerations of protecting the pilot. The problem is, essentially, to accept a face clearance which can scarcely be less than 16 inches, (the value assumed in discussing instantaneous field) and the consequent limitation of field.

Fortunately, the instantaneous field is adequate for a 4 inch collimator mounted centrally in the panel, as a folded system, with a 16 inch face clearance, but it may not be adequate at the increased viewing distance due to a non-central position, as noted above. However, the underlying difficulty, of reducing viewing distance without reducing face clearance, would not arise if the exit pupil were placed close to the face without encroaching mechanically on the face clearance. For example, the pupil might be projected into position by an auxiliary optical system. But because of the increased difficulty of protecting the consequently extended optical path from vibration, and because of resulting increases in size and weight, this method seems unlikely to succeed.

Now, discussion has so far been limited to installations with the collimator barrel below eye level, but mountings above eye level can equally well be made if the same optical and mechanical problems are solved. Clearly, orientation of collimator and reflector continues according to Fig. 10, except for inversion about the forward sight line. Barrel volume remains the same, except as a result of changing optical parameters, but a straight optical system is more suitable to the available space. It is convenient to separate barrel from reflector, leaving the latter in the forward sight line and beyond the face clearance envelope, while bringing the barrel well aft to avoid obstructing the forward view. As a result, viewing distance is increased, the exit pupil being imaged well ahead of the reflector, and it may therefore become necessary to accommodate an increased optical aperture. An immediate advantage is to eliminate the hand clearance problem, by removing all equipment from the region of the control wheel. The face clearance problem remains unchanged, however, because the reflector is in much the same position as before.

An overhead, separated mounting for the DC-9 due to W.S. Cook is shown in Fig. 16, a photograph taken in the All Weather Landing Simulator[15]. From eye datum, a clear view is obtained through the windshield, although this is less evident in the photograph than in the next illustration, Fig. 17. The viewing distance is 25 inches, and the instantaneous field with a 4 inch aperture is a little over 9°, the adequacy of which is to be judged by flight test. The photograph clearly shows that the system is not allowed to encroach on normal hand and face clearances.

Head Clearance. An additional body clearance is required as a consequence of overhead installation: it is necessary to ensure adequate space above the pilot's head for safe, comfortable operation. The problem is essentially to

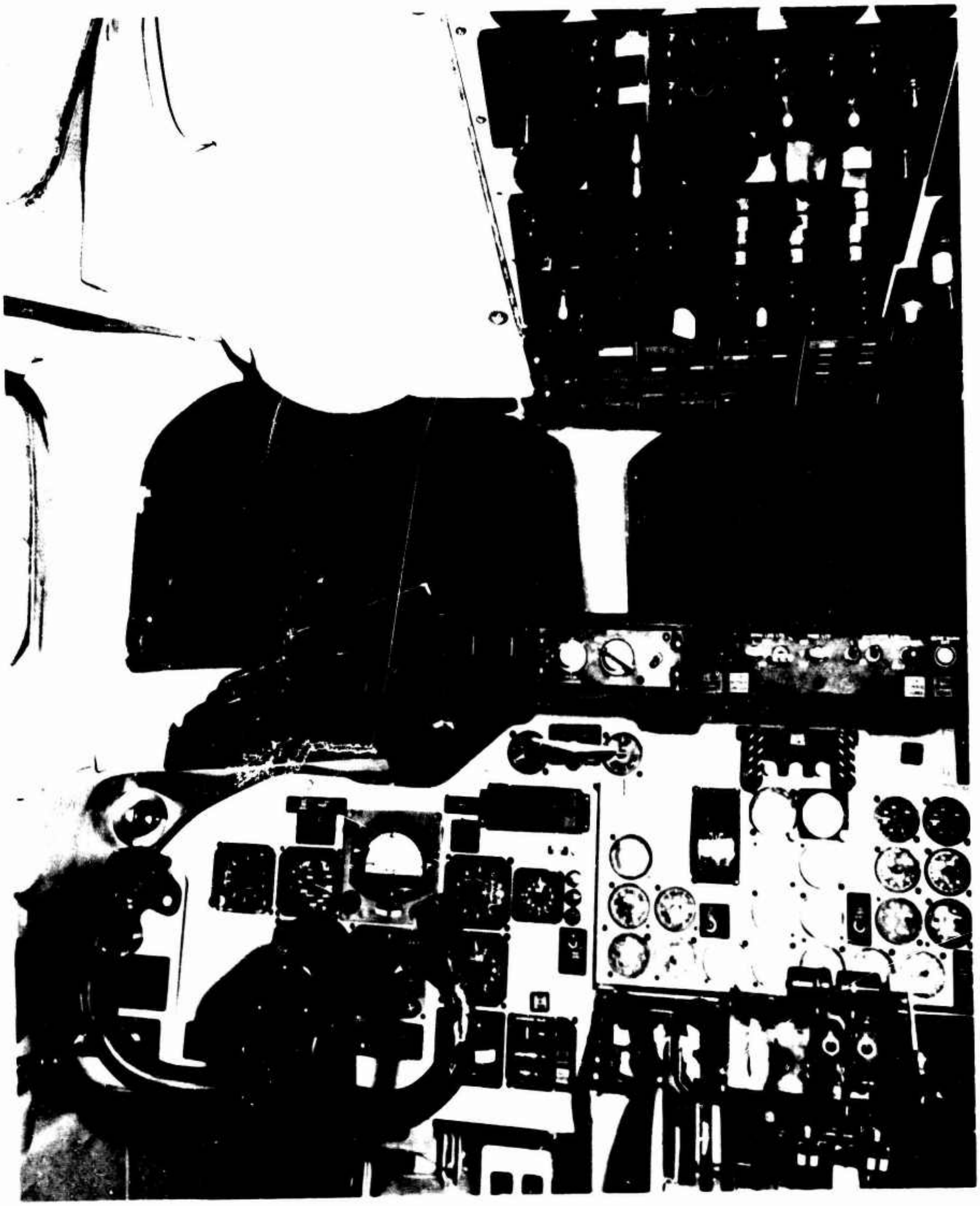

FIGURE 16 CAPTAIN'S OVERHEAD INSTALLATION

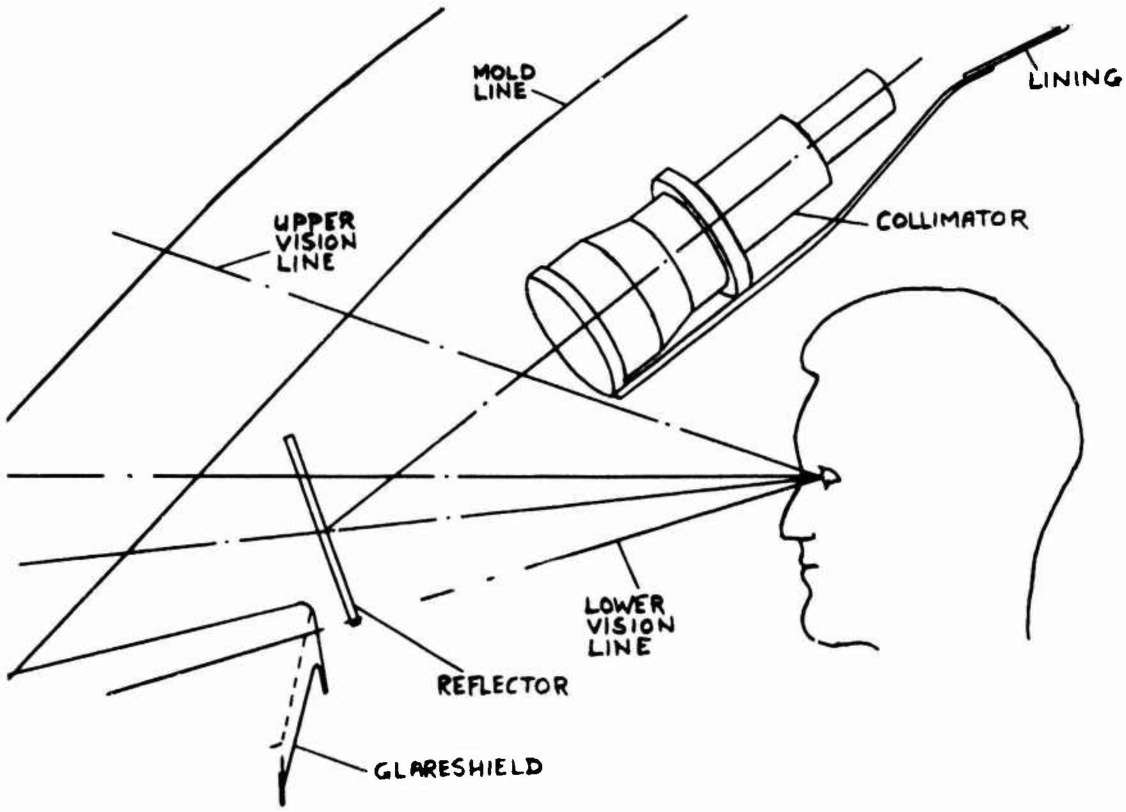

FIGURE 17 OVERHEAD INSTALLATION SHOWING HEAD CLEARANCE AND UNOBSTRUCTED WINDSHIELD

determine whether the collimator may extend downward below the regular level of the head liner, intruding upon the overhead space normally available to the pilot. It could be argued that some of this space may be sacrificed because the pilot's restraining harness is sufficient protection against being thrown upwards, but it is nevertheless important to preserve space for all the pilot's head movements, including those which occur in taking, leaving, or adjusting the seat. Clearly, the extent to which this space can be invaded depends on a careful balance of conflicting requirements.

It could also be argued that head clearance may be reduced on a temporary basis, bringing the collimator into position only when required for use. It is not difficult to see, however, that costly, elaborate and precise mechanism would be needed for a retractable installation, and that pilot acceptance could not be automatically assumed. Otherwise, this method might well provide a solution to both head and face clearance problems.

The relation between the pilot's head and the collimator in the DC-9 overhead installation is indicated in the side elevation of Fig. 17. The barrel extends below the head liner and is covered by fairing. It can be seen that contact between head and fairing is unlikely to occur while in harness, and could only happen with a combination of upward and forward movements, through a distance which is a little more than 2 inches. The chance of this happening is a matter for flight test.

Protection Against Vibration. Another mechanical problem is to remove vibration effects from the display system without unduly elaborating the method of mounting. The effects of vibration on the internal functioning of the system will naturally be kept within specified limits in the manufacturing process, and tested prior to installation. However, effects on the installed system must also be limited, by preventing movement of the equipment or its components. Translational movements are unlikely to give trouble because the display format is imaged at infinity, but rotation of the reflecting collimator or its components, about lateral or vertical axes, can cause apparent movements, with broadening of symbols and loss of information. It is unlikely that the system will rotate as a whole, whether it is attached directly to main structural members or mounted in the glareshield, because it is massive. It is more likely that the less massive reflector will move, especially when it is separated mechanically from the collimator.

An experimental form of anti-vibration reflector mount for the DC-9 overhead installation is shown in Fig. 18. As in the arrangement of Fig. 16, the reflector is mounted separately in the glareshield, and this part of the airplane is considered more likely to move vertically than in any other direction. The resulting movements of the reflector would not be expected to have an effect on image quality since they would be mainly in the plane of the reflector, but they might cause the reflector to rotate resonantly about its lower edge, where it is hinged. To reduce any such motions, and the risk of image broadening in a vertical direction, supporting struts are used to tie the glareshield to the panel, and side struts are added which can be attached at selected points up and down the sides of the reflector, to

FIGURE 18 ANTI VIBRATION MOUNT FOR CAPTAIN'S REFLECTOR

vary the amount of control. In the case of the glareshield collimator installation, Figs. 14 & 15, only glareshield supporting struts are provided, since the reflector is integral with the collimator. The degree of essential elaboration in these precautionary measures was to be judged in flight.

Discussion

Examination of the optical and mechanical problems of installation has shown no easy method of finding suitable space for the reflecting collimator. Its reflector must lie in the forward sight line, with the collimator barrel directed towards it, possibly with the help of an auxiliary mirror to fold the system. The barrel will be about the size of an attitude indicator if it is to provide suitable head freedom and picture quality. It will then give sufficient instantaneous field (11.5°) if located centrally in the instrument panel area, as a folded system, assuming that no reduction can be made in the conventional face clearance. But a central location is at present unacceptable in civil aviation and the barrel is therefore to be moved out of the instrument panel. It must also remain below the glareshield to avoid obstructing the forward view. These two conditions can be met, without greatly increasing the viewing distance, if the barrel is housed in the narrow region between panel and glareshield. Since it is also necessary to provide hand clearance, the barrel has then to be moved laterally from the forward sight line, with some loss of instantaneous field (10.25°).

Stages in this discussion as it relates to the Captain's station in the DC-9 cockpit are illustrated in Fig. 19, at A, B and C. The position of the collimator is shown hatched, and the distance from barrel center to forward sight line, FSL, is also shown. At A, the barrel has been moved up from the panel, but without allowing enough hand clearance. At B, hand clearance is sufficient but secondary instruments are concealed. Further movement of the barrel, to the position shown at C, causes less interference with secondaries but the forward view becomes obstructed. The most complete solution is provided at B, and this corresponds with the glareshield installation shown in Figs. 14 and 15. The known penalty for this position is interference with secondary instruments; unknowns are the adequacy of a somewhat reduced instantaneous field and the influence of vibration.

If the barrel is mounted well outside the panel, for example, as a straight system at D, viewing distance is obviously increased, though hand clearance and obstruction problems are solved easily. An alternative solution, with less increase in viewing distance, is to invert the system into an overhead position, leaving the reflector in the forward sight line, and separating it from a straight barrel which is moved aft to clear the forward view, Fig. 16. Here again, no hand clearance problem arises, and it is only necessary to move minor items, such as an air vent and a map light. Unknowns in this case are the acceptability of a reduced instantaneous field (9°), the influence of vibration on the independently mounted reflector, and the adequacy of the head clearance for general purposes. It is also possible that problems other than vibration may be met as a result of using a new type of reflector, since the surface is mounted at an uncommon angle, for which the conventional frontal aspect may be unsuitable. The main factors affecting the installation are summarized in Table III.

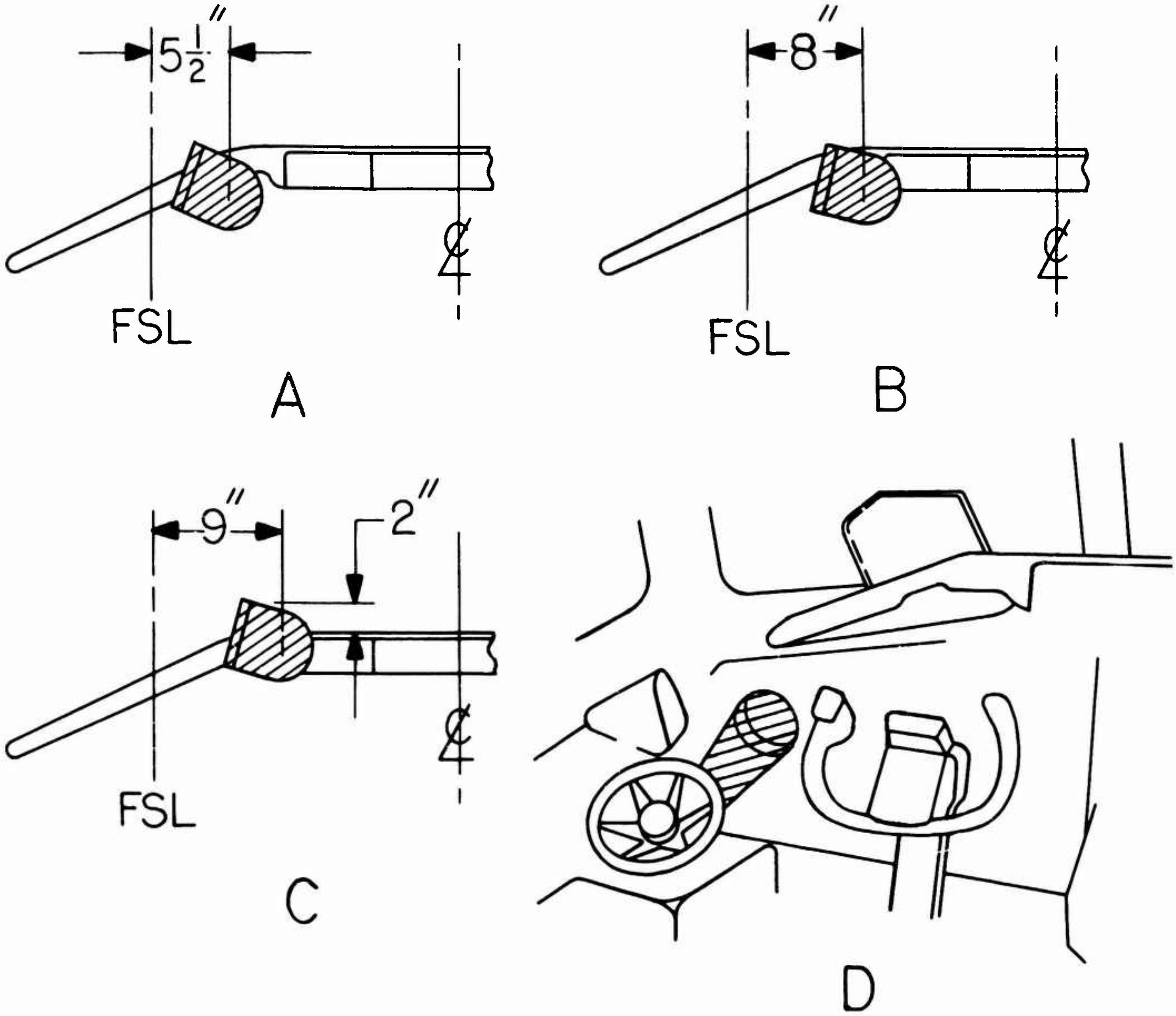

FIGURE 19 POSITIONS OF COLLIMATOR BARREL IN SELECTED DC-9 INSTALLATION MOCKUPS

TABLE III. FACTORS AFFECTING INSTALLATION

(I) OPTICAL	
Orientation	Reflector is in forward sight line with collimator directed toward it.
Barrel Size	Diameter needs to be sufficient for head freedom. Length cannot be reduced without losing optical and/or CRT quality.
Instantaneous Field	Viewing distance is increased for collimator mounted outside inviolable instrument panel, diminishing the field.
Obstruction of Forward View	Barrel is mounted below glareshield or overhead
(II) MECHANICAL	
Body Clearance	Equipment is excluded from envelope of hand positions, and is no nearer face than glareshield. Barrel protrudes below liner if mounted overhead.
Vibration	Oscillation of less massive parts about lateral of vertical axes causes image broadening.
Reflector	Stability, angle, and frontal aspect of overhead reflector are unexplored.
Penalties	Glareshield mounting obscures minor instruments; overhead mounting requires service items to be moved.

Analysis of the installation problem was supported by experimental work, in which twelve alternative possibilities were mocked up. The experimental rig was a simple representation of windshield, glareshield, panel and control column. Orientation was established by means of a mirror having a central aperture for observing the forward sight line, and in which the collimator axis could be seen as the reflected image of an axial rod extending from the barrel. Each installation was investigated as a possible solution to the overall problem. It was confirmed that the glareshield installation of Fig. 14 and the overhead installation of Fig. 16 were best solutions, with the reservations previously noted.

To sum up: two installations have been chosen as meeting most optical and mechanical needs. With a collimator barrel of a size adequate for picture quality and head freedom, a face clearance no smaller than the conventional value, an unobstructed windshield, and a conventional degree of hand freedom, the glareshield can be used to install an integral, folded system; alternatively, a separated, straight system can be installed overhead. There are small penalties of moving minor items, of about the same magnitude in the two cases. Each installation has an instantaneous field smaller than used previously, and carries some risk of being influenced by vibration. The overhead installation may have head clearance and reflector problems. Both installations were to be tested in flight, with display equipment based on optical parameters carried forward from previous work.

4. FLIGHT EVALUATION OF EQUIPMENT, FORMAT, AND INSTALLATION

Equipment for generating the symbol format of Section 2, and for presenting a collimated image according to the optical conditions assumed in Section 3, was supplied by Conductron-Missouri and by Elliott Flight Automation. In each case, the collimator was essentially a 4 inch f/1 system, which could be assessed in relation to performance levels previously achieved with similar systems. The equipment was also to be assessed for contributions to the visual information process originating in the cathode ray tube and the associated waveform generator. The symbol format, however, as an item specified to the manufacturers, was to be evaluated separately, and then only for the changes introduced in the present study, the main properties of the format having already been determined[1]. Finally, and with most significance to this application of HUD, evaluation was to include a comparison of two installations resulting from the analysis presented in the preceding section.

A preliminary assembly was made in the All-Weather Landing Simulator[15], the Elliott equipment being used for the First Officer's installation of Figure 14, and the Conductron equipment for the Captain's installation of Figure 16. The integral, folded reflecting collimator supplied by Elliott was mounted in an aperture formed in the glareshield. The straight collimator supplied by Conductron was mounted overhead by a bracket attached to structure, and the separate reflecting unit, shaped to enclose the exit pupil for all eye positions, was mounted in a recess in the upper surface of the glareshield, into which it could be folded down for stowage. A small control panel was mounted near the base of each reflector unit.

After checking through each system, the assemblies and the glareshield were transferred to DC-9-20 Ship 382 for flight testing of equipment, format, and installations. The chief basis of evaluation was to be the judgment of experimental test pilots, S1 and S2. As a preliminary measure, the display system was calibrated, at the Captain's station, to establish the meaning of movements or changes in each symbol.

Calibration

Flight Director. Control gains, governing movements of the flight director index, were the subject of investigations reported separately in the next section; at the calibration stage it was sufficient, for the evaluation of general features, to set up the system using "production" gains; in other words, with arbitrary gains derived from values suitable for conventional flight director instruments. Electrical gains of the aircraft's flight director computer (production fit) were compounded with optical gains suggested by preparatory work in the simulator (the conventional type of director gain, expressed as volts per degree of demand, has little meaning by itself in head-up presentation) and the overall gain was checked experimentally for order of magnitude and sign. For example, angular deflections for a given heading demand were observed with the help of a small, wide-angle telescope, and null deflections were used to check "compensatory" gains, such as heading to bank ratio. Subsequent adjustments were found to be necessary in flight to avoid capturing the ILS beam with a reversed command, and to prevent premature capture.

Artificial Horizon. The horizon symbol was calibrated to determine the pitch, or elevation scaling; that is, the number of degrees of pitch attitude change in the real world represented by one degree of displacement in elevation of the artificial horizon. Signals representing outputs from the vertical gyro and, therefore, real-world attitudes, were used to move the symbol, through angles observed with the wide-angle telescope. The elevation scaling factor was found to be 12.0. A check was also made for the sign of a displacement by consulting the head-down attitude indicator, to avoid the anomalous situation of the horizon symbol moving in opposition to the visible horizon.

Aircraft Reference. It was not necessary to calibrate the aircraft symbol for movements or changes because it remains fixed and invariant, in its regular function as reference for director and horizon symbols. It was also unnecessary, in regular use, to establish meaning for its position since the symbol is associated with the aircraft (by the conformity principle of applying similar rules to a symbol in the display and to a corresponding feature in the field on which the display is superimposed) because it remains fixed in aircraft axes, rather than because it is directly observed to coincide with an aircraft axis. Moreover, the associated director and horizon symbols convey their meaning by relative position, without the need for, or possibility of, coincidence with visible counterparts in the external world, since the concepts of a command and a true horizon are abstract.

There was nevertheless a possibility of using the aircraft symbol position, exceptionally, to show the direction of an aircraft axis; as might be useful, for example, in attempting to project the direction of the flight vector. In calibrating for this purpose, the aircraft was parked on level ground with its longitudinal axis horizontal, and a distant marker was set up in the forward sight line at the same height as eye datum. Shift controls in the display control panel were then used to align symbol and marker, as seen by telescope, so that the aircraft reference would show the direction of the longitudinal axis. At the same time, the shift controls were calibrated in degrees of azimuth and elevation, allowing the symbol to be displaced through the angle of attack, say, so as to represent the elevation of the flight vector. Unfortunately, a similar calibration procedure was, of course, necessary after each change in position of the reflector plate, a consideration tending to limit this application of head-up presentation.

Another possibility, suggested by pilots, was the inverse function of fixing the aircraft symbol and moving the datum position of the horizon symbol through the angle of attack. Experience in flight, however, soon showed this type of horizon trim to be potentially dangerous and it was removed, returning to the condition of an undeflected horizon symbol at zero pitch attitude.

Speed Display. The speed display was calibrated to establish meaning for deflections of the movable marker. This was done by measuring the angles of attack needed for full-scale deflections, using a protractor and moving the angle of attack vane by hand. The center of the speed display was found to represent an angle of attack of 12 deg, and full-scale deflections represented 8 deg changes from this value.

Height Read-Out. Calibration of the digital height read-out was needed to determine the relationship between displayed height and radar altitude, which was the data source. A signal representing radar altitude was used to drive the digital read-out and the conventional radar altimeter, thus showing the radar heights corresponding to the heights sampled by the digital read-out. The same procedure was repeated in real flight with actual radar altitude, during slow descents over the sea. The sampling interval was set at 20 feet, the value expected to be most generally used.

Results of the calibration can be understood with the help of Figure 20 which illustrates some of the methods available for sampling height in a digital read-out. In method A, samples are in effect taken at the top of each interval; for example, the interval from 80 to 100 is called 100, while in method B, samples are taken at the bottom of an interval. Clearly, a maximum error of one sampling interval (20) is possible in both methods. The situation is improved in method C, where intervals are sampled centrally; for example, the interval from 70 to 90 is called 80, and here the error cannot exceed half an interval (10). The method used with the equipment tested was to sample at the bottom of an interval (B), with the important consequence that in the lowest interval the digital read-out showed zero at a height of 20 feet. At the other end of each interval, agreement between radar and digital height was within one foot.

Control Logic. Another aspect of calibration was to establish a control logic ordering the correct appearance and disappearance of symbols, enabling the format to be varied with information requirements for en route and terminal flight modes. The control logic was also to be used to remove symbols associated with a defective data source (Continuity, Section 2). The tests were made simply by operating the flight director mode selector switch, and by injecting dummy signals representing failed sources. Faults were found affecting the selection of raw ILS, speed, and master warning symbols; more seriously, the director symbol could not be occulted for signal failure and would allow beam capture in a "flagged" condition. No major problems were met in correcting these faults or in meeting an additional requirement for Altitude Hold in the VOR mode.

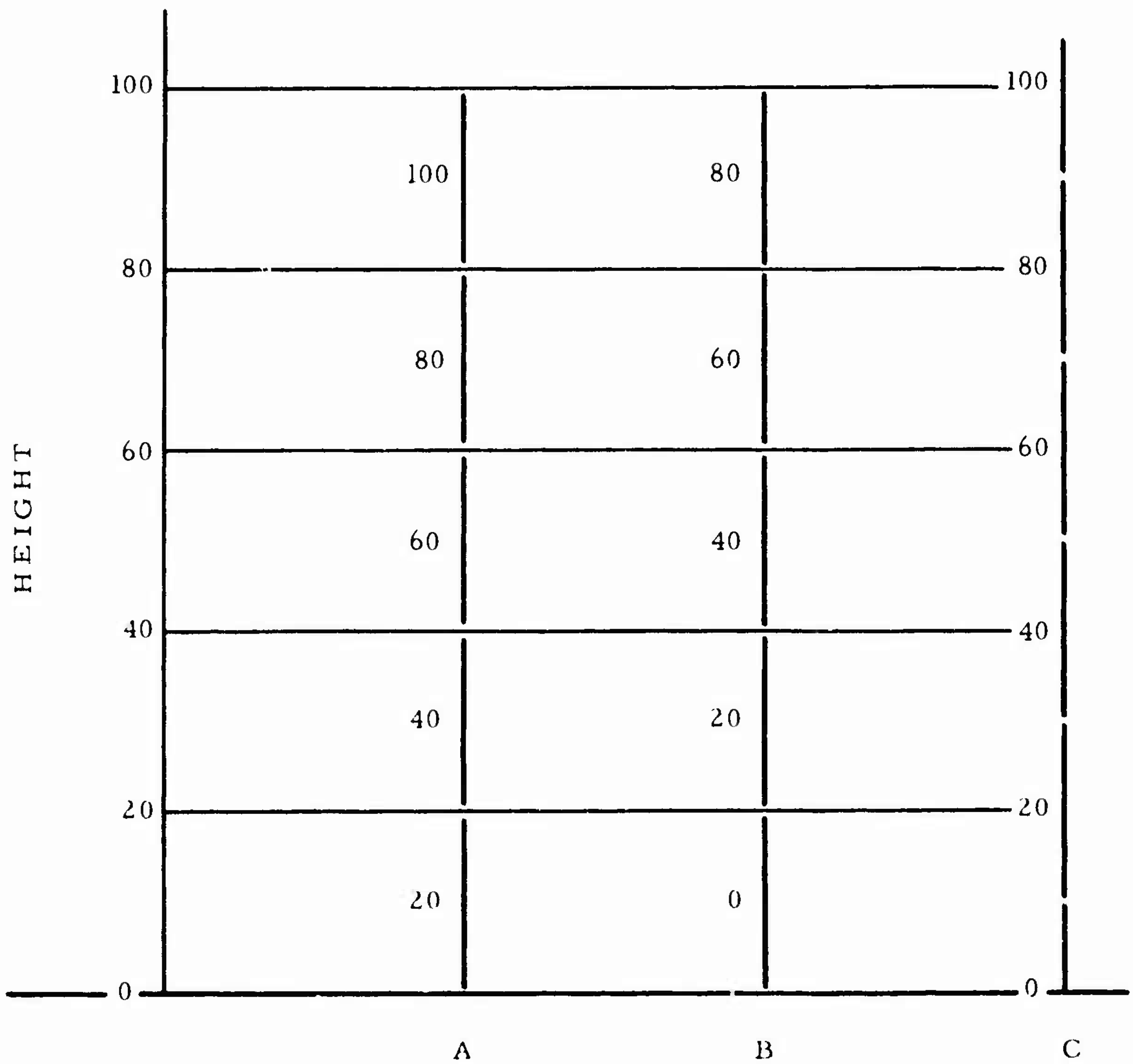

FIGURE 20 METHODS OF HEIGHT SAMPLING

EQUIPMENT

Optical Characteristics of Collimator

After calibrating the system, evaluation began with optical characteristics of the collimator, which were to be judged, as far as possible, in terms relating to the transfer of information. For example, it was considered better to observe degradation of an information process than to measure the optical aberration in which it originated, such as parallax, distortion, or chromatic aberration, and a similar approach would be used for the cathode ray tube and waveform generator. Other optical features of the collimator include head freedom and field of view, although these will later be discussed as characteristics of the installation, being independent of the way the equipment had been manufactured.

Parallax. In the absence of parallax, the display user is able to move his head from side to side without seeing relative movement between a symbol fixed in the format and an object fixed in the external world, the vehicle being in a stationary state. This condition is desirable because an apparent movement in a nominally stationary symbol could degrade the information process; for example, movement of the aircraft symbol could suggest a non-existent movement of the aircraft axis. Moreover, absence of parallax allows an independent check on collimator focus.

The test method was for the pilot to move his head from side to side while observing the aircraft symbol against a distance landmark, a procedure which could more easily be carried out under stable flight conditions than on the ground because of difficulties in obtaining sufficient horizontal visibility. The tests showed no relative movements over the greater part of the field. Some movement was noted at the edge of the field, with both sets of equipment, but the effect was evidently complex because the motion was oblique. Both systems were judged free of parallax to an acceptable degree.

Distortion. The effect of distortion in the collimator is to change the apparent shape of symbols. It should not be a serious effect because the symbols used in the format are able to withstand fairly extensive changes of shape without disturbing the transfer of information[16]. But the user is also concerned with drawing information from the external world, against which a distorted symbol becomes an impediment to the conformity principle, or at least a source of annoyance. Distortion is therefore undesirable, especially in the more frequently used symbols.

The test for distortion was to observe any lack of straightness in the horizon symbol as it moved through the field, and this test was easily made with the aircraft grounded. Some distortion was observed with the symbol displaced to a mid-field position, as a slight curl in the outer end of the line, which may have had the same origin as the symbol movement noted under Parallax. Since only peripheral symbols were affected, and only to a slight degree, the amount of distortion was considered acceptable.

Chromatic Aberration. The occurrence of chromatic effects in a format intended to be of uniform color tends to degrade the information process, by presenting an irrelevance. Since light emitted from the cathode ray tube is not necessarily monochromatic, it follows that the collimator must be achromatised within visible limits.

The test was simply to look for colored edges to the symbols, for the full range of display brightness and against various backgrounds. No such adverse effect was found.

Cumulative Effects. It is to some extent possible for the eye to compensate for defects of focus in the collimator: for example, if an object supposedly at the focus K in Figure 10 is in fact in an adjacent plane, so that the image is not presented at a very large distance, the eye may accommodate for the actual image distance without the viewer's knowledge. Against a background of distinctly visible objects in the external world, such unconscious compensation would be unlikely, but under flight conditions, where external objects may be difficult to fixate because of movement or poor visibility, it might be possible for aberrations associated with defects of focus to go undetected. The user could then suffer eyestrain through the less-than-perfect viewing conditions, especially in extended use of the display system. The presence in the collimator of spherical aberration, astigmatism, and coma, which otherwise would be difficult to limit on the basis of information transfer, is thus only acceptable at levels allowing protracted use without eyestrain.

Flight tests gave somewhat conflicting evidence about the cumulative effect of residual aberrations. Both S1 and S2 used the system continuously without eyestrain during flights of up to three and a half hours duration, and under widely different conditions. At a later stage in the tests, there were some complaints of poor image quality and visual fatigue, as reported under User Comment, Section 6. The conflict may be explained by a deterioration in viewing conditions; for example, because of an apparent loss of focus due to too much brightness, or through changing tube characteristics. This possibility could not be checked during the course of flight tests, and it could only be concluded that optical quality was at least good enough during early stages of the work to avoid cumulative effects.

Instantaneous Field. The (monocular) instantaneous field defines the visual region from which information can be drawn without change of viewing position (Figure 12). It is consequently important when there is a tendency to spread symbols, notably through adding symbols to a known format. An instantaneous field of about 11.5 deg was sufficient on previous occasions (1, 5) for presenting a format similar to Figure 5. In the present flight tests, the format was enlarged by the addition of peripheral ILS scales, while the instantaneous field was somewhat reduced, giving some cause for concern.

Its sufficiency was judged from opinions formed in varied conditions of use over a period of about two months. At the Captain's station, the instantaneous field was 9 deg, and this was considered to be adequate for seeing all that was needed of the format at any one moment. At the First Officer's station, however, although the instantaneous field was 10.25 deg, it was considered a little too small. The anomaly was evidently due to the format being somewhat larger in the First Officer's equipment, through being written on the tube face at a different scale, so that peripheral symbols were closer to the edge of the instantaneous field and the user was required to take greater care in maintaining his viewing position. After allowing for the obvious possibility of shrinking the larger format, it was concluded that the instantaneous field was sufficient, and could be as small as 9 deg for the format in use.

Head Freedom. The head freedom normally determines how much the head may be moved without losing sight of a given symbol (Figure 11), and is nominally equal to the aperture. It is significant when the user is concerned with a continuous flow of information from a given region of the format. A head freedom of 4 inches was found sufficient in previous work[1, 2, 5].

The basis for judging head freedom in the present work was to be able to make routine movements from a correctly established eye position, return to what was believed the same position, and find the same part of the format immediately. It would then be possible to maintain a sufficiently continuous flow of information despite interruption for a task such as setting the compass, the head freedom being sufficient to absorb small differences of eye position arising in the process. As a result of extended use, it was judged that both installations provided entirely acceptable head freedom, thus confirming previous findings.

Total Field. The total field includes all the visual area made available for collimated presentation of the format. It is usually greater than the instantaneous field and covers areas of the object plane, that is, the face of the cathode ray tube, which can only be seen by change of viewing position, whether by moving the head or using the other eye. For example, light from the object point shown in Figure 12 just reaches the eye, but light from an object point further below the optical axis could only reach the eye when displaced to a position above the axis. The significance of the total field in airborne use is that it allows the format to be moved, by shift controls, for alignment with an external reference, while moving the head to keep the format in view. Conversely, if the viewing position is unchanged, parts of the format lying in the periphery of the total field can be brought within the instantaneous field by the shift controls. The need for external alignment may arise, of course, through crosswind and aerodynamic effects displacing the longitudinal axis from the direction of resultant motion.

The total field is determined simply by the working diameter of the cathode ray tube and the collimator focal length: for example, a tube diameter of 1.8 inches is sufficient for a 25 deg total field with a focal length of 4 inches, and a field of this magnitude was available in the equipment tested. Judgment of the total field was based on slewing the display in crosswind conditions and observing whether all the format could be seen by moving the head.

Sufficient field was found to be available for this purpose, as is reasonable since an instantaneous field of 9 deg can be slewed 8 deg within a total field of 25 deg, allowing operation with a crosswind component of about 18 knots during an approach at 130 knots. It may be noted, however, that many users considered this method of operation to be unnecessary, as reported under User Comment, Section 6, in which case a smaller total field would have sufficed.

Visual Characteristics of Cathode Ray Tube

A picture drawn on the cathode ray tube may be described in terms of its brightness, color, line width, and shape. Of these visual characteristics, which all affect the information process in some way, the first three are considered at this point, as contributing to the optical quality of the complete collimator unit. On the other hand, shape is determined by format requirements and errors arising mainly in the waveform generating equipment, so it will be considered separately under Form Errors.

Brightness. The cathode ray tube surface is required to provide sufficient brightness for symbols to be seen against all backgrounds encountered in flight, so that the flow of information is never interrupted. An appreciable level of tube brightness is thus desirable because the contrast threshold increases as the background becomes brighter, according to Weber's Law, which is true at high brightness levels[17]. Blackwell's observations[18] suggest that the contrast threshold could then be perhaps one-twentyfifth of the background brightness, for an object subtending one milliradian, under experimental conditions. But this value should no doubt be increased to, say, one tenth, to allow for the stress of flight conditions. The display format would then need an apparent brightness of 1,000 ft. lamberts to be seen against a background of 10,000 ft. lamberts, an extreme brightness normally attributed to sunlit clouds. Since the maximum brightness provided by the test equipment was nominally 2,450 ft. lamberts, as seen with an 80 per cent neutral density transmitter, no difficulty was expected in using the system in high brightness conditions. At the other end of the scale, the symbol format was, of course, expected to be visible against a dark ground, but the converse problem of seeing the dark background when using a dim display would be influenced by the fineness of the brightness control, at levels associated with dark adaptation, since the user would then be performing with enhanced sensitivity.

In the flight tests, each set of equipment was used with a reflector plate having a 15 per cent to 20 per cent reflection coating. The range of external brightness was very large, the background varying from a mountainous terrain of snowcaps to the almost complete void of the night sky. Under these conditions, the format was always visible; it was also conveniently maintained at a level of brightness appropriate to the background by an automatic control, except that the control was too coarse for use by night; moreover, a special procedure was needed for dealing with the localized brightness of approach and runway lighting, as discussed under Night Flying, Section 6. Besides using coated reflectors, the system was also flown satisfactorily under most daylight conditions with uncoated glass plates, showing that an adequate reserve of brightness was available, but this arrangement allowed less flexibility of operation, particularly when using automatic brightness control. The brightness of the cathode ray tube was therefore judged adequate for practical purposes, and it was noted that all parts of the format were equally bright.

Color. It is sometimes desirable, or necessary, to use color as a means of identifying, classifying, or coding displayed information. No such need was expected to arise in presenting the format of Figure 5 because each symbol was intended to be recognized by its distinctive shape, as mentioned in discussing the simplicity principle, in Section 2. Moreover, there were reasons for avoiding color in head-up presentation; such as the possibility of chromatic relief, or objects appearing to be at different distances because of differences in color[19]; and the possibility that colored symbols may appear as part of the external world, especially against the multicolored background of night flying. These possibilities, and their probable effects on the information process, give rise to doubts about using color in head-up presentation and reinforce the concept of keeping the format as simple as possible.

The formats furnished by the test equipment were of a uniform, green color with a peak emission nominally in the neighborhood of 5500 angstroms. What was to be verified was that the symbols of Figure 5 would always be distinguished from each other in a monochromatic presentation, and unambiguously recognized as belonging to the format. The backgrounds against which symbols were seen included city environments, snow-covered mountains, desert, agricultural landscape, blue sky, and yellow-brown haze, as seen in clear weather between about 11 a.m. and 3.30 p.m., while the range was later extended to cover bad-weather and night operations. It was found that symbols were always distinguished from each other, except in respect of some minor effects which were resolved by purely geometrical methods, as reported under General Aspects of Format Modifications (Identification) in this section. It was also found that the display color gave coherence to the format, enabling all symbols to be distinguished from the background, yet without causing unnecessary distraction. Use of a monochromatic display of this color was therefore considered to be satisfactory.

Line Width. The width of line used in writing symbols on the cathode ray tube is limited by the need to resolve all detail significant to the information process. It can be seen from Figure 8 that the format would not be changed greatly by a small increase in line width, except that the alphamerics would become more difficult to recognize. These characters are sensitive to small differences in form which would easily be masked by an increase in line width, and it is convenient to make the stroke width one fifth of the character size to secure adequate recognition, as is often the practice in designing visual test charts[20]. The size of an alphameric character was about 20 minutes of arc, and if these symbols are taken as defining the limiting detail, the appropriate stroke width should be 4 minutes, or a little more than one milliradian. This value can be taken as the limiting width for lines having steep edges, or it might be used to derive a limiting value for lines having diffuse edges.

The nominal line width for the equipment under test was in fact one milliradian, at maximum brightness but for an unspecified profile. As would be expected, the test flights showed the alphamerics to be completely recognizable against the backgrounds already described, at least in early flights. It was noted later, however, that lines were fuzzy, perhaps through using too much brilliance (User Comment, Section 6), and there was some broadening on the left side of the First Officer's format. In spite of these uncertainties, it was clear that line width, however measured, could be made small enough for the purposes of information transfer, at least with equipment in prime condition.

Errors in Generating the Format

The display equipment includes a waveform generator used to form and maintain the required picture shape on the face of the cathode ray tube. Its ability to perform this essential part of the total function of presenting the display obviously depends on avoiding errors in forming individual symbol shapes and in giving them their correct positions within the format. A suitable basis for evaluation is thus the incidence of form and position errors affecting the transfer of visual information, including variations of these errors with time, or visual noise.

As mentioned under Integrity in Section 2, symbols which convey information without being analogs of real-world situations, having forms governed by coding conventions and positions specified only in a relative sense, are more easily protected from form and position errors than symbols in one-to-one correspondence with objects in the external world. Moreover, symbols thus protected are immune to the influence of visual noise, except for the effect of rapid oscillations in causing blurring, and the effect of local, or partial-field noise on the symbols sensitive to relative position[14]. The format contained only symbols of this kind, so form and position errors were not expected to trouble the user, except that noise might make symbols difficult to see, or might degrade information when affecting only parts of the format.

Form Errors. No measurements were taken of form errors: their occurrence was simply inferred from complaints made in flight test reports. Only the digital height read-out gave trouble, and this was confined to the First Officer's equipment. Here, the numerals were formed by joining a relatively small number of points, as can be seen in Figure 21, where zeros have a hexagonal form. The resulting shapes were considered unsatisfactory, especially the numeral 4. By contrast, the numerals in the Captain's display were formed from a larger number of points, as can be seen in Figure 22, where at least one extra point has been added to improve the shape of the top and bottom of each zero, with very satisfactory results.

FIGURE 21 FIRST OFFICER'S FORMAT WITH DIGITAL HEIGHT READ-OUT

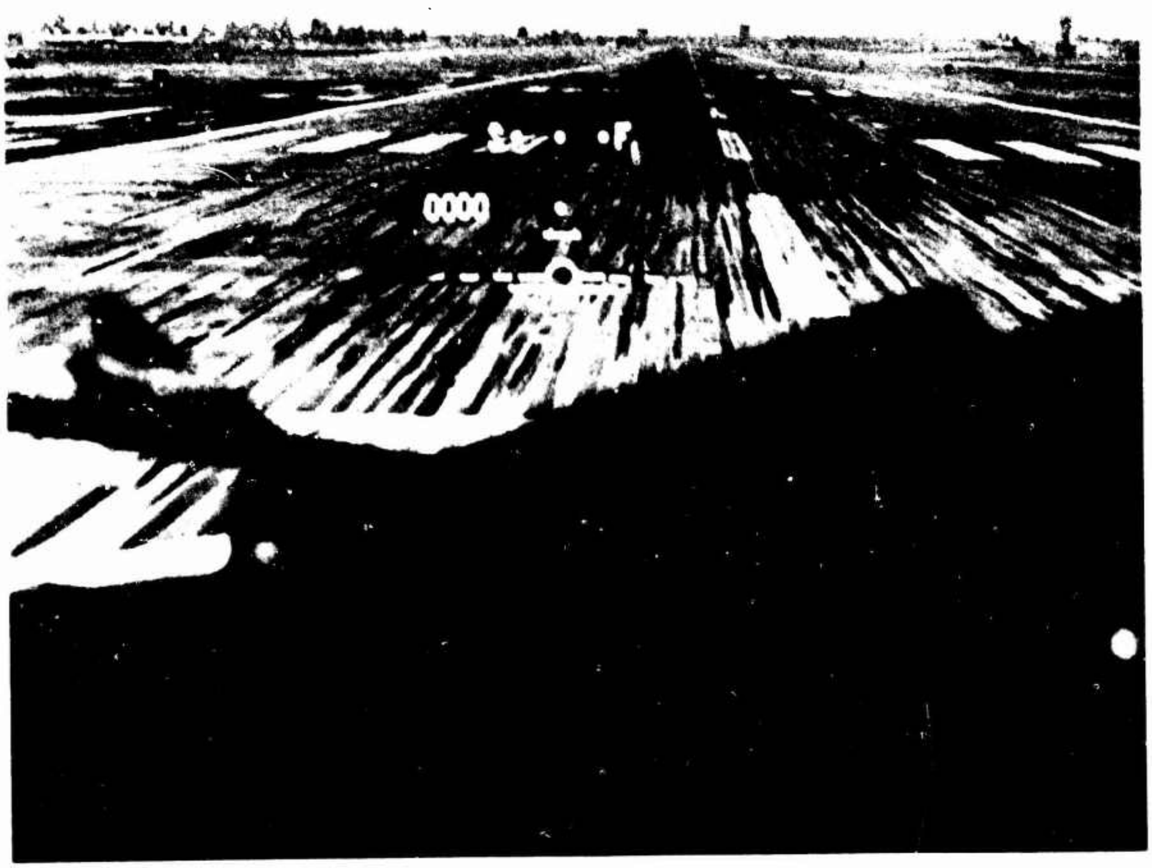

FIGURE 22 CAPTAIN'S FORMAT WITH IMPROVED READ-OUT AND DISCONTINUOUS HORIZON SYMBOL

There were no incidents reported with either format of being unable to recognize a numeral, though the complaints about the form of numerals indicated some measure of interpretative difficulty. There was an isolated complaint about lack of roundness in the First Officer's aircraft symbol. Otherwise, there were no indications of form errors troubling the user and it was concluded that no serious impediment to the information flow resulted from this cause, as was expected. Nevertheless, a certain amount of attention to waveform generation was needed in the First Officer's equipment to equal the standard satisfactorily demonstrated at the other station.

Position Errors. Flight test reports were also used to assess position errors, which were expected to be significant only as errors in bank angle, or as errors in the relative position of director index and aircraft reference. The flight tests confirmed expectations, for after removing some residual errors of bank angle by reorientation of the reflector plate, only errors in the flight director were reported. In the null condition, as defined by the head-down flight director, the index was observed to have drifted away from the aircraft symbol. It was also found that legitimate excursions were non-linear. These effects occurred in the First Officer's equipment.

It was possible to eliminate non-linearity but zero error could not be entirely avoided, and appeared to accumulate with time, as a drift. An error of this kind, with its obvious effect in reducing flight path accuracy, was not acceptable. In other respects the First Officer's equipment was evidently free of position errors. The Captain's equipment was entirely free of observable effects of position error.

Noise. Two kinds of noise were evident in flight test reports: a jittery movement affecting all symbols, making them difficult to see, and jumpy movements affecting part of a symbol, degrading the information represented by the complete symbol. Both types of noise were in line with expectations and both were experienced with each set of equipment. They were also both of electronic origin, although some jittery movements were due at one stage to vibrations of the reflector plate, as reported under Installation.

Jitter was seen as an oscillatory motion of up to four line widths, at two or three cycles per second. It was occasionally reinforced by periodic variations of brightness. Jitter was reduced to an acceptable level by improvements in grounding.

Jumps were frequently observed in the flight director symbol, in early flight tests. They were usually caused by external transients, arising during changes in flight mode, during trim control actuation, and during operation of auxiliary hydraulic equipment. A particularly troublesome kind of director jump occurred during approaches with an aircraft parked near the runway, through reflective interference. Jumps were largely eliminated by the use of rate limiting in the flight director computer.

Other types of noise included occasional spikes on line symbols, which were annoying, and a more serious effect originating in the sine-cosine potentiometer used to resolve director and horizon symbols in bank. This was first experienced as a slight twitching, in bank, of the resolved symbols, and was brought on by buffet. The effect became more severe in later flights, and culminated in complete collapse of the format. It was cured by improving the contact between wiper and winding.

These observations showed the extent to which the display system could be affected unless great care were taken to eliminate noise. Jitter caused some loss of information and had a nuisance value proportional to its visual prominence: director jumps, while equally prominent and annoying, also degraded the guidance information; the sine-cosine potentiometer could cause the format to vanish. Exceptionally, there was some value in allowing a jump to mark onset of a flight mode but noise was otherwise an annoyance, all too easily induced, and a cause of information loss.

FORMAT

Format Modifications

Certain features of the format were new, or had not been investigated sufficiently in previous flight tests, and these were to be evaluated as concepts rather than as characteristics of the supplied equipment. Slight changes had been made in the aircraft, horizon and director symbols: the digital height read-out, though used successfully in earlier flight tests[5], had not been covered in previous DC-9 flight tests; raw ILS scales and the master warning symbol were new additions. These features were to be judged individually, and in relation to such known properties of the whole format as might be affected by the changes.

Aircraft Symbol. Variations were made in the length of wing attached to the aircraft symbol with a view to finding a configuration suitable for the estimation of bank angle. At the same time, the gap in the horizon symbol was adjusted to the changed wing span. As a result of use in flight, it was found that each wing could conveniently be given a length equal to the diameter of the reference circle. This variation was made in the Captain's equipment, with the result shown in Figure 8.

Horizon Symbol. As an alternate to the regular horizon symbol of Figure 5, the same symbol was presented as the discontinuous line shown in Figure 22. The object of this change was to increase the power of distinguishing between artificial horizon and flight director symbols. Tests showed, however, that the object was not altogether achieved, and this form of symbol was not incorporated as a permanent modification.

Flight Director Symbol. Two variations were made in the form of the flight director symbol. The first was to give the symbol "elasticity" in both command channels, so that it would expand and contract in a vertical direction for elevation commands, besides shearing laterally for azimuth commands, as shown in Figure 5. This change, which was intended to provide a more homogeneous concept, was made in the Captain's format, while using "elasticity" only for azimuthal shearing in the First Officer's format, where vertical commands were shown by vertical displacement of the complete director symbol. As in earlier investigations[5], the change was found to be an improvement, and it was considered to result in less interference between director and aircraft symbols.

The second variation was to replace the director index by a small circle, which is just visible in the photograph of Figure 8. The object was to make the index more prominent, without sacrificing the capability for accurate placement within the aircraft reference circle. In the opinion of S1 and S2, the change was successful, especially because it allowed the top crossbar of the director symbol to be moved away from the index and thus reduce the chance of interfering with the aircraft symbol. Subsequent users were divided in their opinions, as reported under User Comment in Section 6, and this change could therefore hardly be considered essential.

Digital Height Read-Out. The height component of the format has been described in Section 2 as having a visual form and position intended for take-off and approach, where a numerical value is taken to be the kind of presentation sought by the pilot, who also needs to find it in an easily accessible position. Height was sampled at numerical intervals, so that rate of change of height was given by the rate at which the read-out changed, and the user was thus required to exercise a somewhat new technique in acquiring rate information. The method of sampling has already been described under Calibration, and reference has been made to the shape of numerals in the First Officer's format, under Form Errors. It remains to enlarge on the recognition of numerals, and to deal with position in the format, choice of height interval, and efficiency in acquiring height rate information.

Evaluation of the height read-out continued throughout the course of flight tests, with the user given choice of sampling interval. As the tests progressed, it became clear that the well-shaped numerals of the Captain's format could be recognized without ambiguity, though they were felt to be a shade thick. Also, the location of the read-out was suitable, though a corresponding position in the upper right quadrant would also have been acceptable. On the other hand, it was noted that the passage of hundred foot intervals, which was significant information, was more easily understood with a 50 ft sampling interval than if the read-out changed every 20 ft., indicating the need to keep significant digits within easy reach of the central format area, as the left-hand position more easily allows. In any event, it would be undesirable to fix the sampling interval at 50 ft., since information requirements change with height, as the users confirmed in m g the following recommendations: from 1500 ft. to 1000 ft. the interval should be 50 ft., between 1000 ft. and 200 ft. it should be 20 ft., and below 200 ft. it should be further decreased to 10 ft. Aside from the problem of recognizing hundred foot intervals, there was no difficulty in setting up a rhythmic flow of information without looking too directly at the numerals, once the new technique of estimating height rate was understood.

Incidental comment was made about the possibility of superseding the height read-out by speed information when above the cut-off height, which was 1500 ft., although an increase to 2500 ft. was suggested in later demonstrations (User Comment, Section 6). It was also noted that if the height read-out were used, inadvisedly, at a fixed height, difficulty was experienced with dithering digits, as would be expected. These comments in no way detracted from the conclusion that the digital height display fulfilled its intended function, given time to absorb the new height rate method, while operational values had been obtained for use in take-off, go-around, and approach modes.

Raw ILS Scales. The biggest modification to the format was the addition of raw ILS scales, which pilots had suggested as an aid to better operation during the approach. The presentation was in the form of two simple linear scales, placed in peripheral positions to avoid interference. For economy in waveform generation, the 3-dot pattern of the speed scale was again used, as shown in Figure 23, but this was subsequently replaced by the 5-dot pattern shown in Figure 8, which was similar to the conventional indication. The scales were given positions in the format which were also conventional, with localizer displacement below and glide slope displacement at one side, except that the side chosen could be altered to allow slewing the format in either direction. These symbols were made to appear automatically on selecting the approach mode.

The raw ILS scales were added to the format mainly as supporting information, for since the same data source was used in computing command information, little in the way of integrity would be added by the new symbols. They could nevertheless help in understanding important side effects, such as the anomalous behavior of the display format in relation to the forward view in the presence of beam bends or wind shear, by offering a different "view" of the guidance information. Their main usefulness would perhaps be in allowing the quality of an approach to be monitored, by a comparison of allowable and actual displacements from the beam. These possible advantages would be weighed against the obvious penalty of an increased amount of clutter.

Flight evaluation showed that the raw information was in fact useful in verifying side effects. For it was sometimes found when using the display for guidance during a visual approach that, as the approach progressed, the format would be aligned with different directions in the external world. By checking that raw displacements were zero, it could be confirmed that the aircraft was on the beam, and not just in a state suitable for regaining the beam. (Another method of reaching the same conclusion would consist

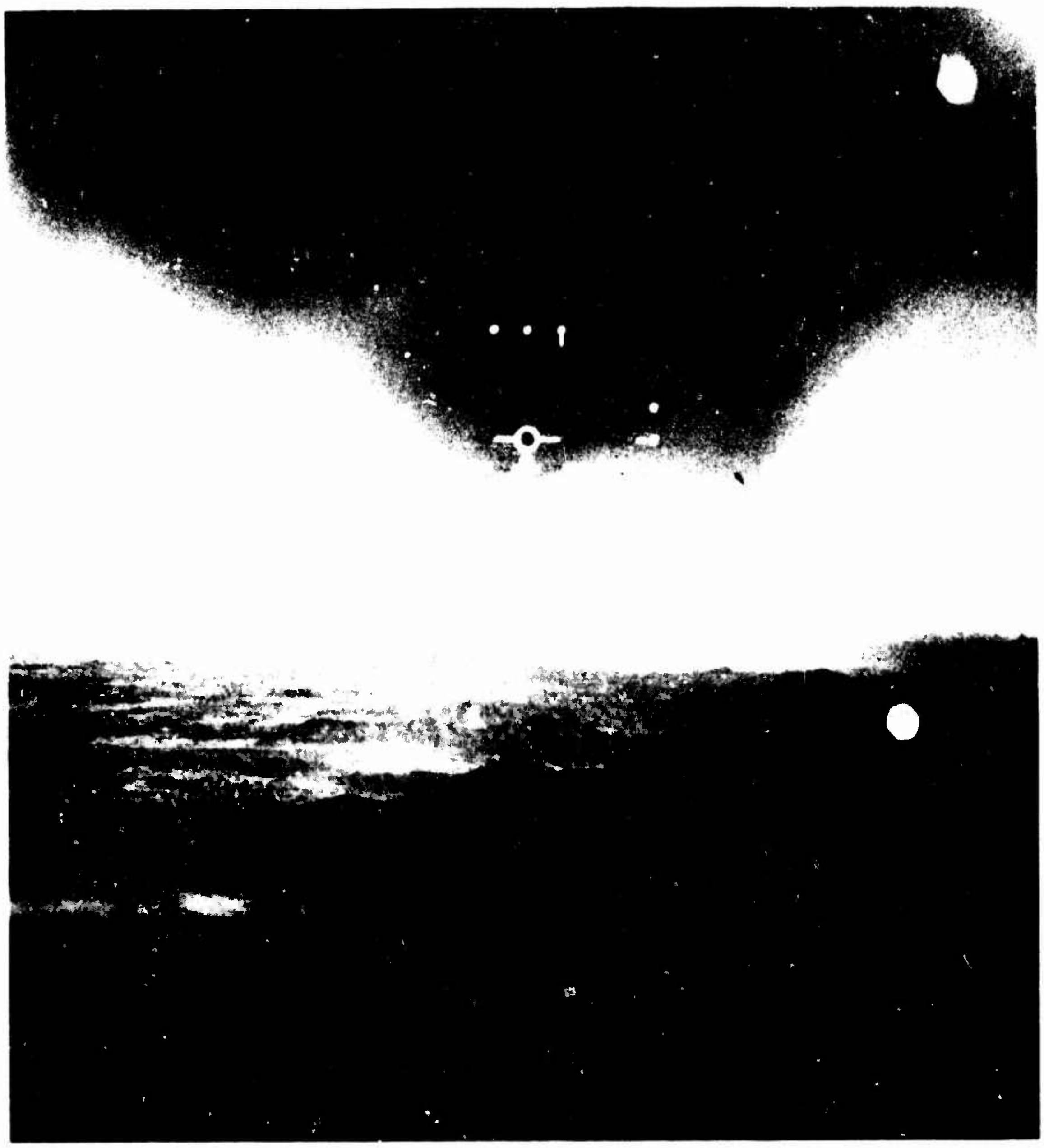

FIGURE 23 CAPTAIN'S FORMAT WITH EARLY FORM OF RAW ILS SCALES AND MASTER WARNING SYMBOL
(Note hexagonal patterns due to sun in recording camera)

of keeping a continuously nulled director in the absence of control action.) Change in the external direction of alignment, as shown by the aircraft symbol, would then indicate a bent beam or wind shear. This capability is also discussed under Photographic Recording in Section 6.

The raw ILS scales were of principal value in monitoring the approach. It was noted by Sl that, for this purpose, the pilot needs a complexity of information: command action to regain the beam, displacements from the beam, and the amounts of displacement allowable at various heights. Since most of this information was available in the format, the pilot simply being required to remember tolerances, the monitoring capability was felt to be quite good.

As will be mentioned in discussing more general aspects of the format, the clutter caused by the scales was at first considered unacceptable, but this view was later reversed. At the same time, the important observation was made that, quite apart from the question of cluttering the forward view, there was no time available for using raw ILS information at heights of less than 200 ft. because the director was then watched continuously. The recommendation was consequently made that the scales be occulted automatically at low altitude, a practice also followed by Morrall(21). There was thus little penalty in adding these useful symbols to the format, especially if only on a temporary basis.

Master Warning Symbol. A new symbol was added to the format for use only in a state of warning, when it would be flashed on and off at a suitable rate. It took the form of a small square, subtending about the same visual angle as the aircraft circle and located in the lower left quadrant, as shown in Figure 23. In this position, the symbol could be introduced with very little interference, in particular, without impairing guidance information. What was lost in prominence by an off-axis position was restored by choosing an occultation rate of between 2 and 4 cycles per second, which was calculated to gain attention without being troublesome. This warning symbol was intended to serve the same purpose as the conventional master warning, showing a state requiring the pilot's attention to auxiliary displays. It was initiated by the same signal used to turn on the master warning and was removed from view by the same cancellation button. It was not provided for the purpose of showing failures associated with other symbols, for which complete occultation was to be used (Continuity, Section 2).

No specific evaluation of the symbol was made. It was assessed chiefly as a result of inadvertent use during a set of approaches when the cancellation circuit became defective. User comment, supported by a movie taken during one approach under these conditions, showed the remainder of the format to be usable while the master warning symbol was in operation. It also showed the symbol to be very prominent. The symbol was thus found to fulfill its purpose without rendering useless the rest of the display.

General Aspects of Format Modification

Beyond effects localized in individual symbols, modifications to the format might have caused more general effects, through influencing the organizational principles outlined in Section 2, viz, the principles of framework, simplicity, zoning, position, continuity, and integrity. Of the alterations made to the format, only changes in the director symbol could affect the framework principle, of showing command and attitude in the same co-ordinate scheme, and since the changes were small and inconsequential (added "elasticity" and circular index) the principle appeared to be unaffected. Similarly, the simplicity principle had not been affected by the introduction of unduly elaborate visual forms, but there had been an increase in clutter, as already noted for the ILS scales; and there might have been some loss in the power of identification simply through increasing the number of symbols, though each visual form was still only used once. The zoning of symbols had been largely preserved in adding new symbols; the height read-out had been placed outside the command and attitude zone, Figure 6, and the warning symbol was also remote and only likely to cause interference peripherally, during temporary appearances; on the other hand, the ILS scales, though peripheral, were more extensive and more permanent, and would perhaps be subject to more noticeable interference. The positions given to new symbols were consistent with their importance and with conventional practice, so no violation of principle was involved, except for the departures made in positioning height digits and in alternating the position of the glideslope scale, which have already been discussed. Continuity had not been interrupted by adding symbols except for the deliberate purpose of gaining attention during a state of alarm. Finally, no information had been added which affected the integrity of symbols except, and then only positively, by adding raw ILS information. The general aspects for further investigation were thus: identification, interference and clutter.

Identification. It was soon evident from the flight tests that all symbols were uniquely identified, so no problem had arisen simply through increasing the number of symbols. This was after making two minor configurational changes to the format: the 3-dot scale was replaced by the conventional 5-dot ILS scale, as noted above, and the letters S and F were added to the speed scale to help in distinguishing slow and fast directions.

Interference. There were some references to interference in flight reports. The localizer scale was found to overlap the lowest crossbar of the director symbol at small bank angles, and this was expected with these very adjacent symbols, since the localizer scale remained fixed in aircraft axes while the crossbar was presented in earth axes. Pilots stated, however, that the effect was acceptable. There was also some interference between the top crossbar and the aircraft reference circle. As an improvement, pilots suggested that this crossbar be moved away from the index, to reduce interference during the relatively frequent displacements of small amplitude. This was a change which, as noted above, could more easily be made with a small circular index, because there would be less effect on the perspective appearance of the symbol than with a point index. The effect of the changes as regards interference was thus to introduce a small, acceptable amount in peripheral regions, and to reduce it in the central area. (There were also a very small number of references to interference between horizon and director symbols, an effect associated with the unchanged format.)

Clutter. It was clear from early test flight reports that pilots were more concerned with clutter than had been the case in previous DC-9 trials(2). There was no difficulty with the basic format in the cruise mode, where traffic could easily be seen through the display, but a sense of annoyance, or irritation was experienced at having the augmented format superimposed on the critically important runway scene during the approach mode. Later, it was realized that displayed information could nevertheless be acquired under these conditions, and this was particularly apparent through using the very relevant height information. Pilots were suprised at this result and said there was no longer any sense of clutter, although the result is less surprising in the light of a previous finding that it takes time to learn how to use display and forward view concurrently(22). The complete format was less acceptable at night, when it was found that external objects could more easily be acquired if the ILS scales were occulted. From these observations, it was concluded that ILS scales should be removed when practicable, to decrease clutter, though no severe effects resulted from the augmented format under most conditions of use.

INSTALLATION

The two test installations were intended to provide solutions to problems elaborated in Section 3. Sufficient material has already been presented to allow discussion of the optical problems except that little has been said about visual obstruction. In this connection, it will be observed that pilots made no reports of obstruction to forward or cross vision, and there was only a small amount of obstruction of panel instruments, which was limited to the glareshield installation, as noted below. As regards mechanical problems, vibration, reflector design, body clearance, and installation penalty remain to be considered, together with incidental effects due to panel design and internal reflections, of which the latter was to prove a decisive influence in choosing between the two methods.

Vibration. As protection against vibration, the glareshield had been supported on both sides of the cockpit, and the Captain's reflector braced with side struts, as shown in Figures 14, 15 and 18. It was soon clear, however, that these provisions were inadequate, for the whole format was disturbed by noisy movement, especially at flap buffet, and the effect was seen in both installations. Investigation showed the entire glareshield to be moving, evidently causing small rotations of the reflectors and consequent image movements. The vibration was reduced by improving the bracing below the First Officer's equipment, where most weight had been added to the glareshield. Both formats were then found to be stable. Furthermore, the Captain's independently mounted reflector could be held steady with the side braces lowered to the base of the reflector (which adjustment could be made without altering the angle of reflection), and this was clearly a less obtrusive arrangement. Effects of vibration could thus be controlled in both installations simply by bracing the glareshield for added weight. No tests were made to determine whether bracing would be needed if the First Officer's installation were removed.

Reflector Design. The reflecting plate had been designed with attention to frontal aspect, reflectivity, and optical quality. The frontal area was required to accommodate the whole exit pupil for a range of eye positions. To this end the upper part of the plate was kept as wide as possible, giving a somewhat rectangular aspect but with the top edge of the Captain's reflector sloped slightly downwards on the outboard side, to clear the windshield when folded down, and with corners cut away to improve appearance. To maintain image brightness against all backgrounds, both plates were hard coated with a 15 per cent to 20 per cent reflecting layer. The plates were cut, without chamfer, from selected plate glass and checked visually for change of deviation across the surface, to ensure an undistorted forward view.

After flight testing, the shape of the reflector was not considered altogether satisfactory because of a tendency to transfer the level suggested by the top of the plate to the outside world, with a slightly disorienting effect. At the pilots' suggestion, the upper edge of each plate was given a semicircular frontal aspect. In this form, the plates were acceptable to S1 and S2, and to other company pilots, but it was to be noted during the later demonstration flights (Section 6, User Comments) that some users experienced a sense of constriction. On the other hand, plate edges were considered reasonably unobtrusive, as were the supporting brackets. The reflective coating was also entirely adequate and, as noted above,* could even be dispensed with for most conditions of use. Reports of poor image quality, noted under Cumulative Effects in this section and under User Comment in Section 6, did not appear to originate in the optical quality of the reflector.

The main shortcoming of the reflector was thus in its frontal aspect and, as an attempt to find a more satisfactory shape, another form of reflector was fitted at the Captain's station. By carrying the plate across the full width of the windshield, between brackets at the lower left and upper right corners, as shown in Figure 24, it was hoped to make the sides less prominent. However, as only part of this large surface could be given a reflective coating, a strong edge effect was nevertheless obtained. The greater reflecting area also allowed reflections from the interior of the cockpit, increasing the chance of distracting the pilot. Another difficulty was in maintaining optical quality across the full width of the plate. Finally, a fair degree of complexity was needed in the mounting brackets to ensure a sufficiently positive location, while allowing for the possible necessity of removal during flight. For these reasons, the alternate design of reflector was not successful and the problem of finding an entirely acceptable frontal aspect could not be considered as solved. In other respects, however, the design of reflector was satisfactory for both installations.

* p. 25

FIGURE 24 LONG REFLECTOR FOR OVERHEAD INSTALLATION

Body Clearance. Each installation had been designed to provide clearance for the pilot's face, head, and hands; so no clearance difficulties were expected, except that there had been some doubt about the correct basis for specifying head clearance, and it had not been clear whether the pilot's head could strike the equipment during exceptional conditions. The flight tests showed that there were, in fact, no problems of face or hand clearance, though the First Officer's hand clearance was only marginally acceptable. There were also no difficulties about head clearance in either installation during normal operation, even pilots of large stature finding the Captain's overhead clearance to be acceptable. The only difficulty was that seat height could not be adjusted when leaning forward, at the Captain's station, a limitation most likely to be felt during an approach, when the eye position might need to be changed to obtain the best balance between the external visual field and the view of the instrument panel. Otherwise, the provisions for body clearance were sufficient in each installation.

Cockpit Layout. Penalties entailed by the two kinds of installation differed more in the nature, than the number of items displaced from their usual positions in the cockpit. Whereas the Captain's installation only required service items to be moved, such as a ventilator or a map light, from positions of a noncritical nature, the First Officer's installation affected items associated with the information process, such as the Bow Tie display or annunciator lights, having positions which could hardly be changed without affecting operating procedure in some way.* It was therefore no surprise when pilots preferred the overhead mounting, a preference to be confirmed during the later demonstration flights, and this view was mainly based on consideration of displacement penalties.

Control Panel. The control panel was developed to meet needs of a general nature, its design being largely independent of the type of installation with which it would be associated. The concept emerging from the users' wishes was of a panel separated from the flight director mode selector and situated close to the reflector plate, within easy visual reach of the display format. It was to provide lateral and vertical shifts, brightness override (to vary the differential maintained by automatic brilliance control) and an on-off switch. In addition, it could perhaps house the mode annunciator lights.

These needs were met equally in both control panels, after making minor changes to improve the legibility and sense of control markings. The only aspect of panel design related to the installation was that concerning obscuration of the panel instruments. For it was found at one time that each unit obscured something of importance; the panel assembly shown in Figure 25 obscured the brake pressure gauge, at the Captain's station, and the panel shown in Figure 14 obscured the First Officer's Bow Tie and annunciators, as did the collimator barrel on which it was mounted (Figure 15). It was then obvious that although the situation was improved by moving the Captain's panel, for example, to the location shown in Figure 16, there would be no improvement on moving the First Officer's panel because instruments would remain obscured by the collimator body. Except for this

* nor without quite extensive rearrangement of the panel

FIGURE 25 EARLY FORM OF CAPTAIN'S CONTROL PANEL

secondary effect, design of the control panel bore no influence on the choice of installation.

Internal Reflections. A possible source of interference with the visual information process of head-up presentation is in the spurious optical effects caused by light entering the reflecting collimator from its environment. In the first place, light from a nearby source, such as a cabin light, may simply be reflected from the combiner plate directly to the eye. Secondly, light may enter the open end of the collimator and, after reflection at one of the many optical surfaces within the system, may reach the eye by a less direct path. Both types of reflection are undesirable but whereas the first type can be to some extent controlled, by reflector design and cockpit layout, the second type can be very troublesome because it may originate in objects external to the aircraft, such as the sun.

Flight tests showed both installations to be free of reflections of the first kind, except as reported for the unsuccessful long reflector. Neither were reflections of the second kind experienced with the overhead installation, for this could only happen with the aircraft flying almost directly into the sun. But a serious situation arose with the First Officer's installation, where the collimator faced outboard and upward, into a direction where the sun might well be found during cruising flight. In such an event, the display field was grossly affected; for example, in the manner shown in Figure 26. The situation was somewhat improved by interposing a directional filter in front of the collimator aperture but some bright halos persisted; moreover, image quality was impoverished and there was a loss of brightness. It was concluded that t[illegible] glareshield installation was more difficult to protect from sources [illegible]ernal to the aircraft than the overhead installation.

DISCUSSION

The main issue to be decided was whether a satisfactory head-up installation could be made in a commercial airplane. The material for this purpose was drawn from reports on alternate solutions to the installation problem, submitted by two test pilots. Clearly, some risk would normally be entailed in relying on such a small group of contributors, but it was subsequently to be found that their opinions were accurate anticipations of the views of other users. This was not true in those areas where opinions were unlikely to assume their final form after only limited use, as in the demonstration flights; for example, there were different views about using a limited reflector surface, and about the amount of brilliance needed which, in turn, would determine the amount of line broadening to be tolerated. Such differences were to be expected and were insufficient to invalidate general conclusions drawn from the test pilots' reports.

The preliminary process of calibration showed that desirable values and scaling had been incorporated in the equipment, and these were subsequently to prove satisfactory for flight purposes. Some interesting issues were also brought to light. First, there had been an error in the method used to identify height intervals, which could more efficiently be done by sampling

FIGURE 26 EFFECT OF SUN ENTERING COLLIMATOR MOUNTED IN GLARESHIELD
Images of the sun are formed by internal reflection and glare illuminates the exit pupil

at the middle of each height interval, rather than at either end. Second, it was difficult to show flight vector information except by boresighting, with the implication that to develop the system in this direction would entail a more complicated method of installation, approximating to military practice. Third, it was potentially dangerous to provide a trimming adjustment for the artificial horizon. Finally, there was a definite need to check the logic used in controlling the presence of symbols in the format, which, if faulty, could lead to danger; for example, in showing a failed director. These results may be of importance in more general applications of head-up presentation in commercial airplanes. They are summarized in Table IV.

Equipment

Before discussing the installation, the equipment will be considered for its contribution to the performance already assumed in choosing system parameters. In previous installations, it had been possible to obtain a suitable standard of optical quality with an f/1 system having an aperture of 4 inches, and a similar result was expected in choosing the same values for the present installation. A departure had nevertheless been made in using a cathode ray tube about 7 inches in length, which was considerably smaller than previous tubes, and it was important to know whether the shorter tube gave adequate performance. Finally, the equipment was to be judged for its ability to generate the symbol format in a satisfactory manner. Contributions of the collimator, cathode ray tube and waveform generator were all required to be of a standard such that the transfer of visual information would not be seriously affected.

Optical characteristics of the collimator were assessed in terms of observable effects of parallax, distortion, and chromatic aberration, together with the cumulative effect of aberrations. Parallax, which happened to be more easily judged in flight than on the ground because of inadequate facilities, was small enough to avoid the effect of suggesting a non-existent movement of the aircraft axis, and it was small enough to allow head movement to be used as an independent method of checking focus. Distortion was very slight, being observed as a small curl in the end of the horizon symbol, insufficient to annoy the user by suggesting lack of conformity with the external world. Chromatic aberration was unnoticeable, and in no way disturbed the concept of a deliberately monochromatic format. The cumulative effect of aberrations was not enough to cause tiredness in experienced users after periods of about 3-1/2 hours, though pilots with less chance to learn adjustments promoting efficiency were later to experience fatigue after about 1-1/2 hours, and some eyestrain was to be experienced by perhaps using too much brilliance, causing an apparently fuzzy image. From these results, it was concluded that the optical design placed no significant limitation on the information process, and the design parameters used in previous installations were also suitable in the present case.

This conclusion was, of course, without prejudice to other consequences of the choice of optical parameters. For example, instantaneous field and head freedom depend on aperture but these were to be considered features of the installation, since they did not depend on the way equipment manu-

TABLE IV. INCIDENTAL RESULTS OF CALIBRATION

Height Sampling	Preferable at mid interval
Flight Vector	Boresighted mounting needed
Horizon Trim	Potentially dangerous
Information Channels and Control Logic	Check routines needed for magnitude, sign, and source failure

facturers had used the specified values. On the other hand, total field could be taken as a feature of the equipment because of its dependence on tube diameter. The total field was found to be reasonably sufficient, allowing the whole format to be seen, with head movement, when slewed through an angle of 8 deg. In the unlikely event of needing to use slewing for alignment of format and runway, the total field would allow operation with a crosswind component of 18 kts, and thus cover a reasonable proportion of working conditions.

Visual characteristics of the cathode ray tube were assessed in terms of brightness, color, and line width. Tube brightness, nominally 2,450 ft. lamberts, was amply sufficient for the format to be visible in all conditions of use, and this result was consistent with theory. There was even a reserve of brightness, since the format could often be seen without the help of a 15 per cent to 20 per cent reflection coating, though more adjustments had to be made with the manual override and the system then became less flexible. There was also an even distribution of brightness, without local variations such as bright spots or weak lines. Color, nominally centered on a wavelength of about 5500 angstroms, was entirely suitable. All symbols could be seen against a very wide variety of backgrounds, while use of a single color gave coherent identity, yet allowing symbols to be recognized unambiguously. Clearly, the format had not been allowed to assume proportions where color coding became necessary; moreover, the difficulty of chromatic relief was avoided. Line width, nominally one milliradian, was sufficient for the smallest significant detail to be resolved, viz, a height digit subtending about 20 minutes of arc. This result was consistent in a numerical sense, though no clear meaning had been given to the width of a line.

The foregoing results allowed the conclusion that visual characteristics of the cathode ray tube were suitable for the transfer of information from the head-up display to the pilot. It is interesting that this standard of picture quality had been achieved with the shortened tube, for this change, together with a simplification of the glass envelope due to taking the high voltage lead straight through the wall, had led to a considerable reduction in the space needed to install the collimator, perhaps to an extent marking the difference between success and failure. It is also interesting to note that the tube in the Captain's equipment had been mounted in potting compound without serious trouble, though no investigation had been made of long term effects or tube replacement problems.

The delineating capability of the waveform generator was assessed in terms of form errors, position errors, and noise. As the format had been designed with a view to eliminating symbols subject to these effects, it was not surprising to find a freedom from form and position errors. The only appreciable form errors were found in the First Officer's height digits and this was simply due to relying on an insufficient number of points to form each numeral. The only significant position error was in the drift of the First Officer's director index. Both types of error had an unacceptable effect on the information process, and reflected adversely on waveform generation.

Noise effects were incident in a more general fashion and this was perhaps the least satisfactory aspect of the installation. Noise experienced as a jittery motion of all symbols affected their visibility, and noise experienced as a jumpy movement in the director symbol affected the flow of command information. It was possible to remove jitter by improved grounding, but jumps were more troublesome and could only be subdued by rate limiting techniques. In general, the precautions which had been taken to eliminate noise effects were not commensurate with the sensitivity of the cathode ray tube as a device capable of showing some of the smallest and most rapid electrical disturbances. Clearly, this is a subject requiring careful attention in future installations.

The noise caused by bad contacts in the sine-cosine potentiometer was in a different category because this method of bank resolution had been specified, as a deliberate replacement for a method based on the use of electronic multipliers. For when multipliers are used to resolve symbols, by generating a function of the general form

$$x \cos \theta \pm y \sin \theta,$$

it is possible for one term of the computation to disappear through failure of a multiplier. Then if the angle θ has a value near zero or 90 deg, the resultant of the two terms may suffer a considerable change of direction, with disastrous effects if the aircraft happens to be close to the ground. The alternate method of resolution by sine-cosine potentiometer is free of this danger but, in severe cases, can be subject to noise sufficient to incapacitate (though not invalidate) the display. There is an obvious need for an improved method of bank resolution, equally free of noise and catastrophic possibilities.

To sum up: the equipment had performed favorably in all aspects touching on the transfer of visual information. Optical quality was entirely adequate, though it could be adversely judged if the system were not properly adjusted. The performance of the short cathode ray tube was also entirely adequate, though work might be needed later in designing a more controllable method of mounting, in providing an expanded brightness scale for low levels of background illumination, and in agreeing upon an acceptable line profile. Waveform generation was to an acceptable standard, except for deficiencies in forming numerals and in defining zero command, in the First Officer's equipment. Noise effects, though capable of elimination, had not received sufficient attention, and there was need for improved bank resolution. After giving the care needed in these areas, it was evidently possible to achieve sufficient standards of optical and visual performance within the limits imposed by design parameters and in the airborne environment. The experimental results are collected in Table V.

Format

The object in evaluating the format was to assess modifications intended to improve or expand its capability. At the same time, it was important to ensure that known properties had not been affected by the modifications.

TABLE V. EVALUATION OF EQUIPMENT

(1) Collimator	Parallax, distortion, and chromatic aberration insufficient to affect transfer of visual information. Cumulative effects of aberrations insufficient to cause eyestrain (S1, S2) in 3-1/2 hour periods. Total field sufficient for 18 kt crosswind. Design parameters acceptable (4 inch aperture).
(2) Cathode Ray Tube	Nominal brightness of 2450 ft. lamberts adequate for continuous operation, and evenly distributed. Low level control too coarse. Color, nominally at 5500 angstroms, general suitable. Color coding unnecessary. Coherent format. Line width, nominally 1 milliradian, allowing all detail to be resolved. Short tube acceptable. Efficiency of mounting not investigated.
(3) Waveform Generator	Digit form errors and director position errors in glare-shield mounted equipment. Insufficient protection from noise, rate limiting needed to eliminate jumps. Better method of bank resolution needed.

Minor changes, of increasing wing length and of adding "elasticity" to the director, made the display easier to use, in agreement with previous findings.[5] Of the major changes, the chief was in the addition of digital height, which was found to be an easily understood, unambiguous, and conveniently located display component, again confirming previous results[5]. It is interesting to note that no complaints were made about recognizing digits during a change of read-out, often a source of difficulty with mechanically operated digits, and it is evident that the almost instantaneous change of digits in a cathode ray tube display does much to remove a well known limitation of the digital method of displaying information. It is also interesting that pilots found no difficulty in proposing sampling intervals for use in various stages of the approach, and were able to adapt to the method of inferring height rate by observing the frequency of changes in read-out. It may well be that digital presentation, given an electronic method of generation, is the most direct and simple way to convey height information. At the same time, a different sampling technique would obviously be needed for use at constant altitude.

Another main change was in adding raw ILS scales, which were found suitable for monitoring an approach, by judging the acceptability of displacements, and for observing side effects such as beam bends. This result was consistent with the concept of using raw ILS information in a supporting role and of relieving the pilot of the task of remembering the time histories of director displacements. In finding that these symbols could only be used before reaching a height of about 200 feet, the earlier practice of Morrall was confirmed; that is, of occulting the scales at low altitude[21]. Finally, an important but non-continuous format modification was in adding a master warning symbol, and the efficiency of this component was shown by an ability to warn the pilot without hindering regular use of the system.

In their more general influence on the format, the modifications had done little to affect the framework, position, continuity, and integrity principles, though simplicity and zoning principles had been somewhat compromised.* Nevertheless, identities of the more numerous symbols were well protected by continuing the practice of only using each form of symbol once, and though clutter was increased it became acceptable in time, except at night, when there was perhaps a greater need to remove the ILS scales. Moreover, interference, due to incomplete zoning in the peripheral regions, was at an acceptable level and central interference was reduced through the minor change of increasing the diameter of the director index. The format modifications were thus without serious effect on the organizational principles of the system, as well as being successful in their own right. It was nonetheless clear that further changes could only be made with caution because the time needed to become accustomed to increased cluttering of the forward view was a sign that a state of saturation might be at hand.

To sum up: The format had been improved by small refinements to existing symbols and by adding new symbols to increase the scope and effectiveness of the display system. A new, flexible height display was available which could be used efficiently during approach and takeoff. An approach could be monitored with the help of raw ILS information. The pilot could be advised of a state of warning without loss of performance. These improvements had been made without sacrificing existing properties to any great extent. Results of the evaluation are summarized in Table VI.

*As a result, there was some doubt about preserving properties of identity, interference, and clutter.

TABLE VI. EVALUATION OF FORMAT CHANGES

(1) MINOR CHANGES	
Aircraft Reference	Preferred wing length equal to circle diameter.
Flight Director	Two-dimensional "elasticity" (shearing) desirable. Small circle preferred to dot (S1, S2).
(2) MAJOR CHANGES	
Digital Height	Easily understood, unambiguous, conveniently located. No problem of digital change-over. Sampling rate variable with height. Inferred rate of change of height.
ILS Scales	Usable above 200 ft. for monitoring approach and observing beam bends and wind shear. Conventional position(s) and shape desirable.
Master Warning	Attracts attention without disabling rest of format.
(3) GENERAL EFFECTS	
Organizational Principles	Framework, position, continuity, and integrity unaffected. Simplicity and zoning somewhat compromised, but:
Dependent Properties	Symbol identities protected, Clutter acceptable, except at night, Peripheral interference at acceptable level.

Installation

The installations were to be judged as alternate solutions to the problems of Section 3, as embodied in a separated system mounted overhead and an integral system mounted in the glareshield. Considering first the optical problems, it will be clear from the results already discussed that each collimator barrel was large enough to allow adequate optical and visual qualities. Also, the flight tests had shown that sufficient head freedom was available, and that the equipment had been installed without obstructing external vision at each pilot's station, with an orientation suitable for general flight purposes. These results simply confirmed that design objectives had been achieved. The main concern, however, was for the instantaneous field, which had suffered through an increase in viewing distance, above values previously used with collimators of similar aperture. In finding that the instantaneous field was sufficient in both installations, a major source of uncertainty was removed, for a larger field would have entailed an increase in aperture, thus enlarging the barrel and invalidating the analysis. Fortunately, each installation offered satisfactory solutions to all the optical problems.

As regards mechanical problems, it was als fortunate to find vibration effects limited to the glareshield. For if structural members had moved to the same extent, the effects would have been less controllable. The two installations were equally free of vibration effects, thus eliminating a possible disadvantage for the overhead method in that no special side supports were needed for its independently mounted reflector, which might otherwise have become obtrusive. The installations were also equal as regards the design of reflector, of which the frontal aspect could be varied within quite wide limits. An entirely suitable shape may not have been found at either station, however, because some later users were to complain of a feeling of constriction, arising perhaps through limited experience. In any event, problems remain to be solved in providing an alternate reflector of greater surface area.

Another uncertainty had been in providing sufficient body clearance but the flight tests showed this problem to have been solved almost completely. There was a rather small margin of safety for the First Officer's hands, at extreme positions of the control wheel, and a restriction on adjusting seat height at the Captain's station. Of these disadvantages the former was perhaps the less severe.* On the other hand, the overhead installation carried smaller penalties of displaced equipment, with less effect on operating procedure. Also, the control panel, which could easily be adapted to the concept of an independent yet adjacent unit, was more readily placed in a non-interfering position at the Captain's station. Mechanical problems were thus solved equally well in each installation, a slight advantage in body clearance at the First Officer's station being offset by small advantages in avoiding layout penalties at the Captain's station.

The most important difference between installation was in their susceptibility to reflection effects caused by light sou s outside the aircraft. Ineradicable effects due to the sun shining directly into the glareshield

* though it might be unacceptable in a production installation

mounted collimator were all too frequently sufficient to impede the pilot in using this type of installation. For this preponderating reason the overhead method of installing a reflecting collimator was preferred for the DC-9 cockpit.

To sum up: satisfactory solutions to the main optical problems of orientation, barrel size, instantaneous field, and visual obstruction were achieved in both the overhead and glareshield methods of mounting equipment for head-up presentation. Mechanical problems of vibration and body clearance were also solved in both cases, though overhead installation caused some restriction in adjusting seat position. This disadvantage was balanced by freedom from penalties of displacing significant equipment, which were more serious with the glareshield installation. Both installations allowed suitable designs of reflector, though it was not certain that the best frontal aspect had been achieved. The most powerful difference between installations was in their resistance to sun reflections, causing effects which very much reduced the acceptability of the glareshield mounting as a solution to the problems of installation in commercial airplanes: in other respects, the installations were broadly equivalent. These results, and those relating to equipment and format, were obtained without particular need to consider the precision or ease with which the aircraft could be flown, and should thus be independent of the fact that production values were used as interim control gains, before exploring the more dynamic aspects of the system. Table VII summarizes the results used in comparing the two test installations.

TABLE VII. EVALUATION OF INSTALLATIONS

Desirable Feature	Overhead	Glareshield
(I) OPTICAL		
Orientation suitable for general flight purposes.	Yes	Yes
Barrel size allowing adequate optical & visual qualities (Table V).	Yes	Yes
Instantaneous field sufficient for general flight purposes.	Yes	Yes
Unobstructed forward view.	Yes	Yes
Head freedom sufficient for comfortable operation.	Yes	Yes
(II) MECHANICAL		
Imperceptible vibration effects (after bracing glareshield).	Yes	Yes
Suitable reflector design (excepting frontal aspect).	Yes	Yes
Freedom from restrictions due to body clearances.	No (seat adjustment)	Yes (but hands tight)
Collimator installed without affecting instruments contributing to information process.	Yes	No
Control panel installed without affecting instruments contributing to information process.	Yes	No
Freedom from effects of sun reflections	Yes	No

5. FLIGHT EVALUATION OF CONTROL GAINS

Adapting Display Dynamics to the Human Pilot

In dealing with the installation and evaluation of head-up display equipment, the issues were mainly static in nature. Where dynamic matters were considered it was generally in a restrictive sense, seeking to reduce noise effects, to remove discordant relations, either within the format or between format and forward view, and to reduce large angular velocities. It was recognized, however, that symbols may change shape or position when they represent time-dependent information, especially the horizon and director symbols. Movements of the horizon symbol have already been discussed, noting that one-to-one movements in bank are both desirable and practicable, while one-to-one movements in elevation are less practicable and may be undesirable. Movements of the director index have been considered only briefly, noting that conformity of direction is advantageous, but saying little about magnitude, except that zoning requirements impose limiting values. It is now time to discuss the presentation of command information exclusively, in terms of the gains determining displacements and their rates of change.

In earlier investigations[(1), (5)], control gains were chosen to suit a limited number of highly experienced and specially trained pilots, who were expected to know how much movement would suit subsequent users. A similar approach has been followed in the preceding parts of the present work, using production values for electrical gains and values for optical gains suggested by simulator work with selected pilots (Calibration, Section 4). Such methods were useful while investigating purely graphical relationships within the format, but a move objective approach is to be followed while investigating dynamic effects, when control gains are themselves under examination.

In tracking the flight director, the pilot acts on information conveyed by the moving index of the symbol, and closes the control loop. As he follows commands, with the least possible tracking errors, he makes control movements which in turn affect the displayed commands, subject to the influence of loop gains. Efficiency in the tracking task should therefore be related to gains controlling the observed symbol motion, and it should be possible to adjust gains for best performance, much as autopilot gains are adjusted, but in this case adapting display dynamics to human, rather than automatic, pilot capabilities. And since both gains and performance can be measured, an objective approach is available.

The basis for optimizing gains could be a theoretical model of the control situation, in which the pilot is represented by describing functions, and an investigation is currently being carried out by M. Abramovitz in which a model of the pilot and airplane is analyzed by means of Bode plots and root loci, starting with the inner loops. In the present investigation, gains are optimized by purely experimental methods, seeking a condition in which the pilot is able to follow commands most continuously and accurately; that is, with least integrated tracking errors in the channel affected by the gain. At the same time, it may well be found that minimum tracking errors occur under conditions which are not wholly acceptable to pilots; for example, because unacceptable control movements are required. Gains are therefore to be optimized also with respect to pilot opinion about handling quality in the affected channel, and for this purpose the Cooper Scale provides a convenient basis of measurement.

As in earlier work, it is still necessary to work with a very small number of pilots, at least in the airborne phase. The reason for this is that only a limited number of approaches can be flown in a test program of moderate budgetary proportions, and it is in the approach mode that the most immediate application of accurate tracking can be made in commercial flying. Generality will then be sought by attempting to apply the results to a wider selection of pilots in the succeeding section (Demonstration Flights). Another aspect of the work is the relation between real and simulated flight tests, which is important because of the need to select control gains in advance of a flight test program. What follows is thus a gain survey made with a small number of subjects, using an approach not limited to subjective methods and intended to be related to a larger population of subjects, and to corresponding work performed in simulated flight.

EXPERIMENTAL ARRANGEMENT

The measurements to be reported were obtained in a flight test program with a DC-9-20 aircraft, and in a program carried out subsequently with a simulation of the same aircraft. To this end, the entire experimental assembly, for generating and displaying command information and also for measuring tracking accuracy, was designed to be transferred easily between laboratory and flight deck.

Airborne Equipment

The display format and installation are shown in Figures 5 and 17, respectively, from which the pilot s visual field and immediate environment may be understood. During experimental runs, the external view was blanked off by covering the main forward-facing panel of the windshield with a sheet of polaroid, and by subjects wearing (crossed) polaroid goggles, through which only the display could be seen. Mode annunciator and display control facilities, though playing no direct part in the recorded sections of experimental runs, were placed close to the reflector plate.

The flight director commands were generated in an experimental analog computer supplied by Sperry, Phoenix, for which the block diagrams are shown in Figures 27 A and B for heading and elevation channels, respectively. The diagrams have been drawn without some devices used for limiting, washout and filtering, thus considering only the dynamics within the frequency range relevant to the tracking task; namely, between about 0.2 and 6 radians per second. It will be seen that, in addition to the usual mixture of a glide path signal and an attitude signal, an attitude rate term has been included for the purpose of providing a more immediate display response on changing attitude.

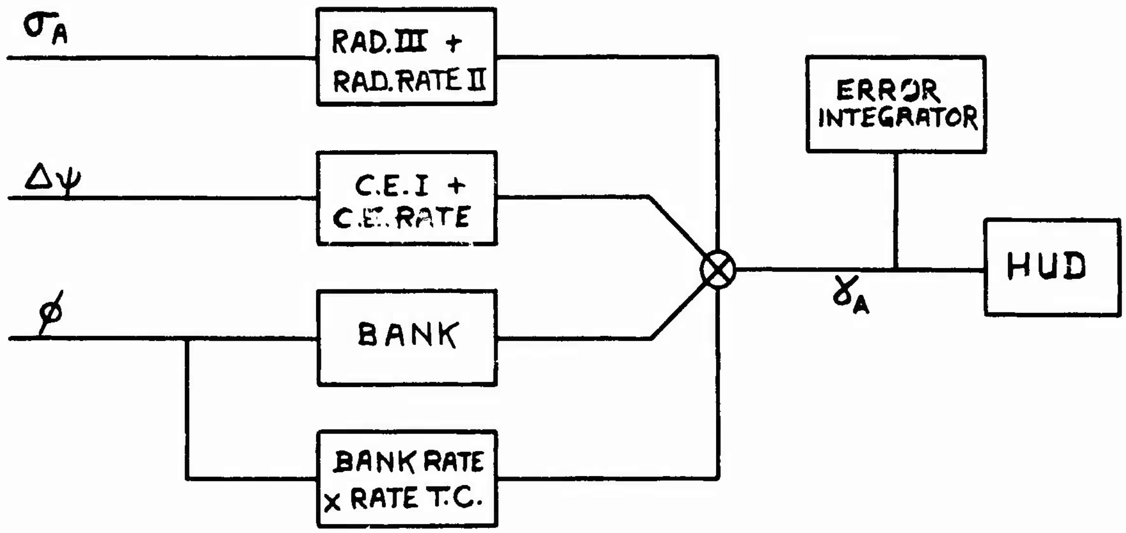

FIGURE 27A AZIMUTH COMMAND COMPUTATION

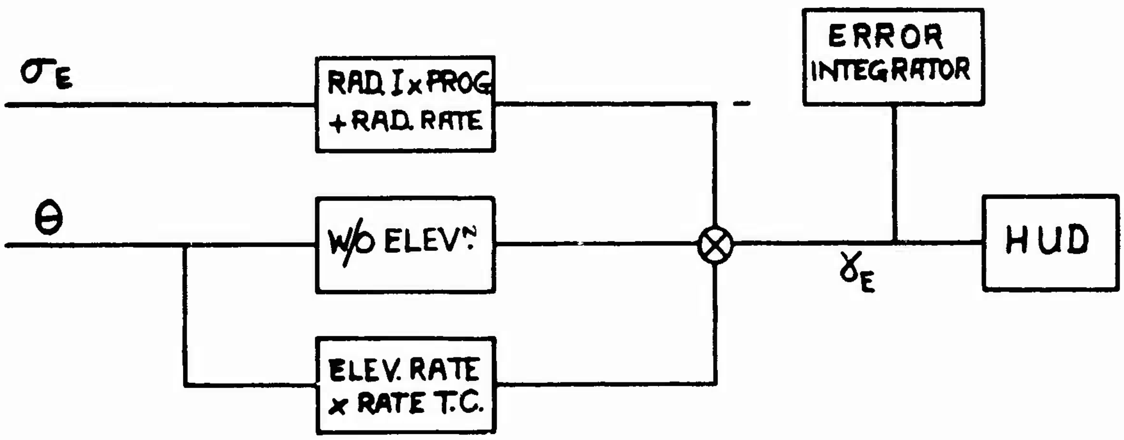

FIGURE 27B ELEVATION COMMAND COMPUTATION

The method of expressing gains was based on relating angular displacements of the flight director index, γ_A , γ_E , to the Euler angles of attitude, ϕ , θ , ψ , and to angular deviations from the glide path, σ_A , σ_E . For example, heading gain, K_ψ , was derived from the azimuthal deflection of the director index in the collimated display field and the associated change of heading input. In computing gains, the total input signal was used; that is, contributions were included from paths not shown in Figures 27A and B so that computed gains did not coincide with the static gains (for example, in cases where washout circuits eliminated the very low frequencies).

Tracking errors were integrated between heights of about 1200 feet and about 250 feet, during which period the flight director computer was used in a fixed mode with selected, constant gains. The error integrating unit was designed to yield the mean absolute, or mean modulus, error in azimuth and elevation during experimental runs of about 100 seconds. Its position in relation to the director computer and Head-Up Display circuits is shown in Figures 27A and B. Error scores in the two command channels were calibrated in terms of equivalent angular glide path errors, $\langle\sigma_A\rangle$, $\langle\sigma_E\rangle$, having fixed values and giving the same error score during the same interval of time.

Simulator Equipment

At the conclusion of the flight test program, the experimental equipment was transferred to the simulator and used with very little modification for the laboratory program. The collimator was now clamped directly onto the pilot's side of the instrument panel and the display format was presented against a dark background by a temporized reflector plate, mounted at 45 deg to the forward sight line, as shown in Figure 28. Mode annunciator and control facilities were provided in the vicinity of the reflector, without any requirement for precisely copying the airborne arrangement. Conventional flight instruments were not used for the experimental task but were included in the experimental rig to maintain similar electric loading on data and computer sources. The flight director computer and the error integrator were used without change, but the measuring equipment was re-calibrated at this stage. Standard analog methods were used to simulate a DC-9-20 approaching at 1.3 Vs + 5 kts, with slats extended, gear down, and flaps deflected 50 deg.

EXPERIMENTAL METHOD

Airborne Test Program

The experimental runs were made mostly by one subject, S1, but in one case (K_{σ_E}/K_θ) another subject (S2) was used. The basis for experimental procedure is shown in Table VIII, where each column includes a set of gains held fixed at values suggested by preliminary studies, while varying the gain chosen for investigation, V. In the course of the program, some values were changed to suit subjective rating: notably, rate gain ratios were reduced nearly fourfold and elevation gain, K_θ , was reduced

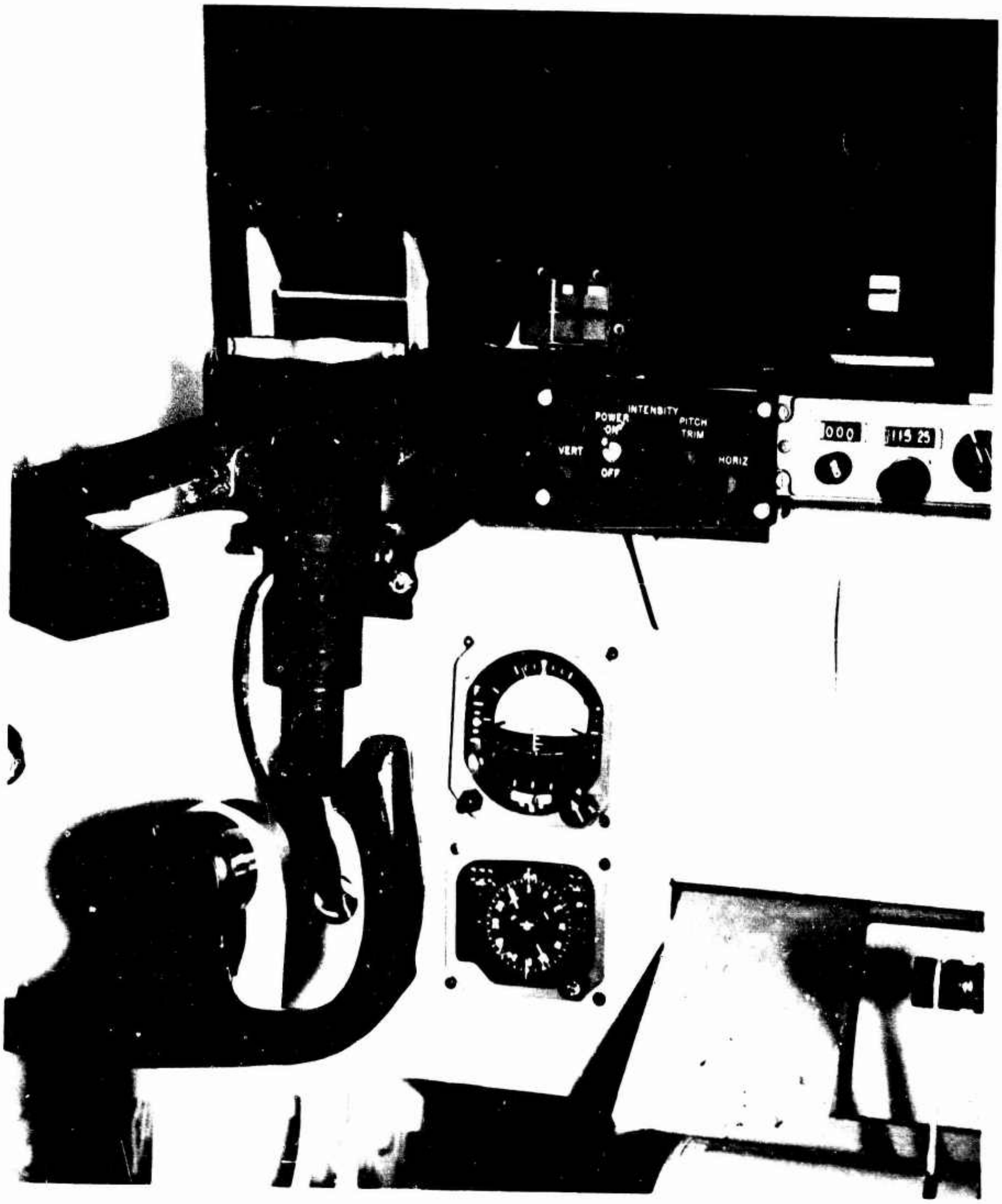

FIGURE 28 INSTALLATION FOR SIMULATOR PROGRAM

TABLE VIII. METHOD OF SURVEYING GAINS

K_ψ	V	0.088	0.088	0.088	0.088	0.088	0.088
$K_{\dot\phi}/K_\phi$	1.25	V	0.67	0.67	0.33	0.33	0.33
K_θ	0.284	0.284	V	0.141	0.141	0.141	0.141
$K_{\dot\theta}/K_\theta$	1.25	1.25	1.25	V	0.33	0.33	0.33
K_ψ/K_ϕ	1.5	1.5	1.5	1.5	V	1.3	1.3
K_{σ_E}/K_θ	15.2	15.2	15.2	15.2	15.2	V	15.2
K_{σ_A}/K_ψ	33.6	33.6	33.6	33.6	33.6	33.6	V

V signifies variable gain

by a factor of two, the latter having some effect on error score. However, most gains were already set at near optimum values and it was thus unnecessary to take the variable gains in strict sequence. For each gain investigated, it was usually possible to choose seven values, each being flown for one approach. In this way, two or three gains were surveyed during a test flight of three to four hours duration.

The experimental task was to fly an approach, between the prescribed heights, while correcting the small path errors arising through beam noise. The approaches were flown at Ontario, Bakersfield, March Air Force Base, and Stockton, California, mostly in smooth air and with autothrottles engaged. There were no practice runs, or replicated runs, because the learning effect was known to be negligible for the format of Figure 5[7]. Values of the variable gain were taken in random sequence, and these values were unknown to the user.

Simulator Test Program

The same subject, S1, made the experimental runs in the laboratory test program. Gains were investigated in the same order as in the flight test program, Table VIII, with the same sequence of (unseen) values for the variable gain, V. Two or three gains were investigated in each experimental session, which was only of about an hour's duration because no time was needed to reach the experimental venue or to fly downwind legs. Some practice runs were flown to make up for this.

The experimental task was again to correct path errors due to beam noise during an approach in smooth air between the same prescribed heights. The beam noise was set to give the same subjective impression as in real flight conditions. For this purpose, it was sufficient to inject at the glide slope receiver a noisy signal having an r.m.s. amplitude of 30 mv, corresponding to an r.m.s. path error of 0.14 deg, and flat to 30 cycles/second. The corresponding figures for the independent noise input to the localizer receiver were 3.8 mv, or 0.056 deg path error, and 1.5 cycles/second. All runs were performed without the help of autothrottles and the subject was thus loaded with an auxiliary task, not called for in the flight tests.

RESULTS

Results of the experimental runs are shown in Figures 29 to 35, inclusive, as plots of tracking error and Cooper rating against the gain or gain ratio under investigation. The results always relate to the command channel affected by the gain change; for example, heading gain, K_ψ, is plotted against lateral error, $\langle \sigma_A \rangle$, and against Cooper rating for the azimuth channel, in Figure 29. Error scores for the other channel are not shown because they were always found to be invariant within experimental limits.

Curves are drawn on the assumption that human performance and subjective evaluation, under the experimental conditions, are single-valued and continuous functions of the gain varied, except for chance effects. By inspection,

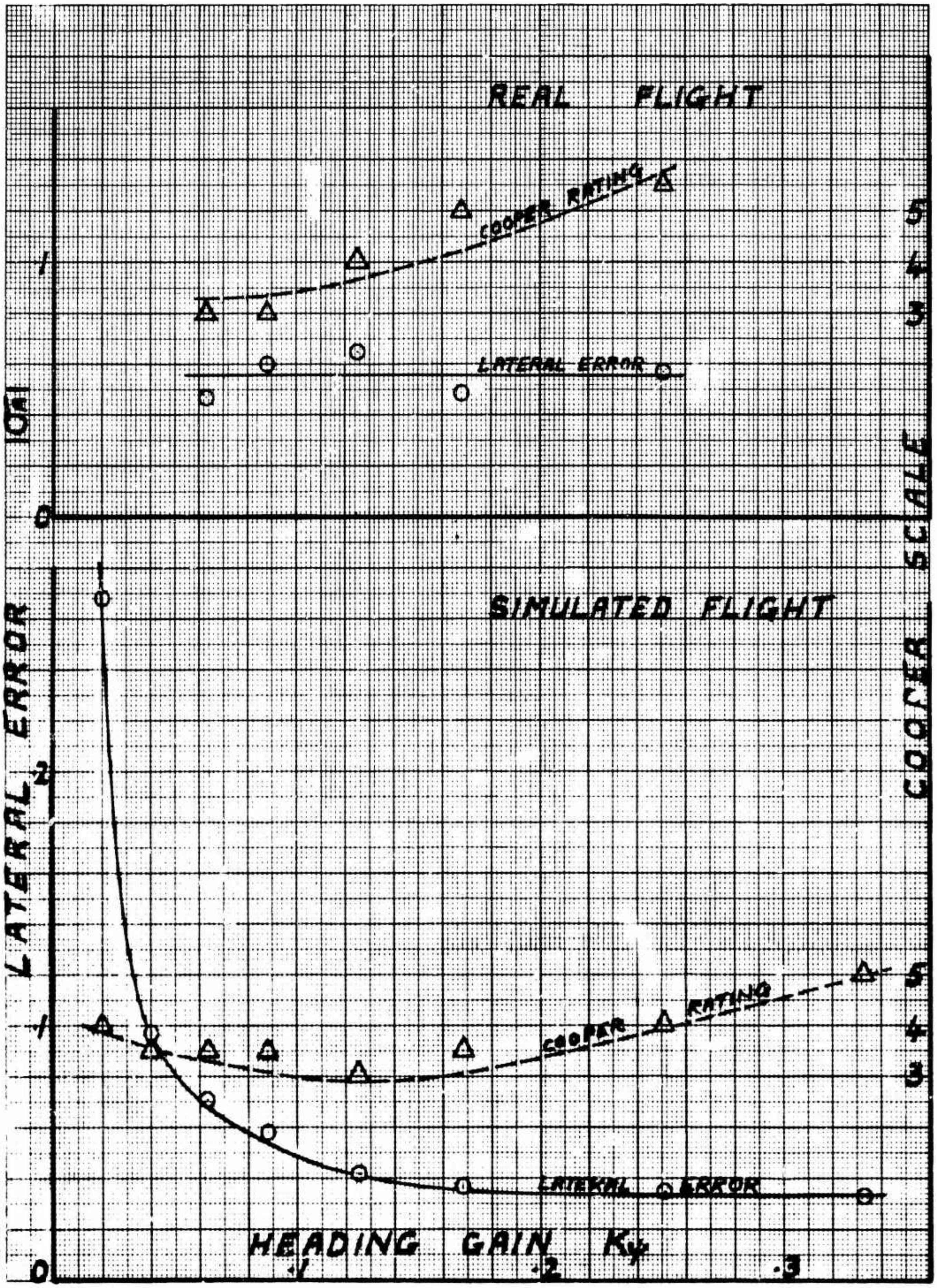

FIGURE 29 INFLUENCE OF HEADING GAIN ON TRACKING AND COOPER RATING

values are then selected which reflect the best operating conditions according to each method of assessment, with the results shown in Table IX for real and simulated flight. In some cases, lowest scores are approached asymptotically and the gains shown are then values at which performance starts to deteriorate.

Heading Gain, K_ψ , Figure 29. Variation of heading gain in simulated flight caused tracking errors to increase for values of the gain less than 0.15, and the best Cooper rating was given at about 0.125. The gain was varied over a smaller range in real flight, yielding less information. There was no recognizable trend in error score, and the mean error, of 0.056 deg, was larger than the asymptotic minimum of 0.033 deg for simulated flight. Cooper ratings decreased to a possibly stationary value of 3 in real flight, which was the same as the lowest rating given in the simulator and might therefore be a true minimum, occurring at a gain of about 0.075.

Bank Rate Gain Ratio, $K_{\dot\phi}/K_\phi$, Figure 30. Variation of the bank rate gain ratio caused distinct error minima in both experimental situations. Lateral error was least at a value of 1.25 in real flight and at 1.5 in simulated flight, where the general level of tracking error was somewhat higher. Cooper ratings were least at a gain ratio of 1.25 in simulated flight. In real flight, subjective evaluation was best for ratios less than 1.0.

Elevation (Pitch) Gain, K_θ , Figure 31. Each measure behaved similarly in real and simulated flight. Tracking errors started to increase at elevation gains less than about 0.3, from a plateau having a height of 0.027 deg in real flight, and 0.018 deg in simulated flight. Cooper ratings were least for a pitch gain of 0.2, in both cases.

Elevation Rate Gain Ratio, $K_{\dot\theta}/K_\theta$, Figure 32. The measurements taken in simulated flight showed a minimum tracking error occurring at an elevation rate gain ratio of 1.0 and at an error level of 0.03 deg. In real flight, minimum error scores on the order of 0.04 deg were obtained at gain ratios less than 1.0.

Subjective evaluation in simulated flight showed a possible minimum at a ratio of about 0.8 which was less discernible than in real flight, where the preferred ratio was about 1.4.

Heading to Bank Gain Ratio, K_ψ/K_ϕ , Figure 33. In-flight measurements taken while varying heading-to-bank ratio showed no trend away from a uniform performance level of 0.04 deg. Simulator results showed a slight upward trend in lateral error score from the 0.02 deg level, at gain ratios greater than 1.2. Similarly, Cooper ratings were uniform throughout the experimental range of heading-to-bank ratio in flight, whereas in simulated flight there was a shallow minimum at about 1.2. The airborne results were obtained in slightly choppy conditions.

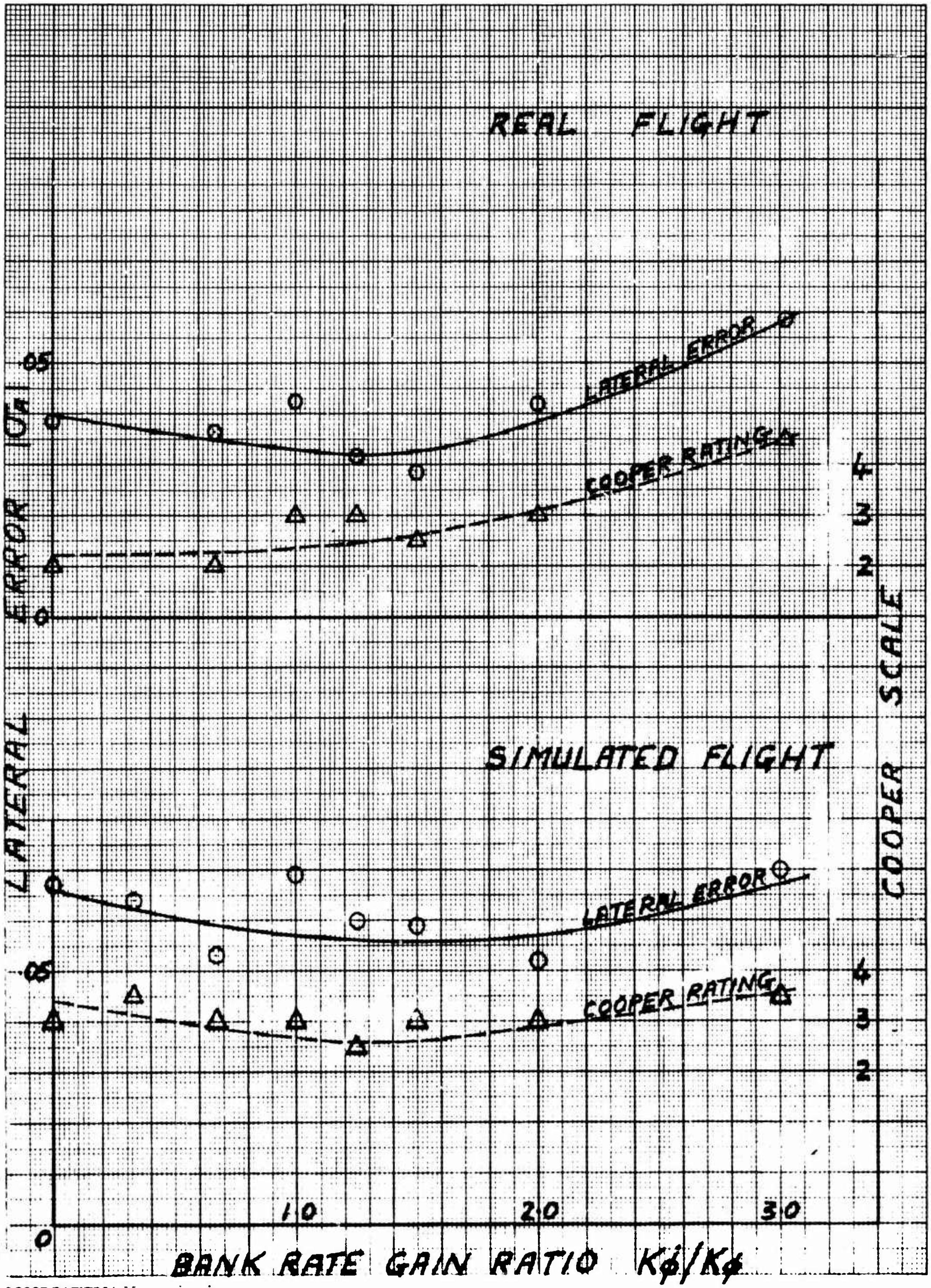

FIGURE 30 INFLUENCE OF BANK RATE GAIN RATIO ON TRACKING AND COOPER RATING

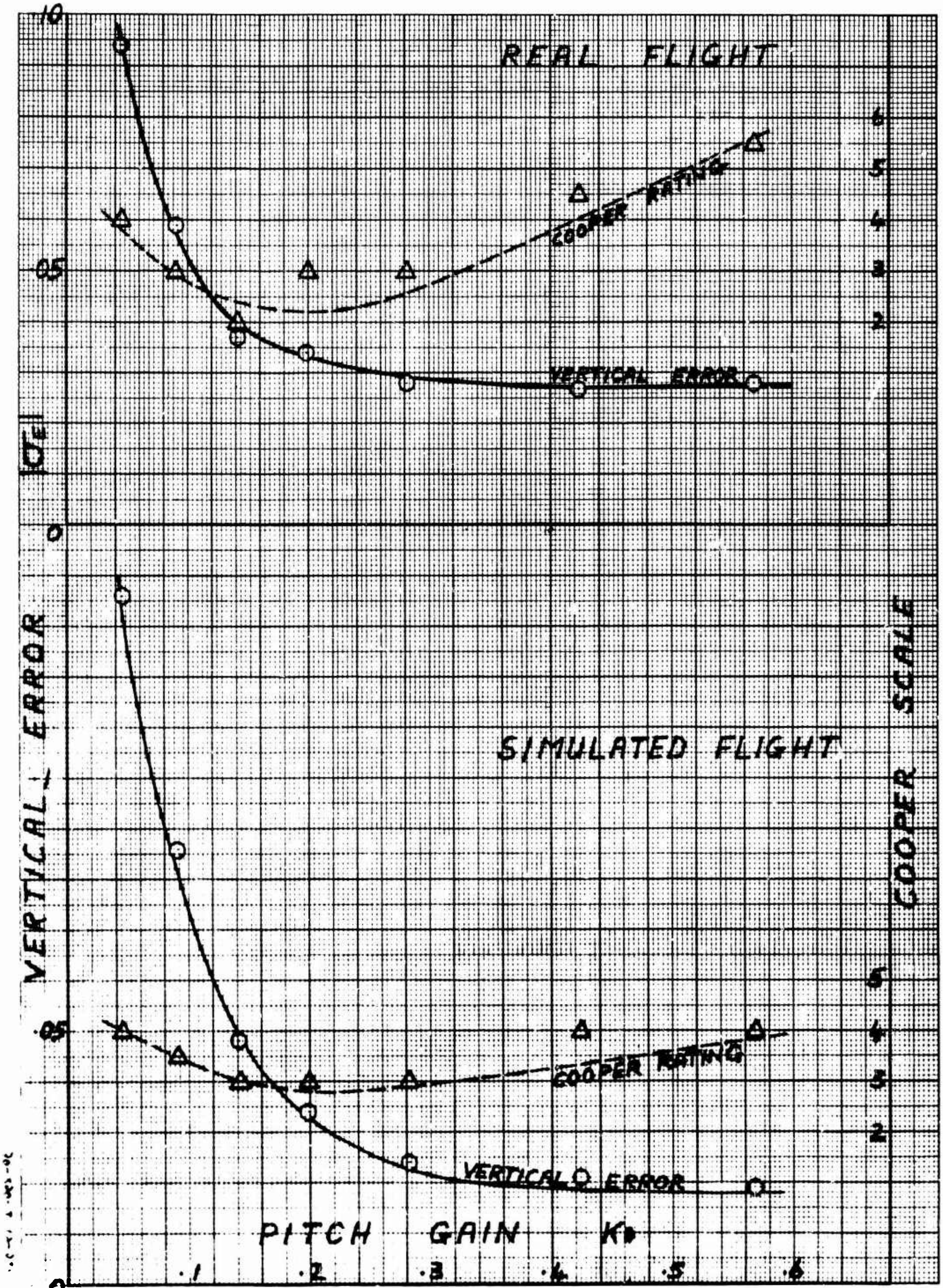

FIGURE 31 INFLUENCE OF ELEVATION OR PITCH GAIN ON TRACKING AND COOPER RATING

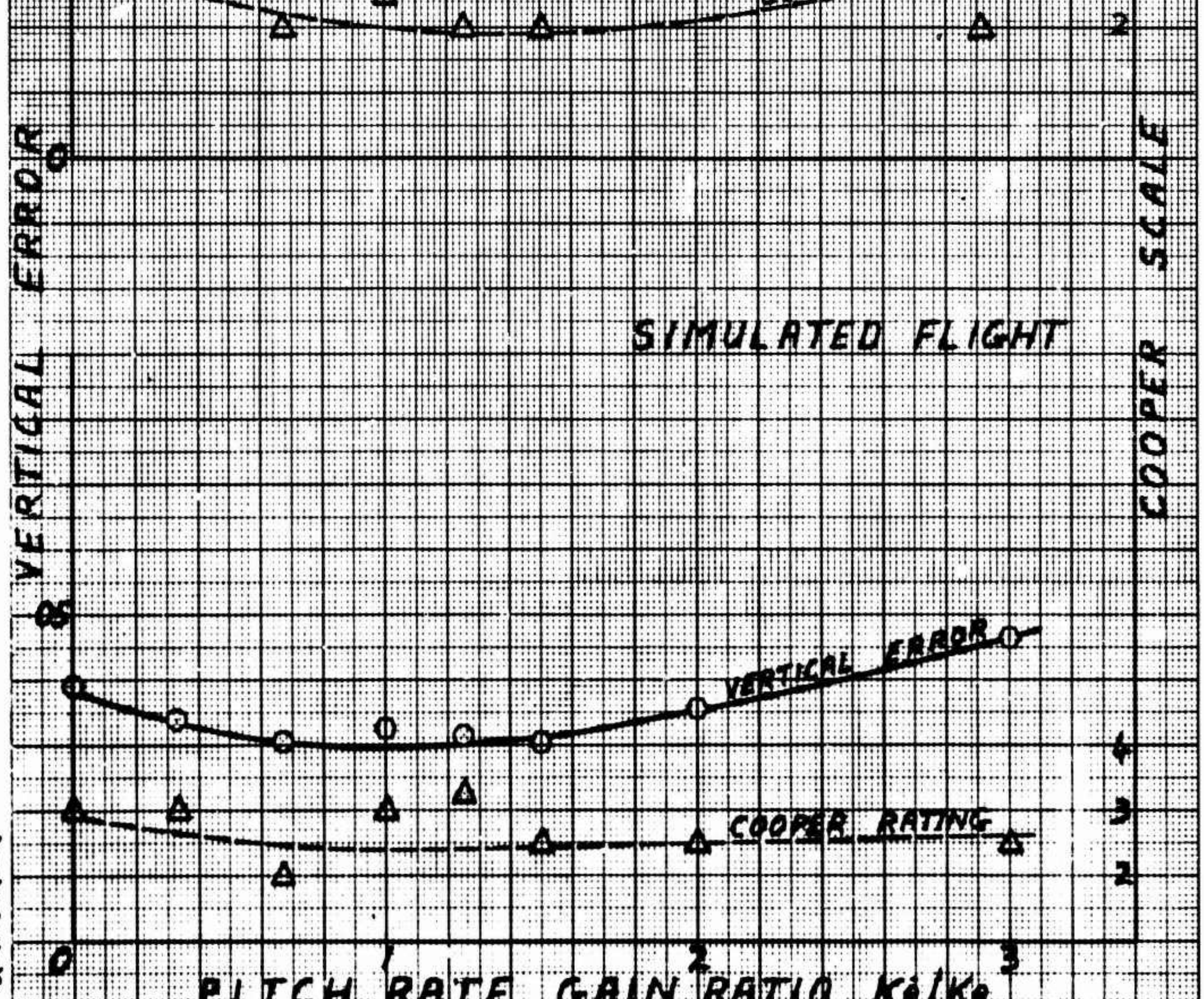

FIGURE 32 INFLUENCE OF ELEVATION RATE GAIN RATIO ON TRACKING AND COOPER RATING

TABLE IX

Optimum Gains for DC-9-20 Aircraft found by Objective (O) and Subjective (S) Methods in Two Experimental Modes and used in Demonstration Flights

Mode	Method	Subject	1 K_ψ	2 $K_{\dot\phi}/K_\phi$	3 K_θ	4 $K_{\dot\theta}/K_\theta$	5 K_ψ/K_ϕ	6 K_{σ_E}/K_θ	7 K_{σ_A}/K_ψ
Aircraft	O	S1	i	1.25	0.3	1.0	i	(S2) 17	40
	S		0.075 (?)	1.0	0.2	1.4	i	15	i
Simulator	O	S1	0.15	1.5	0.3	1.0	1.2	(S1) 17	40
	S		0.125	1.25	0.2	0.8	1.2	15	i
Flight Demon-strations	-	S3-5	0.088	0.33	0.141	0.33	1.3	12.9 to 31	33.6
	-	S6-41	0.079	0.33	0.127	0.33	1.3	10.3 to 31	25.6

i signifies invariance

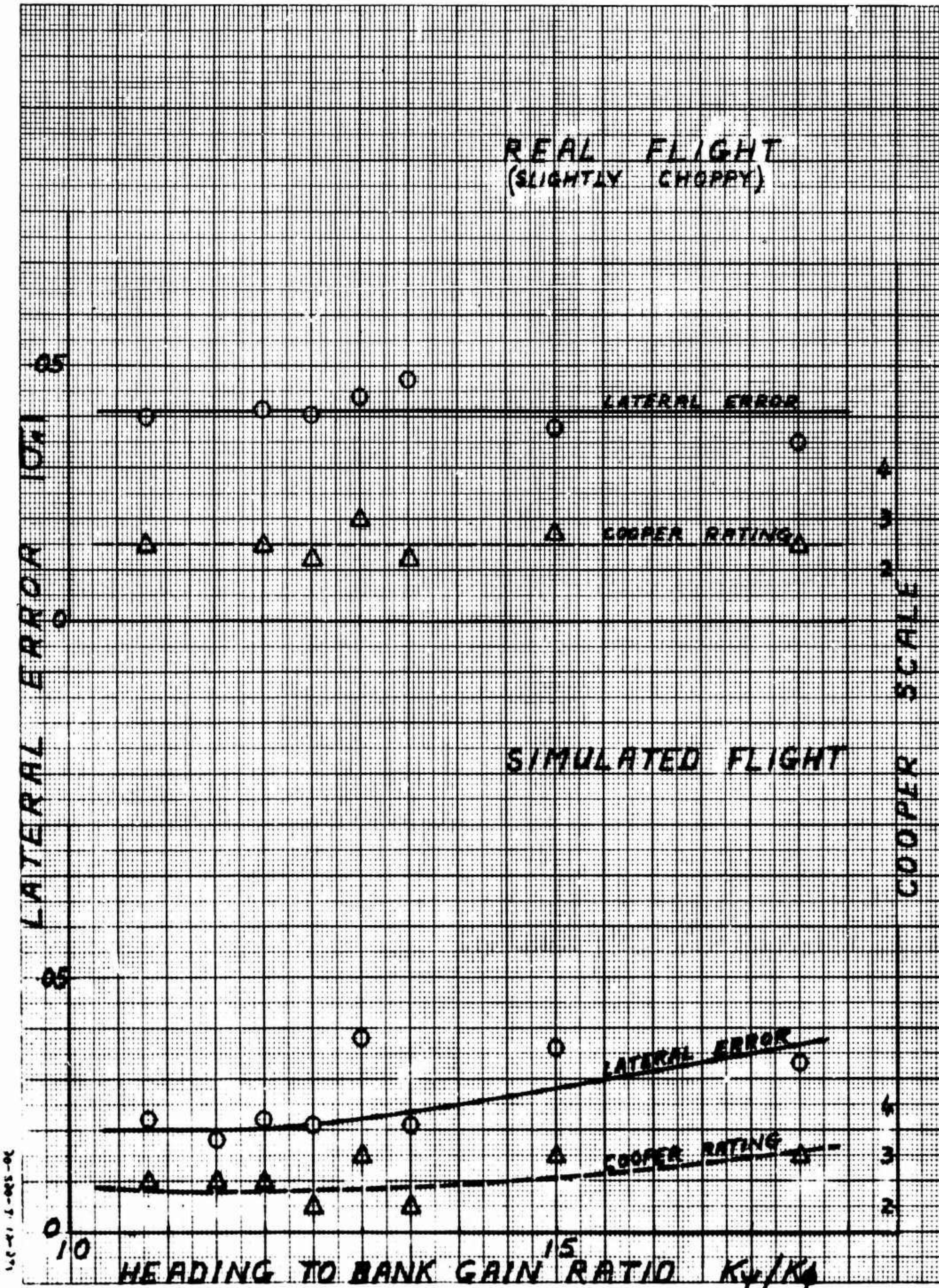

FIGURE 33 INFLUENCE OF HEADING TO BANK GAIN RATIO ON TRACKING AND COOPER RATING

Glide Slope Gain Ratio, K_{σ_E}/K_θ, Figure 34. Vertical error in flight, for subject S2, decreased slowly throughout the experimental range, reaching a steady value of about 0. 03 deg at a glide slope gain ratio of 17. In simulated flight, a similar trend was found for subject S1, with vertical error again becoming steady at a gain ratio of about 17, at a level of 0. 02 deg. On the other hand, Cooper ratings were found to increase slowly as errors decreased, both in simulated and real flight situations. In each case, ratings levelled out at gain ratios less than about 15.

Localizer Gain Ratio, K_{σ_A}/K_ψ , Figure 35. Variation of the localizer gain ratio caused similar effects in real and simulated flight. In each case, lateral error decreased to a steady value at gain ratios exceeding about 40. The level of the plateau was 0. 045 deg in real flight and about 0. 025 deg in simulated flight. Cooper ratings were uniform throughout the gain range and equal in both experimental situations.

DISCUSSION

Considering first the experimental runs obtained in simulated flight, it is seen that most results lie close to a smooth curve drawn through the data points. Exceptionally, there is one wild point in the lateral error plot of Figure 30, that is, a point removed by more than an experimental error of about 0. 005 deg, and there are two in the lateral error plot of Figure 33. These exceptions are sufficiently rare to allow the inference that tracking performance could be regarded as a continuous, single valued function of a control gain. This view was reinforced by the fact that gain values were unknown to subjects, who also found it impossible to distinguish empirically between one control gain and another. The results obtained in real flight were somewhat less consistent, with departures from the error curve of nearly 0. 01 deg in Figures 29 and 30. This difference is attributed to the greater difficulty of preserving uniform operating conditions in real flight. As regards Cooper Ratings, it will be seen that experimental results fall mostly within half a point of a smooth curve drawn through the data points, and this amount of variation appears to be reasonable in a subjective measure. Both measures of performance were evidently functions of the control gain and this view is supported by the observation that scores were invariant in the command channel bearing no theoretical relation to the gain being varied.

The effect of adding another task in simulated flight, where subjects were required to operate the throttles, was evidently without adverse effect on performance of the tracking task. In all cases but one the level of tracking error was lower in simulated flight than in real flight: the exception is seen in Figure 30, where lateral errors were greater in simulated flight. For this reason the simulated flight results probably reflect relationships between performance and gain better than the real flight results, where there were evidently influences, such as turbulence, tending to mask the effects under investigation.

It was unfortunate that the same subject could not be used in all experimental runs and some degree of consistency has been lost for this reason.

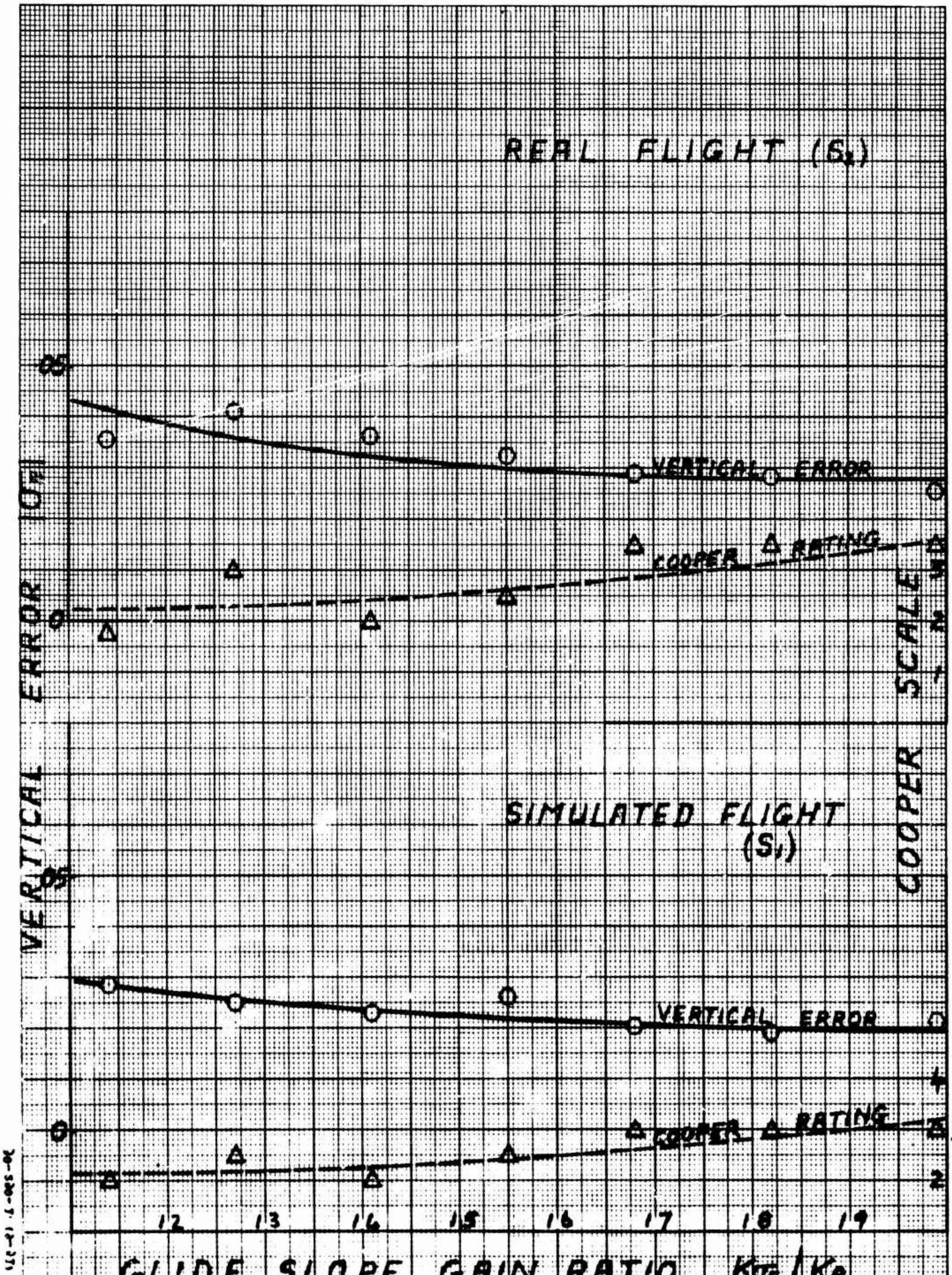

FIGURE 34 INFLUENCE OF GLIDE SLOPE GAIN RATIO ON TRACKING AND COOPER RATING

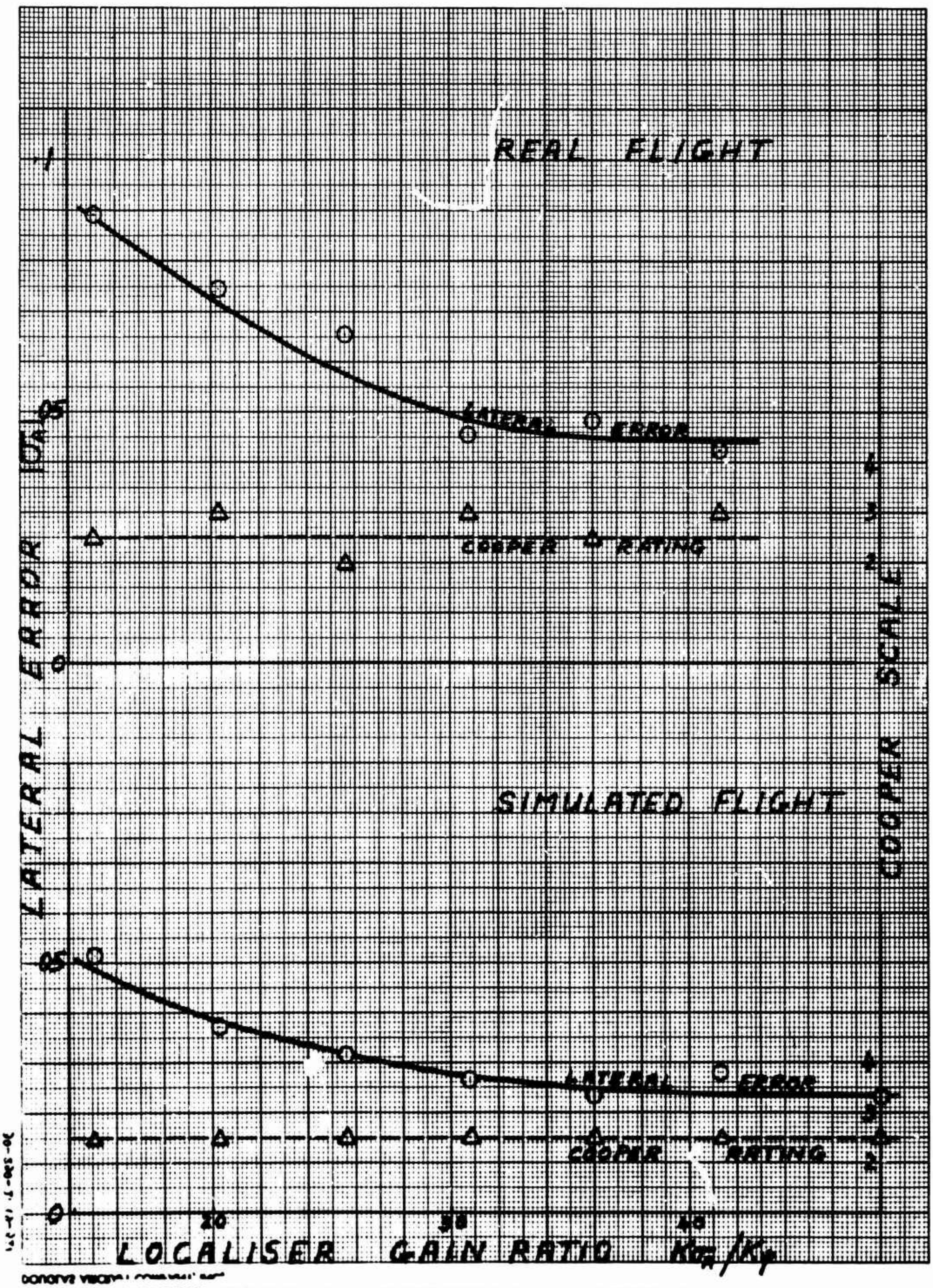

FIGURE 35 INFLUENCE OF LOCALIZER GAIN RATIO ON TRACKING AND COOPER RATING

The effect of changing subjects was evidently very small, however, as can be seen from the results shown in Figure 34, for variation of the glide slope gain ratio. After allowing for increased error in flight, comparison of the performance levels and trends in the two experimental situations indicates that no great confounding effect was introduced by the change of subject, a view which was supported by subsequent comparisons of performance for S1 and S2.

The inference that the experimental results revealed relationships between performance and gain is further illustrated by a comparison of results obtained in simulated and real flight. On this basis, the results collected in Table IX show the same value for the control gain giving minimum tracking error in four out of seven cases; viz, elevation, elevation rate, glide slope and localizer (columns 3, 4, 6, 7). In two of the other cases there was no variation in tracking performance in real flight, columns 1, 5, and in the case of bank rate (column 2) the difference for the two kinds of flight, of 0.25, was smaller than would correspond with an effect of chance. From this comparison it was concluded that the same relationship between gain and performance was shown in real and simulated flight, except in cases where the range of gain values was insufficient or where masking effects, possibly due to turbulence (Figure 33), concealed trends in performance. Simulation methods could therefore be used with some confidence in estimating gains for head-up presentation prior to flight.

When the optimum gains found by the two methods of measuring performance are compared, two kinds of effect are seen, which the experimental curves show better than the tabulated results. In some cases the tracking error curve is seen to be roughly parallel with the Cooper rating curve, with minima at nearly the same gain or gain ratio, as in Figures 30, 32, and 33. In the case of heading gain, Figure 29, and elevation gain, Figure 31, an entirely different effect is found: the curves have different shapes, and their minima are not coincident. A similar but less marked effect is seen in the curves for glide slope and localizer gain ratios, Figures 34 and 35. It follows that the objective method of measuring performance cannot always be used to give the best operating conditions, but should serve rather as a basis for cooperative adjustment.

The results obtained in varying elevation gain, Figure 31, best illustrate how the objective and subjective methods of measurement can be used to understand the control process and arrive at best operating conditions. The objective method shows that elevation gain cannot be reduced much below a value of 0.3 without increasing tracking error, in both kinds of flight. But the user prefers a value of 0.2, at which tracking error is about 50 percent greater, in simulated flight. The reason for preferring the smaller gain appears to be that the pilot then has the feeling of a less busy control situation, with less tendency to overcontrol in turbulence, and it can be seen that in almost all cases the gain preferred by the user was less than the minimum revealed by tracking performance. In choosing values likely to give the most satisfactory operating conditions, it is obviously desirable to strike a balance between the requirements for satisfactory handling qualities and small tracking errors, and this may be done with the help of the results summarized in Table IX.

To sum up: evidence has been presented showing experimental relationships between unseen gains and two measures of human performance, as a set of smooth curves with only small departures due to chance effects. Results were less consistent in real flight than in simulated flight, and masking effects, such as turbulence, led to increased tracking errors. The results obtained in the two kinds of flight were similar, however, the same gain value giving minimum tracking error in all cases, except where the range of variation was too small or where masking effects appeared to conceal the expected trends. The two measures of performance did not always give the same result, and each needed to be considered in selecting gains for the best operating conditions. The results were essentially for a single subject, and the broader question of whether they represented general relationships could not be decided without attempting to transfer the optimum control conditions to a larger population of users.

6. EVALUATION BY DEMONSTRATION FLIGHTS

At the conclusion of the gain investigation, a series of demonstration flights was undertaken in which a relatively large number of pilots acted as experimental subjects. It thus became possible to make the desired test for generality of the control conditions optimized for one subject. At the same time, attention was directed to the other significant properties of the system besides tracking accuracy, namely, the ease with which the system may be learned and used, and its capability for eliminating the all-or-nothing nature of the transition from instrument to visual flight, both of which have been discussed in Section 2. The information gained in this way would be expected to give a fairly comprehensive idea of the conditions under which the pilot would operate during a head-up manual instrument approach, and since an approach of this type can be continued to touchdown[2], it would thus be possible to compare it with automatic approach and landing on a reasonably broad basis.

This part of the work is an extension of the experimental investigation of Section 5, using the same equipment but modifying the method to deal with the new question of generality, and the transfer of known properties: in particular, subjects' comments are used to provide some of the experimental material. This section concludes the investigation of the more important aspects of the system and gives a brief account of its use in various flight modes. It also deals with night flying, where the state of the art is advanced through experience gained in fairly extensive use, but little is done to answer current questions on the efficacy with which a head-up presentation of the flight vector may be used. Development in this direction was limited by the lack of boresight facilities mentioned under Calibration in Section 4, and the difficulty of providing a stable yet responsive angle of attack signal (a difficulty also encountered in earlier work[23]). With the elimination of these difficulties, it might be possible to improve the quality of a visual approach, especially in the new generation of large aircraft, and it might also be possible to advance the concept of independently monitoring an ILS system if information of similar quality could be provided concerning the position of the flight vector in relation to the runway. Some attention is directed to the crosswind approach but with emphasis on the question of pilot disorientation rather than on matters of operational procedure, and in this latter area there is a need to work out an appropriate division of duties for pilots using either single or dual display systems. Another subject receiving little attention is the relatively complex art of learning to acquire information from both display and forward view, which takes more time to learn than the simpler process of using the display alone[22]. It is in these directions of exploring modes and operating procedures that future work may be directed.

EXPERIMENTAL METHOD

The demonstrations were given to two groups of subjects, using gains derived from the results previously obtained with S1. In each group, subjects were highly experienced pilots, the chief difference between groups being in the degree of familiarity with the DC-9-20 test vehicle. The first series of flights was for three company pilots, for whom gains were set (on the advice of S1 and S2) to the values shown for S3-5 in the lower part of Table IX. These are the values used in the latter stages of the gain survey, which also appear in the last three columns of Table VIII, except that a range of values was provided for programming the glide slope gain ratio, column 6; this program was only used below 250 ft. in the first series; that is, below the lower limit of recorded runs. The selected values were generally lower than the minima found experimentally for S1, which appear in the upper rows of Table IX. It was not expected that these changes would affect real flight error scores to any appreciable extent, as can be inferred from the experimental curves for S1, Figures 29 to 35. By comparing the tracking error at the selected gain with its minimum value, it can be seen that the effect is negligible except for increases in vertical error of 0.013 deg and 0.007 deg due to changes in elevation gain and glide slope gain ratio, respectively, and an increase in lateral error of 0.005 deg due to change of bank rate gain ratio.

Subjects taking part in the second series of demonstration flights were visiting pilots having less experience of the test vehicle, and it was thought desirable to make further reductions in some gains, since these pilots were expected to feel more at ease with smaller symbol movements. The values used were those shown for S6-41 in the lowest row of Table IX, which include 10 percent reductions in heading and elevation gains and a 25 percent reduction in localizer gain ratio. Further inspection of the experimental curves shows that the effect of using these values instead of the S1 minima could be to increase vertical errors by 0.015 deg and 0.016 deg through changes in elevation gain and glide slope gain ratio, respectively, and to increase lateral errors by 0.005 deg and 0.014 deg through changes of bank rate gain ratio and localizer gain ratio, respectively; so that these changes were made with the possibility of incurring small performance penalties. Another difference in the second series was that the gain program was started at the outer marker, necessitating a corresponding change in computing tracking errors.

A small group of pilots took part in each flight, one acting as subject while the others were free to watch a monitored presentation of the display format on cathode ray oscilloscopes at the experimenter's station, which can be seen in Figure 36 together with the absolute error integrator, left, and the Sperry control law computer, right. Subjects took the wheel during a downwind leg, thus acquiring about five minutes of familiarization before starting the first of three manual approaches; exceptionally, two subjects used the display system during takeoff, as mentioned later in describing learning effects. The approaches were all continued to a height of 100 feet, using the same overhead installation as in the gain survey (Figure 17). After completing the first approach in visual conditions, the second and third approaches were made with crossed polars, thereby reducing forward visibility to a value lying between a few hundred feet and one mile, depending on the amount of illumination in the external scene. One of these approaches was used to investigate the possibility of the pilot becoming disoriented, by deliberately slewing the format in azimuth so as to be out of alignment with the direction of advance in the external visual world, as shown (with sufficient accuracy) by the position of the emergent

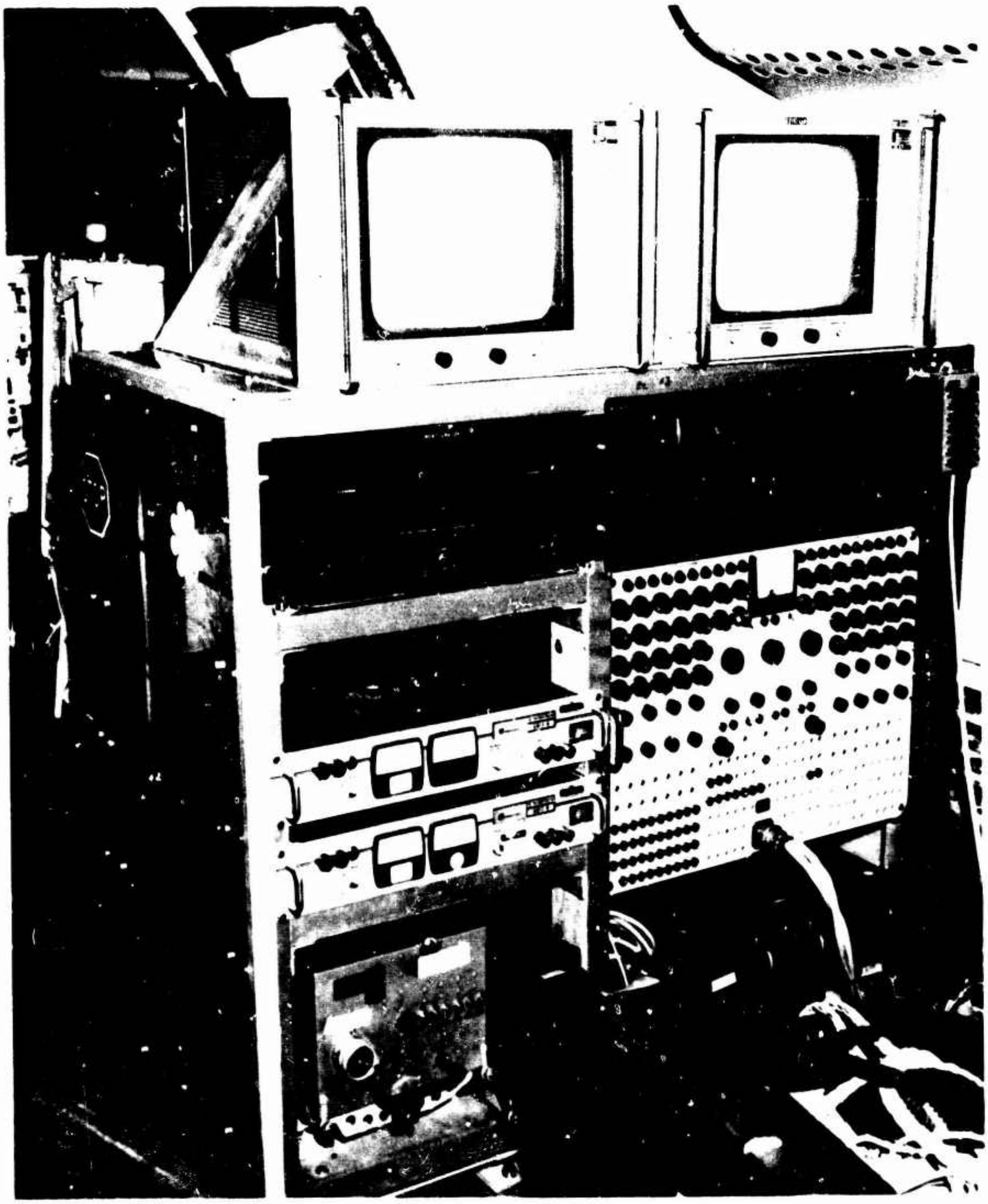

FIGURE 36 EXPERIMENTER'S STATION

runway. On the last approach, a touch and go landing was to be made if the aircraft was suitably placed when forward visibility was restored to the subject, at a height of 100 feet. This judgment was made by the demonstrating pilots, S1 and S2, who also removed the restriction on forward visibility by flipping up the subject's polaroid vizor.

Absolute tracking errors were integrated between heights of approximately 1200 feet and 250 feet, as in the gain survey, while performance could be watched on the monitors to confirm the absence of large scale director excursions (which might otherwise invalidate use of the mean absolute error as an informative measure of tracking performance). In computing angular offsets from the glide slope for the second series of flights, an equivalent constant gain ratio was assumed in place of the gain program. Approaches were flown by day and by night, in smooth air, at March Air Force Base, Oakland, Fresno, Palmdale, Edwards Air Force Base, and Long Beach, California. Most approaches were made with autothrottles engaged.

RESULTS

Tracking Accuracy

Lateral errors were usually found to be greater than vertical errors and were therefore more useful in comparing the performance of subjects. The histograms of Figure 37 show the distribution of lateral errors for each of three approaches in the demonstration flights, during smooth air conditions. The hatched areas show results for company pilots, S3-5, and the solid shading shows results for visiting pilots, S6-41, of which all made the first run, but only 33 and 28 made the second and third runs, respectively. The lowest scores achieved previously by S1 lie between dotted vertical lines drawn at values of approximately 0.03 deg and 0.055 deg. These values are the levels of the plateaus to which error scores descended in real flight and smooth air, the lower level occurring during the investigation of bank rate gain ratio, Figure 30, and the upper during the investigation of heading gain, Figure 29.

Comparing, first, the tracking errors for company and visiting pilots with those of S1, it can readily be seen that a close relationship exists. Error scores for company pilots were either within or below S1 limits, on all three approaches. Of the visiting pilots, 69 percent on their first run, 70 percent on their second, and 61 percent on their third run had scores falling within the S1 limits. The scoring level of a pilot very well experienced in using the display system could thus be reached by all company pilots, using slightly different gains, and the majority of visiting pilots were able to approach the same level, using more extensively downgraded gains.

The general level of performance reached by all subjects can be assessed by comparing these results, next, with the criterion used for approval of Category II landing weather minima[24]. Using the lateral tolerance applicable between 300 feet and 100 feet for the whole of a recorded run, the permissible lateral error would be within 25 microamperes, or 0.33

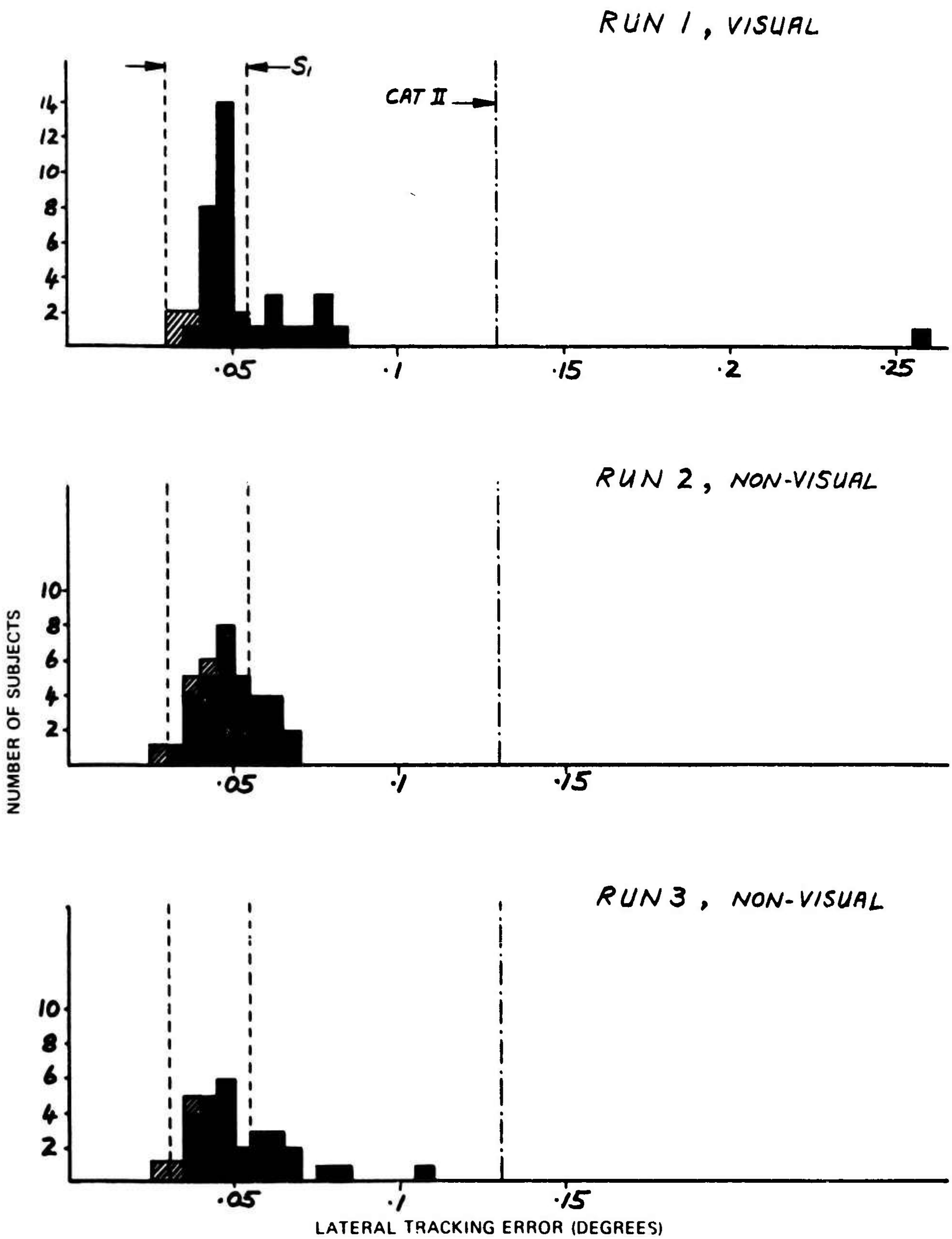

FIGURE 37 LATERAL ERRORS IN DEMONSTRATION FLIGHTS
Scores for company pilots shown hatched, for visiting pilots solid

deg, of the indicated course, with 95 percent probability. Assuming a Gaussian distribution of errors during a run, the mean value of the permissible error would then be 0.13 deg, which is shown in Figure 37 by a chain dotted vertical line. It is immediately apparent that, except for one case during the first set of runs, all lateral errors were within this Category II value, the ratio of success to failure in reaching this standard being 105 to 1. It was also reported independently by the demonstrating pilots that at a height of 100 feet they judged all approaches to be well placed for landing. Moreover, touch and go landings were made successfully on the third approach, under (restored) visual conditions.

Learning Effects

It will already have been evident from the results shown in Figure 37 that the performance levels of the demonstration flights were reached in a very short time. For on the first run there was marked success in approaching the performance of S1, and an even greater degree of success in scoring errors tolerable by Category II standards. These results were obtained after passive exposure to the way other subjects used the system, and after becoming more directly involved during a familiarization period of about five minutes on the downwind leg. In some cases, both passive and active exposures were very much less, for two subjects made ab initio takeoffs. In an isolated case, learning did not take place until the second run but, in all cases, learning was complete once it had taken place, as shown by performance in succeeding runs. Learning time was thus generally between zero and five minutes.

Transition Effects

The experimental method of the present and preceding sections was primarily intended to allow the dynamic aspects of the director symbol to be investigated, without the possible help of information contributed from the real world, which could otherwise confound the experimental results. In obscuring the forward view for this purpose, there was less opportunity to gain information about the transition from instrument to visual flight. There were, nevertheless, some observations which bore on the ability to observe display and forward view on a concurrent basis. The comment was made that it was ordinarily difficult to know aircraft height during the period immediately preceding touchdown, when the pilot cannot observe the head-down altimeter with any continuity, and this difficulty was now removed. There were also reports of observing airborne traffic while using the display in terminal areas, and a situation of this kind is shown in Figure 38.

Another transition effect was apparent in the influence of forward visibility on the acquisition of external information. In one approach at Long Beach the lights of a particular department store were seen before they were expected to become visible. Forward visibility was given as three quarters of a mile but the pilot using the display stressed the point that he saw the lights at a distance of one and a half miles. Under these conditions

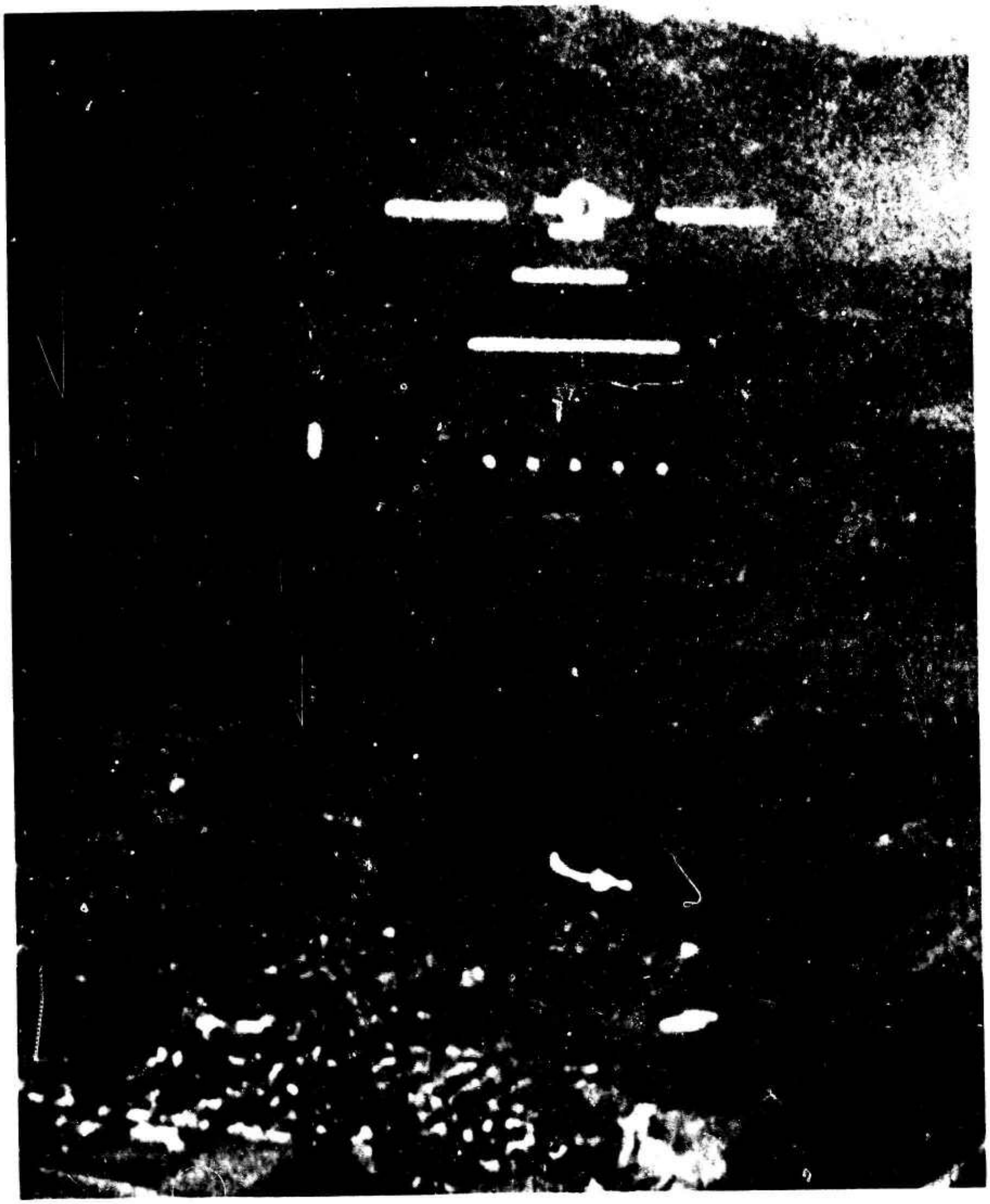

FIGURE 38 TRAFFIC VISIBLE WHILE USING DISPLAY

of poor visibility, the pilot was evidently maintained in a state of visual readiness in which he could take best advantage of unexpected external information, indicating that the previously empty visual field had not induced a state of space myopia.

Finally, an important effect was in the ability to make a smooth transition under a variety of conditions in the external field. At a height of 100 feet, when little time remained for anything but the correct control actions, there was evidently no misjudgment of the situation when forward visibility was restored, and approaches were continued smoothly to touchdown or go around. This was true whether there was an abrupt change from zero visibility, which occurred in about 30 percent of the observed approaches, or whether some external objects were partially acquired as they became visible before reaching a height of 100 feet. It was also true when the format was deliberately misaligned with the direction of advance defined by the approaching runway, in what otherwise might be considered an adverse information condition. There was an isolated case of nausea, attributable to relative movement between external objects and symbols which, through misunderstanding, were evidently expected to be ground stabilized. In general, there appeared to be little difficulty, whether mental or physical, in making the transition between instrument and visual flight, and the display could be abandoned when confident that significant information was available in the external world.

Pilot's Comments

During post-flight debriefing, visiting pilots were encouraged to make comments on the system. The experimental procedure was not ideal, for each subject made his comments in the presence of others taking part in the same flight, and it was not always possible to prevent leading questions being asked. For these reasons, testimony was not wholly uninfluenced, and the body of comment could not be subjected to strict analysis; it nevertheless provided support for issues already examined, and it was useful in drawing attention to areas where work is needed.

Favorable Comment. Visiting pilots made comments falling mostly within the categories listed in Table X, of which the first seven attracted predominantly favorable remarks. This was expected for the first three of these categories, dealing with system concept, ease of control, and ease of interpretation, because subjects were aware of their success in tracking accurately and in learning quickly; in connection with control, however, it was noted that gains at first seemed high because of the magnifying effect of the limited optical aperture. In the next three categories, favorable comment was less expected, for concepts of simplicity, external observation, and lack of need for external alignment would not be suggested simply by success in performing a tracking task; and it is interesting to note, in passing, that the external observation capability was discussed as a safety feature. These favorable comments were taken as endorsing the principles of organization and design of Section 2 because they indicated fulfilment of the basic function of moving freely between display and forward view. Favorable comment was also made about the overhead installation, confirming the earlier findings of S1 and S2 in Section 4.

TABLE X

Analysis of Comments of 37 Visiting Pilots

	Subject Of Comment	Number of Comments	
		Favorable	Unfavorable
(1)	System Concept	18	--
(2)	Ease of Control	17	2
(3)	Ease of Interpretation	6	-
(4)	Simplicity	8	-
(5)	External Observation	8	-
(6)	Alignment	9	1
(7)	Installation (Overhead)	22	-
(8)	Visual Field	1	7
(9)	Image Quality	-	6
(10)	Fatigue (6 users)	-	2
(11)	Instrument Crosscheck	-	4
(12)	Format Change	(tabulated separately)	

Unfavorable Comment. In the next four of the five remaining categories, comment was less favorable. The visual field was felt to be narrow, restrictive, or in some way adversely affected by edges of the reflector plate which, it was felt, should be enlarged. Quality of the optical image was also criticized, with complaints of fuzziness, an image "not at infinity", and "eyestrain". It was not practicable to pursue the latter complaints rigorously, but only to note divergence from the results obtained with S1 and S2, as already discussed. A possible reason for the discrepancy, suggested by S1, was in the use of too much brightness, causing diffuse symbols and a sense of being unable to focus on the format. There was also unfavorable comment about fatigue by two out of a total of six subjects using the display for an extended period of about one and a half hours. Again, this result was contrary to previous findings but in this case, it will be noted, subjects were using the system for the first time, and the incidence of fatigue was thus, perhaps, not unduly high. Finally, unfavorable comment about the difficulty of making crosschecks with head-down instruments was expected because no attempt had been made to arrive at a definite division of duties between Captain and First Officer.

Miscellaneous Comment. Some comments were made in areas falling outside the scope of this work. For example, reference was made to operation in real weather conditions, which has been considered elsewhere(25), and there was a suggestion that a completely independent system would be needed in a supporting capacity, which may be true or false without affecting most of the present results. It was also suggested that the full potential of the system would only be realized by providing for flare in the flight director computation, an arrangement which has already been demonstrated(2). Finally, it was noted that the height digits would dither between adjacent values when flying at a constant height, for which purpose the present form of read-out had not been designed.

Comments were made by company pilots which will not be reported in detail because they were similar in pattern to those of visiting pilots, except that greater emphasis was given to controllability. For example, it was noted that HUD could be flown more accurately than known head-down systems, that it could be easily flown to lower minima, and that it could be flown in Altitude Hold to within $\pm$ 50 feet. One interesting comment was to the effect that the user found himself flying with unusual coordination, applying rudder, which he normally did not touch. This observation may perhaps have arisen through transfer of visual flight skills, as discussed under Framework of Interpretation, Section 2. On the other hand, it was found less easy to anticipate a new heading, when making large changes of course, than with a plan position indicator, where the pilot has a more comprehensive picture of azimuthal relationships.

Format. Suggestions made by visiting pilots for changes in format are summarized according to frequency in Table XI. The most frequent was for shifting the speed display from the top to the side of the format, a change which could be made without prejudice to display properties, except that the range of lateral shift would be reduced, with effect on the capability for slewing the display in crosswind. Some pilots also wanted to move the speed display closer to format center, which would cause increased interference, and this comment was fortunately rare. Another frequent

TABLE XI

Suggestions for Format Changes Made by 37 Visiting Pilots

	Content of Suggestion	Frequency of Suggestion
(1)	Move speed display	10
(2)	Add digital speed	8
(3)	Make digits larger	7
(4)	Show Decision Height	5
(5)	Start height read-out at 2500 feet	4
(6)	Show barometric height	4
(7)	Show more attitude information	4
(8)	Add heading information	4
(9)	Move height display	3
(10)	Add sink rate information	3
(11)	Show flight vector	3
(12)	Add mode annunciation	3
(13)	Lengthen wings on reference symbol	2
(14)	Add: Performance Gate, Collision Warning, ILS Markers, digital readouts; make horizon symbol heavier; provide independent symbol selection.	1 each

suggestion was for the addition of the present value of airspeed, preferably as a digital read-out, which could probably be accomplished with only slightly increased clutter, as in the head-up format of the Harrier[26]. Suggestions for larger height digits (in the Captain's format) were also frequent, a change which should be possible without penalty. Suggestions (4) to (6), which were moderately frequent, were also connected with the height display, asking for the limiting altitude to be increased to 2500 feet, for barometric height to be added, at least above 500 feet, and for an indication of Minimum Decision Altitude, all of which could probably be met without penalty, except for increased clutter due to an additional height read-out.

The suggestion for providing more detailed attitude information, (7), though moderately frequent, was not acceptable for the essentially command information format of Figure 5 because of redundancy, increased interference, and increased clutter, but it could be met by adapting the format for non-directed flight[27], where this information would no doubt fulfill a more fundamental purpose. The next suggestion, for heading information to be added, (8), could be met with a known form of symbol[26] which would not cause interference, nor greatly increase clutter if it replaced the localizer scale. Suggestion (9) was for moving the height display into the conventional right-hand position, which was unacceptable at low altitude for the reason already given. Suggestion (10), for adding sink rate information, was also unacceptable, because this information is redundant when an approach is flown with the accuracy which has been demonstrated.

The suggestion for showing the flight vector, (11), drew attention to a currently felt need in head-up presentation, but could not be met with existing facilities. On the other hand, suggestion (12), for mode annunciation, could no doubt be met by means of conventional alphabetic abbreviations shown in the lower quadrants; and suggestion (13), for longer wings, though implying divergence from the results obtained by S1 and S2, could also be met if necessary. Suggestion (14) included requests by individual users for a Performance Gate, Collision Warning, and ILS Markers, which could perhaps be provided without permanently increased clutter. Proposals to add further digital readouts and to strengthen the horizon bar were less acceptable because of disturbing the balance between other parts of the format, to meet needs which, together with the need for independent selection of symbols, were not very widely felt. Comments were also made on the director index, with an equal division of preference between point and circular forms.

Other Applications

Although the display system was mainly used for instrument approaches, there were other applications in which operational experience was gained. The conventional flight modes were explored by changing the format to deal with differing information requirements, as will be described, the changes being effected through the Flight Director Mode Selector, which can be seen mounted in the glareshield on the right in Figure 13. The flight tests showed that the system could be used satisfactorily in these modes, with little change in customary procedures. The system was also used without difficulty in night flying. In all of these applications photographic recordings were made.

Take-Off and Go-Around Modes. In these modes, the basic format of command and attitude symbols was augmented with height and speed symbols, while the ILS scales were occulted. In conformity with head-down practice, the director symbol was driven in elevation by the speed "command" signal, for various aircraft configurations, but no azimuthal guidance was provided. The information redundancy arising from this practice is illustrated in Figure 22, where an excess of speed is shown by the speed display, and there is a nose-up command shown by the director symbol; for both excursions would be nulled by rotating into a more nose-up attitude.

Flight Instrument Mode. For general and en route use in the Flight Instrument mode, the pilot was provided with Heading Select and Altitude Hold facilities. The format was reduced to the basic combination of director and horizon symbols, with the localizer scale added to help in anticipating the selected heading, while height, speed, and glide slope symbols were occulted. The gains used in this mode were essentially the same as in the approach.

VOR Mode. The same format of director, horizon, and localizer symbols was provided in the VOR mode, which was similar to the Flight Instrument mode, except for replacing the selected heading by the radio signal heading. For purposes of capture, this mode could be used either with or without the help of computed changes of direction, according to whether "radio automatic" or "radio manual" settings were selected.

Approach Mode. This mode was flown with the complete symbol format of director, horizon, speed, height, and ILS symbols (Figure 5). It was available with the Mode Selector set to Radio, as in the case of the VOR mode, the change to the full format being effected by the symbol control logic responding to a descrimination between the received ILS and VOR signals. Again, capture could be made either with or without computational help. Approaches were flown with or without autothrottles, and often to as low as 50 feet. In the special case of an approach flown without ILS being selected, and therefore with only a rudimentary format, it was found convenient for the purpose of Minimum Decision Altitude procedure to select Go-Around, so that the height display would become available, while the superfluous director symbol could be ignored.

Night Flying. The display was used after dark as a regular part of flight operations, and a total of twenty night approaches were completed by visiting pilots. Very few critical remarks were made. There were some comments about reflections from lights inside the cockpit, and it was noted that the conventional mode annunciator now appeared to be too bright. Both of these points could probably be met by small design changes. It was also noted that a more gradual change of brightness was needed at the lower end of the range, to match the enhanced sensitivity of the pilots' vision when adapted to low light levels in the forward view. For this purpose, an auxiliary brightness control might be advantageous.

As regards operational methods, it has already been noted in Section 4, under Clutter, that the complete format was less acceptable by night than by day because external objects could more easily be acquired with ILS scales occulted· otherwise, it was found that the same formats could be used as by day. There was a tendency for some parts of the display to be lost temporarily against brighter parts of the approach lighting, when the format was dimmed to preserve night vision, but this situation was felt preferable to the alternate situation of brightening the display at the expense of a large amount of external observation. Another feature of a night approach affected by head-up operation was the necessity, in conventional procedure, to look up from the head-down panel to an external scene which might resemble "the inside of a milk bottle", when approaching through layers of mist illuminated by ground or aircraft lighting. The display system was found to help in becoming accustomed to this difficult external condition. There were thus no major difficulties in using HUD by night, and satisfactory operating procedures were available, with some advantage over conventional practice.

Photographic Recording. The results obtained by measurement, by observation, and by the analysis of comments, were supported by colored motion pictures taken during flight. The chief interest was in photographing the display format, as seen against the forward view, and for this purpose a hand held camera was used, so that some idea of the degree of turbulence would be given. The camera was focused at infinity, of course, and it was held in what was believed to be a suitable position, the regular viewfinder being unusable through parallax. In this way, sequences were successfully recorded by S1 in all modes of flight. Other sequences showed pilots using the display equipment.

These flight records were useful in making improvements during early stages of flight testing, especially in removing noise effects and various forms of visual interference. A point of particular interest shown in some later approaches was the curvature of an ILS beam. It was found that the position of the circular aircraft symbol, which would remain fixed in relation to a ground point for an approach flown in stable conditions, could steadily change by about 10 deg in the vertical plane. The aircraft was known to be on the glide slope at all times because the vertical displacement from the beam and the elevation command were always zero, within small limits. A persistent change in direction of the aircraft axis, as shown by the symbol, could therefore only have arisen through a change in beam direction, or through a long term change in the angle of attack. The largest change in angle of attack would probably be that needed to compensate for longitudinal movement of the air mass, and it

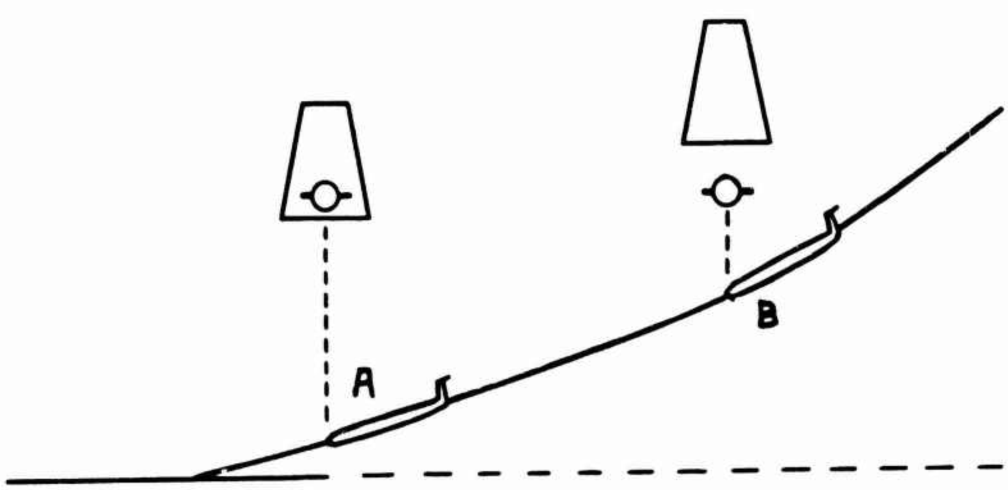

FIGURE 39 EFFECT OF BEAM BEND IN DISPLACING AIRCRAFT-STABILIZED SYMBOLS RELATIVE TO GROUND

is not difficult to show that this would be about 0.5 deg for a 20 knot change in headwind. It could thus be concluded that the observed change of direction represented the effect of an ILS beam bend of the order of 10 deg.

The changes observed in the pilot's visual field under these conditions may be realized with the help of Figure 39, where zero angle of attack has been assumed for simplicity. At A, the beam is directed from the touchdown point, on which the aircraft symbol is therefore superimposed (for a boresighted display). At B, the beam is directed from a ground point nearer to the aircraft, and the symbol is therefore seen below the runway. In other words, the format is moved vertically with respect to the ground as the approach proceeds. It is important to note that the positions implied for conditions A and B are the best which could be occupied by a runway symbol moved in accordance with the output of a computation based on ILS, and the illustration serves to emphasize one of the major practical difficulties met in the head-up presentation of this type of symbol. On the other hand, a command display is not seriously affected in this way by beam bends, and pilots experienced no difficulty in using the system under such conditions of vertical misalignment.

DISCUSSION

Display Properties

The chief property investigated in this section was the tracking accuracy obtained with an appropriate array of symbols, activated in accordance with control gains selected after observing the performance of a single subject. By applying results of the gain survey of Section 5 to a larger population of subjects, it was to be seen whether generally satisfactory conditions had been arrived at which could be transferred to other users, who should then be able to demonstrate a high level of performance, by the standards established for S1. From the experimental results it was in fact possible to judge the success in making such a transfer to two succeeding groups of pilots.

It was found that the lateral tracking errors for company pilots were as good as, or better than the best scores of S1. For this group, gains had been reduced, but only to an extent likely to cause a very small increase in error scores, of the order of 0.005 deg. In the second group, of visiting pilots, error scores were somewhat larger, yet the majority managed to reach S1 levels. In this case, gains had been further reduced to offset the influence on subjects of a smaller degree of experience with the airplane, which would possibly magnify the previously observed difference between gain values for best score and best Cooper Rating. The penalty due to these reductions was expected to be perhaps as much as 0.02 deg, and it can be seen from Figure 37 that if all scores were reduced by this amount they would mostly fall within S1 limits. Thus, in both groups subjects approached the performance of S1, but with a degree of success depending on the closeness with which it was practicable to match gains.

The conclusion was drawn that it was possible, by a series of controlled runs with a selected subject, to arrive at a reasonably general definition of good operating conditions, for which the overall mean vertical error was found to be 0.042 deg (smooth air).

The significance of this experimental result is twofold. It shows the convenience of being able to achieve a general result on a limited budget. It also shows the possibility of achieving a degree of unity in an area of control theory which is sometimes made chaotic through the proliferation of individual preferences. The performance curves, Figures 29 to 35, together with Figure 37, were very helpful in this respect, enabling gain values to be chosen which could be accepted by common consent as suitable on both objective and subjective grounds. In thus discussing results with users, it was perhaps possible to establish better communication and give greater insight than by means of describing functions. Finally, it is interesting to note that tne overall mean error, when doubled to allow for more general conditions of turbulence (as discussed later) was the same as found previously in military aircraft[28]. This result is presented in Table XII with the other results of this Section.

The second property investigated was the ease with which pilots learn to use the system. It was found that a consistent and satisfactory level of accuracy could be reached quickly, usually in something less than five minutes; that is, in a time which was of the same order as the learning time for experienced pilots in military aircraft[6]. This result is attributed to the graphical form of the display format, which is understood through skills already learned in visual flight, as discussed under Framework of Interpretation in Section 2, these skills being transferred to the display and put to immediate use. The significance of the result is that the system can be used with almost no mental effort.

The third of the main properties investigated was the capability for eliminating the all-or-nothing nature of the transition. While observations in this area were limited by the experimental method, it was nevertheless clear that pilots were able to see the external world while using the display. In being able to acquire height information during the flare, at a time when nearness to the ground makes it almost impossible to look at the cockpit altimeter, and in being able to observe airborne traffic while "on instruments", there was a capability for continuous observation in visual fields which are normally quite separate, and can therefore only be regarded one at a time. Moreover, in being able to see ground detail earlier than expected, there was an ability to accomplish the transition more efficiently than in conventional flight, where the acquisition of ground objects can be delayed through space myopia. There were thus sufficient events to illustrate the expected improvement in the transition. An improvement on the normal state of affairs was also evident in the ability to make a rapid, yet smooth, transition when suddenly confronted with the external world at a height of 100 feet, an ability unimpaired by the display format being out of alignment with the runway, either horizontally, through deliberate slewing, or vertically, through the influence of a bent beam.

As noted in Section 2, all results involving dual observation are attributable to being able to move with little effort, whether mental or physical, between

TABLE XII

RESULTS OF DEMONSTRATIONS IN COMMERCIAL AIRCRAFT AND EARLIER INVESTIGATIONS IN MILITARY AIRCRAFT

	COMMERCIAL	MILITARY
Tracking	0.084 deg*	0.084 deg
Learning	0 to 5 mins	0 to 5 mins
Transition	Information discontinuity eliminated; no disorientation when abrupt, or misaligned	Information discontinuity eliminated
Applications	All modes, night flying, bent beam	All modes, aerobatics.

* doubled to allow for general conditions of turbulence

display and forward view, which occupy the same position and are understood by similar rules. For under these conditions there should be no induced shortsightedness, nor any necessity to switch between alternate methods of understanding the environment; so that the transition causes little or no gap in the flow of information, ground detail being seen as early as possible, being acquired slowly if it appears slowly, and accepted in preference to the display when it becomes sufficiently complete. The significance of these results is that, for this display, the traditional concept of an absolute and discontinuous transition, between mutually exclusive visual processes, becomes invalid, and it is thus possible to improve the conditions under which the pilot carries out this difficult process. Another significant aspect is the lack of need for alignment with the approaching runway, which is attributable to the fact that the superimposed fields are not understood by exactly the same rules. This does much to simplify operation in turbulent conditions, and during a crosswind approach, a situation which is illustrated in Figure 40, where the problem of alignment is very evident in the fact that the runway lies outside the field of the display system.

These three main results, confirming known properties of the system, but in its application to commercial rather than military aircraft, were supported by pilots' comments. It has already been seen that many of these comments were in harmony with concepts developed in earlier sections; of accurate flying, easy interpretation, simplicity, safety through external observation, and freedom from disorientation due to misalignment; moreover, the overhead installation was liked. These comments need no further discussion. On the other hand, the less favorable comment was useful in showing areas needing more attention. The shape of the reflector plate, though found acceptable by S1 and S2 in Section 4, was criticized in the demonstration flights, but here there may not have been enough time available to become fully accustomed to working with it. Image quality was also criticized, again in contradiction to previous opinions, and this may have been due to the cathode ray tube line width at high brightness. Another subject of disagreement was the length of time for which the system could be used comfortably, some pilots in the demonstration flights becoming fatigued after one and a half hours instead of about three and a half hours, a difference possibly due to using the display for the first time. Finally, criticism showed the need for developing operating procedures in which it would be possible to include head-down instrument checks, and there was still some difficulty in anticipating a new heading even with the addition of the localizer scale.

Suggestions for changes of format were helpful in showing directions in which it might be possible to expand the system. Most of the suggestions were of a minor nature, and appeared to be acceptable for only a small penalty. If the speed display were to be moved, this could be accomplished simply at the expense of the capability for slewing. If digital airspeed were to be added, height digits enlarged, the read-out modified to show Minimum Decision Altitude, and heading added to help judge crab angle, there should be no great increase in clutter, assuming the use of symbols and techniques which have already been tried. It should also be possible

FIGURE 40 CROSSWIND APPROACH WITH OFFSET DISPLAY
Note that a (congruent) runway symbol would be invisible

to add mode annunciator, performance gate, collision warning, and ILS marker information with only temporary increase in clutter. However, suggestions for including more attitude information, height rate, and more digital read-outs were unacceptable for reasons of redundancy, and it was not desirable to move the height display because of reduced information access. The suggested need for flight vector information has already been discussed, and it has been noted in Section 4 that there is no great difference between using a point or a circle as the flight director index. A few remaining suggestions were unacceptable through lack of essential purpose or because of disturbing the balance of symbols in the format.

Other applications of the system showed head-up operation to be possible in all modes of commercial flying, with little modification to regular procedure, and with the necessary changes in format achieved in a simple, compatible manner. Further changes in format, some of which have already been discussed, might be desirable in some modes, for example, by augmenting heading information in Heading Select and VOR, and by adding Minimum Decision Altitude during Approach. For night operations, only minor cockpit changes and improved brightness control were needed, the same formats being usable as by day, except that ILS scales were less desirable. Approach lights could cause a temporary loss of information, at an acceptable level, but their frequently powerful effect in increasing pilots' problems, through illuminating layers of mist, was very much reduced. These results were generally satisfactory and, when taken in conjunction with the previous finding that HUD plays an important part in helping to fill the "black hole" of a night approach[2], they showed night flying to be a perfectly feasible, and somewhat improved operation. It was also possible to operate with a bent beam, as photographic records showed, and this was in a situation where a display based on a runway symbol would be incongruent (a particular case of position error[29]); however, it could not be concluded from such limited experience that Category II beam requirements could be relaxed for a head-up manual approach. Considering all these results, and the fact that HUD has previously been used satisfactorily in military flight modes and aerobatics[30], it was evident that the system was capable of very wide application; and that properties previously established in military aircraft could be transferred to commercial aircraft.

Human and Automatic Operation

Tracking Accuracy. The experimental results for tracking accuracy have so far been discussed only with the intention of comparing performance among pilots. A more absolute evaluation may be made by relating performance to Category II criteria, and this was made possible for the integrated errors by assuming a Gaussian distribution during the course of a run. It was found that 99 percent of pilots flew an approach acceptable by Category II standards, a level of performance reflected in the testimony of the demonstrating pilots, S1 and S2, who judged the quality of these approaches, and also in successful touch-and-go landings. The consistent accuracy implicit in these results suggests that it may be interesting to compare performance in this method of making a manual approach with the performance achieved in automatic flight.

In order to make the comparison, it is necessary to express results by a common method. For the available autopilot data, the method consists of finding the standard deviation of the height error at a chosen height of, say, 100 feet, during successive runs. For the present experimental results, the same method cannot immediately be used because only the mean absolute error is available for each run. The mean error may nevertheless be used to derive a standard deviation for the run, since the distribution is assumed to be Gaussian. The two methods of arriving at a standard deviation, between runs and during a run, will then be equivalent if each run has the same Gaussian distribution of errors, as will now be assumed.

For the 36 visiting pilots, a typical mean value for a run was a vertical error of 0.042 deg. The corresponding one-sigma value would be 0.053 deg, and this would yield a height error of $\pm$ 2.1 feet at a height of 100 feet on a 2.5 deg glide slope. Since the experimental results were obtained mostly in smooth air, it is necessary to increase this value to allow for more general conditions, and supplementary experiments showed that errors may be twice as great in rough air. A value of between 2 and 4 feet was therefore to be used in making the comparison with an automatic approach, since the operating conditions usually include a range of turbulence conditions. In a similar (DC-9-30) vehicle, and with optimized gains[31], the one-sigma value for 13 automatic approaches at Oakland, where most of the present results were also obtained, was found to be 3.3 feet, using a conversion factor of 6.25 microamperes per foot, for a 2.5 deg beam. The values to be compared, of 2 to 4 feet and 3.3 feet, are shown in the first column of Table XIII.

The comparison indicates that approaches of equivalent accuracy and variability may be made in automatic, and head-up manual instrument flight in DC-9 airplanes. A similar result was obtained by Morrall[32] using essentially the same display in a slow transport aircraft, where a standard deviation of about 5 feet was obtained in each type of operation, as shown in Column 2 of Table XIII. These larger values may have been due to measuring errors by ground theodolite, so that effects of beam bends would be included; or the increase may have been due to differences in control dynamics. In any event, comparison of the two types of flight involved no assumption of statistical equivalence, or any need to eliminate effects of gain programming. Taking both sets of results together, it is concluded that equivalent tracking accuracy may be ascribed to the two methods of flying an approach. From this it would follow that a head-up manual approach is possible under Category III conditions, and the fact that this result has already been demonstrated under artificial Category III conditions in real flight[2] adds weight to the present conclusion. A similar equivalence in tracking accuracy at the Category II level is more directly concluded from the present results.

TABLE XIII

COMPARISON OF TRACKING ACCURACY IN MANUAL HUD AND AUTOMATIC FLIGHT

Standard Deviation of Height Error at 100 Feet

TYPE OF APPROACH	DC-9	SLOW TRANSPORT[32]
Manual HUD	2 to 4 feet	5 feet
Automatic	3.3 feet	5 feet

These results allow the concept of automatic approach and landing to be seen in a new light. For if man and machine are equivalent as regards tracking accuracy, how do they compare in other respects ? A manual approach and landing is an operation carried out by the human pilot, on the basis of available information, with the intention of securing a particular set of physical conditions; viz., of attitude, position, and velocity. An automatic approach and landing is an operation supervised by the human pilot, who may yet intervene, again on the basis of available information, if he is not satisfied that the required physical conditions are being, or will be met. Both operations involve some degree of activity on the part of the pilot: both involve information, mainly visual in nature; and both involve realization, or some degree of understanding, of the state of the vehicle in relation to its environment. An adequate comparison should therefore take account not only of tracking accuracy, but also of the operator's workload, his information, and his problems of orientation, though these other aspects may be less amenable to measurement. Finally, the comparison should take account of the maintenance of flying skill, which is evidently not used to the same extent in the alternate methods.

Workload. Consider, first, the pilot's workload in performing the control task. In automatic flight, this will include some interpretative effort in monitoring the system, some small amount of mental effort in holding himself ready to take over and fly by conventional instruments, should the need arise, and also some effort in understanding the environmental situation. His load, though small, is thus not negligible. On the other hand, in a manual approach with HUD the control task will consist in monitoring activity, such as noting the completion of an approach phase, in continuous tracking activity, but which has been shown to be possible without great mental effort, and in understanding the environment, which has also been shown to be possible without undue effort. The workload will therefore be higher than in automatic operation, but only moderate in relation to the more difficult task of conventional instrument flight[22]. This result is entered in the second column of Table XIV, the results of Table XIII being carried forward to the first column.

Information. In an automatic approach the pilot's head-down instruments and indicators are the main source of information about the control task, whether by showing the status of the system, the progression of flight phases, or the performance of the automatic system, as may be reflected in the flight director instrument. No information is available about the outside world, except as may be communicated verbally by the pilot authorized to look through the windshield, and little time may remain for this between sighting and touchdown. The man in charge of the vehicle may thus remain largely ignorant of external events affecting the operation, such as unscheduled intrusions in the landing area by animals, vehicles, or even illegal operators. And this is especially so because of the influence of space myopia in reducing the efficiency of external observation in poor visibility.

TABLE XIV

COMPARISON OF HUD MANUAL AND AUTOMATIC OPERATION

Operation	Accuracy	Workload	Information	Disorientation Probability	Skill Maintain-ability
Manual HUD	Cat II or III	Moderate	Compre-hensive	Unlikely	Good
Automatic	Cat II or III	Low	Incomplete	Unlikely	Poor

In a manual approach with HUD, the pilot is not thus dependent on the slow process of verbal communication, nor limited by an inefficient visual process. His external vision is direct and critical; moreover, it is permissible, because it does not interfere with the control process. So the information relevant to the control task can be very comprehensive, the pilot being informed about the status of HUD by the presence of symbols in the format, about the progression of phases by mode symbols (which are readily available), about his own performance by the behavior of the director symbol, and about the external world by direct visual contact. This difference in available information for the two methods of flight, which is shown in the third column of Table XIV, should help the head-up pilot not only in his general capability for orientation but also, in particular, it should help him in taking over control in adverse circumstances.

Orientation. The human pilot takes no control action in automatic flight, and exercises comparatively little judgment, for he is mainly concerned with a prescribed sequence of events and a specific set of tolerances. He may nevertheless remain aware of the control situation insofar as he is able to follow the control actions caused by the automatic system, and their effects on the flight instruments. The likelihood of disorientation, as a failure to understand the control situation, is therefore small, whether as a matter of confidence that the requisite physical conditions are being met, or as a result of not being sufficiently aware of the control situation to take over in the event of failure.

In manual flight with HUD, the pilot takes control actions, and exercises judgment continuously. He understands the control situation through the process of satisfying the physical conditions necessary for a successful approach and landing, with the support of feedback from the display. This understanding should not be reduced by what is visible in the external world because of the conformable nature of the format, so the likelihood of becoming disoriented should be small. Theexperimental results showed this to be true, whether the format was aligned or slewed, and whether the transition was gradual or abrupt. Since there also seems to be a lack of reports of disorientation during automatic operation, the alternate methods are probably equivalent in this respect, as shown in Column 4, Table XIV.

Maintenance of Flying Skill. It is obvious that the pilot has less chance of maintaining his flying skill in automatic, than in manual flight. What is less obvious is the significance of this difference in commercial operation. In the case of a medium sized jet transport operating on short-haul or medium-haul routes, it should be possible to maintain a suitably low ratio of automatic to manual operations, because several landings may be made during the same day, at points having different weather conditions. In these circumstances, little reduction of flying skill would be expected. On the other hand, in the case of a large jet transport operating on transcontinental routes, the frequency of landing may be so low that it will be more difficult to overlook the effect of automatic operation. For example, if the rate falls to one landing per pilot per week, it may not be possible to replace lost skill sufficiently by simulator practice. For this reason, the capability for maintaining flying skill is poor in the kind of airplane likely to be equipped for automatic operation, whereas a good capability is clearly available in aircraft equipped for manual head-up operation, as shown in Column 5 of Table XIV.

Before concluding the comparison, some attention must be given to reliability, though this will not be used to judge between the alternate systems. This position is adopted because the reliability of automatic and head-up flight systems can evidently be brought within theoretically acceptable limits by techniques of redundancy, so it would be more informative to compare costs in reaching an agreed level of reliability, and that is not yet possible. Certainly, there is no difficulty in meeting quite a high standard of reliability in head-up presentation, Sleight[33] having calculated a failure probability of about 10^{-9} for a duplicated system, yet without using the fact that the format can be designed to allow various kinds of failure in the waveform generator, as indicated in discussing Integrity in Section 2. As regards practical experience, the present investigation covered only the removal of symbols and bank resolution failure. Moreover, design changes were made which precluded the collection of reliability data. However, previous experience showed a failure rate of about one in 350 hours, with prototype equipment[34], and this is consistent with Sleight's figure of 1160 hours for production equipment. Integrity of information is also excluded from the comparison because the systems use the same information sources, and have equivalent tracking accuracies, so that degraded guidance information, such as a bent beam, has the same effect on each.

General Comparison. The discussion has shown that other characteristics besides consistent tracking accuracy are germane to a full evaluation of the alternative methods of making an approach and landing, while some of the more frequently considered characteristics, such as reliability and integrity, are less so. Of the characteristics considered, only tracking accuracy and disorientation probability allow an equivalence between systems. On the other hand, considerations of workload, information, and skill maintainability show an inequality between systems. The choice to be made is thus between doing little work, with incomplete information, and some risk of getting out of practice, or of doing more work, with fairly complete information, and better chance of maintaining essential skill.

It would, perhaps, be premature to make this choice on the evidence which has been presented, for operational experience may reveal other factors affecting the issue. It is nevertheless clear that there must be some doubt about the wisdom of using the human pilot to monitor a machine of less ultimate capability than himself. This is a situation which has come about largely through the well-known argument that, under the conditions of an all-weather approach and landing, the pilot cannot fly with sufficient accuracy, nor can be make adequate judgments from the visual material in the external world. But this argument is no longer tenable. By introducing a capability for moving freely between display and forward view, it has become possible to avoid many of the shortcomings of conventional instrument flight. Inaccuracies are very much reduced and there is no difficulty in making a visual judgment. This change has come about through adapting the position, content, form, and dynamics of the display to suit the man, instead of using whatever happens to fit into an airplane. In consequence, the automatic landing system no longer performs a service beyond human capabilities.

What has been stressed here is that there is more to an all-weather approach and landing than can be dealt with by an automatic system. A single agency is needed for all relevant information, in order to deal with all possible eventualities. At the present time, it would seem that only the human pilot can fulfill this complex function. He may then be convinced that he can deal with all situations which may arise, including the worst situation in which an automatic system can place him, but it is difficult to see how this can be done without presenting information about status, guidance, flight phase, and environment. With this may go the ability to step in quickly and take over control, without the impediment of deciding between instrument and visual flight, yet knowing that sufficient accuracy can be maintained to touchdown. One way of achieving this goal would be by using HUD to monitor an automatic system, providing an effective method could be found for maintaining the pilot's skill. Another way would be to fly a manual approach and landing with HUD. Whatever method is adopted, it is obviously necessary to give the most careful thought to all aspects of the all-weather problem because of the pilot's responsibility for an increasing number of passengers in circumstances of ever mounting severity, arising through new problems of flight path control, through more complex procedures, and through lower operating weather minima.

To sum up: performance curves for a selected subject during systematic variation of control gains could be used to define, and agree upon, a set of good operating conditions. A very short learning time indicated that HUD was used with little mental effort. A capability for improving the transition was effective in reducing the risk of mid-air collision, in improving a visual flare, and in reducing space myopia, while disorientation problems were not evident during abrupt or gradual visual acquisition, and whether or not the display was aligned with the external world. These results were consistant with an ability to move freely between display and forward view, and were very similar to those obtained in earlier investigations.

The shape of reflector plate was not altogether satisfactory. There was some disagreement about image quality, possibly due to line width at high brightness, and about the maximum usable time. The division of cockpit duties and head-down tasks required study, and there was some difficulty in making large heading changes. Suggestions for extending the scope of the format were mostly practicable. The changes needed for mode flying were made efficiently by the flight director mode selector. Night flying was improved in several ways, but better brightness control was needed and the format was to be kept simple. Quite large beam bends were tolerable.

Comparison with an automatic approach and landing operation showed equivalence in tracking accuracy, and in probability of disorientation. Other characteristics were unequal and the choice was between doing little work, with incomplete information and some risk of getting out of practice, or doing more work, with more complete information and better chance of maintaining essential skill. The traditional argument tending to subordinate the pilot is no longer tenable, because of improvements due to adapting the position, content, form, and dynamics of the display to suit the man. To deal with all eventualities, without impairing performance through inaccurate tracking, indecision, or misjudgment, it appears necessary to present all relevant information in the head-up mode. The choice between manual - HUD and automatic - HUD operation appears to depend on the significance of maintaining piloting skill.

7. SUMMARY

The immediate object of the investigation has been to install HUD in a DC-9 airplane, by solving the usual optical problems of orientation, barrel size, instantaneous field, and visual obstruction, as well as the mechanical problems of vibration and body clearance. The most satisfactory installation was of the overhead kind, which had the advantage of avoiding internal reflections due to the sun, and caused only minor changes in cockpit layout. Some restriction was placed on the vertical adjustment of seat position, but this was not unacceptable. There was also room for improvement in the frontal aspect of the reflector plate. With these reservations, the installation satisfied all known requirements and it was evidently possible, for the first time, to provide an operational system in a commercial jet transport.

The installation was made with a new generation of equipment, differing from the equipment previously flown in military aircraft in having a smaller instantaneous field and a shorter cathode ray tube. Optical qualities of collimator and tube were nevertheless adequate, although there were minor problems of tube mounting, line profile, and low-level brightness control in the Captain's equipment. The standard of waveform generation was acceptable but there were deficiencies in forming numerals and in defining zero command in the First Officer's equipment. Further work was also needed to produce better solutions to problems of noise elimination and of bank resolution. The equipment was otherwise satisfactory, in real flight conditions, and the configurational changes had evidently been made without significant loss of performance.

The symbol format was essentially the same as in previous work, and was based on principles of selection, organization, and design which promote the flow of information, and which allow freedom of movement between display and forward view. Small changes were made in the basic combination of director and horizon symbols, an adaptable form of digital height display was provided for takeoff and approach, raw ILS scales were used for monitoring, and a new symbol was available for warning purposes. These changes were generally advantageous and led to only minor changes in the properties previously established for the system. Suggestions for further changes were mostly acceptable, and could probably be used to extend the scope and effectiveness of the display.

New ground was broken in developing a procedure for adjusting control gains. This depended on establishing empirical relations between gains and measures of performance, for a selected subject, which were obtained by objective and subjective methods in real and simulated flight. Except for the influence of masking effects, the results obtained in the two modes of flight were similar. But there were differences for the two methods of assessing performance, and best gains were sometimes to be chosen by sacrificing a little tracking accuracy for better handling. In all cases, values could be chosen to represent best operating conditions for this one pilot.

The same set of selected gains also defined good operating conditions for a much larger group of pilots. A general relationship had evidently been found, and it was consequently easier than usual to reach agreement on the gains most suitable to vehicle, system, and user. The tracking performance achieved by pilots showed an almost universal success in reaching Category II standards, and was at the same level as in previous work. Besides tracking accuracy, known capabilities for rapid learning and for an improved transition were also realized in the present study, with implications of reduced workload, improved chance of avoiding collision, reduced space myopia, lower disorientation probability, and improved accuracy in the visual flare maneuver. All flight modes were possible: night operations could be carried out with some improvement on normal conditions, the format being kept simple; and beam bends of some magnitude were acceptable. These results showed a general transfer of properties from the military to the commercial application of the system (and this is reasonable since the original investigation was not slanted towards a particular type of airplane).

In comparing the accuracy of an automatic approach and the accuracy of an approach flown manually with HUD, an equivalence was found. But a broader consideration of the approach operation showed some inequalities, for although the probability of disorientation appeared to be similar for the two methods, there were differences in workload, information, and the maintenance of flying skill. The shortcoming of an automatic system, in providing only incomplete information, could be met by combining it with HUD, enabling the human pilot to deal with all eventualities from a position of greater knowledge. The difficulty of maintaining flying skill would remain, however, and this appeared to be a major objection to the concept of a completely automatic approach. It was perhaps appropriate to recall that the pilot no longer need be subordinate to the machine, since tools now available allowed him to do a better total job.

The results of the investigation can be applied generally to improve the pilot's working conditions, especially through the capability for better visual judgment, which may be expected to lead to better standards of safety, even if only through reducing the chance of mid-air collision. A more specific application is in commercial jet transports as a support for, or as an alternative to, an automatic approach and landing system. Such use may be desirable in a fail-operational system, as improving the pilot's managerial capability; it may be more necessary in a fail-passive system, as allowing the pilot to take over control in circumstances where the use of head-down instruments would be inadvisable. Another application of HUD is for presenting information associated with an independent monitoring system.

Some matters remain for further study: the division of duties between pilots, including cross-checks; the systematic division of attention between display and forward view, especially in the early stages of use; and the length of time for which the system may be used. Another area for future attention is in developing the format according to the suggested changes, especially in augmenting the height display, and in providing mode annunciation and improved heading information. Finally, a new area of inquiry may well be found in studying the benefit, and the possibility, of presenting velocity vector information.

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