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AN EXPERIMENTAL EVALUATION OF HEAD-UP DISPLAY FORMATS

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SUMMARY

The investigation deals with three types of head-up display format in which there are differences in the choice of framework and in the kind of information processing used to form driving signals. Type 1 is an unreferenced (conventional) flight director. Type 2 is a ground referenced flightpath display. Type 3 is a ground referenced director. Formats are generated by computer and presented by reflecting collimation against a simulated forward view in flight. The subjects are pilots holding commercial licenses who fly approaches in the instrument flight mode and in a combined instrument and visual flight mode. The approaches are in windshear with varied conditions of visibility, offset, and turbulence. Tracking accuracy is measured as vertical path error and workload as column displacement. Speed error is also measured. Comments and answers to a questionnaire are recorded. Displays are placed in rank order by subjects and display properties are evaluated. As a secondary task subjects respond to visual events in HUD and in the external scene to illustrate transition between these two fields.

To all practical purposes, displays are equivalent in pure tracking but there is a slight advantage for the unreferenced director in poor conditions. Flightpath displays are better for tracking in the combined flight mode, possibly because of poor director control laws and the division of attention between superimposed fields. Workload is better for the Type 2 displays. The flightpath and referenced director displays are criticized for effects of symbol motion and field limiting. In the subjective judgment of pilots familiar with director displays, they are rated clearly better than path displays, with a preference for the unreferenced director. There is a fair division of attention between superimposed fields.

INTRODUCTION

The aim of this work is to provide data on the performance of pilots using various symbol formats in a head-up display of flight instrument information. Previous work of this nature has usually been concerned with individual arrays of symbols examined in isolation (e.g., refs. 1, 2, 3). Unfortunately it is not readily possible to translate the results of such investigations into a common scheme because of differences in test conditions and experimental methods. It is therefore appropriate to examine alternative types of display format by similar methods and in the same experimental setting.

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Factors Affecting Performance

The formats of interest are those which differ sufficiently to affect user performance, especially if the factors affecting performance can be recognized. One such factor may be the frame of reference used in presenting the symbols, or the scheme of interpretation by which their meaning is understood. This may be the framework of the aircraft, as is the case with many of the conventional panel instruments. Or it may be the pictorial framework of the external world, on which the display is superimposed. Both of these frames are conceived as lying in a vertical plane normal to the pilot's forward line of sight. Other frameworks may be possible but these are the most familiar to the pilot.

Besides an obvious effect on the interpretation of what is seen in the display, the choice of framework has an indirect effect on the acquisition of information. This is because the field of view of the display is generally smaller than that of the aircraft windshield. It follows that when there is a change in aircraft attitude an external object appears to move through the display field before reaching the limits of the windshield. In the same way a symbol moving in one-to-one relationship with the external world tends to exceed the limits of the display before exceeding windshield limits. So unless the display field can be increased to match that of the pilot's normal forward view there may be either a loss of displayed information over a period of time or a limitation of aircraft motion. On the other hand, no such loss or limitation need occur if symbols are presented in the aircraft framework and do not have one-to-one correspondence.

Another result of choosing an external frame of reference is that symbols tend to move with greater angular velocities than corresponding symbols in panel instruments. For example, the angular displacement of the artificial horizon in a typical attitude-director indicator is one sixth of the corresponding displacement of the external (true) horizon during a change in pitch attitude. So if the horizon symbol in a head-up display has a one-to-one relationship with the true horizon it will move 6 times as fast as the symbol to which the pilot is typically accustomed. But this does not obtain if there is no requirement for exact correspondence with features of the external world.

On the other hand a referenced display could evidently be used to show where the runway would emerge during an approach in poor visibility. Whether this would be beneficial to the overall transfer of information is not clear, however, because attention might be paid to a runway symbol at the expense of the real runway. Moreover it is known that the visual acquisition of external objects is independent of display misalignment for angles up to 10° (ref. 4). Another feature of a referenced display should be the capability for showing realistic motion, in the sense that a display symbol might move in the same way as the corresponding feature in the outside world. The flightpath could thus be shown in its true position at all times, but whether this would be desirable could depend on the method chosen to show flightpath during a change in the direction of motion. Should the flightpath remain in the same position when control action has been taken to alter the path but has not yet affected that path? Or should the flightpath symbol be moved in response to control action at the expense of conformity?

The referenced display should also allow conformity of position for, say, an horizon symbol. But it is not at all clear that the artificial horizon in HUD should be conformal. Hubner and Blose (ref. 5) found overlapping of real and artificial horizons to be objectionable and they recommended that an offset and possibly a reduction in scaling be used (a result anticipated in earlier studies, ref. 6). This finding is consistent with the fact that the position of the visible horizon is not absolute but is affected by height, visibility, and terrain configuration. To sum up: the choice of framework may well be a factor influencing the performance of tasks based on displayed information because of effects of interpretation, field limitation, angular velocity, visual pickup, and conformity of motion and position.

Another factor may be the information processing used in signals driving the display symbols. On the one hand, symbols may simply show the information provided by a data source without having been processed and in true scale. For example, the so-called situation (flightpath) displays show the present values of flight variables, such as path deviation and path direction in real world coordinates. In this case the action required of the pilot may be implied but it is not defined. On the other hand, symbols may be used to show the result of combining information from several sources, in chosen proportions and with the help of signal shaping networks, as in a flight director display. When information is processed at this level of complexity it may be used to define the action required of the pilot. This indicates that various degrees of information processing may exert a differing influence on the acquisition of information from the display.

Format Categories

If these two factors of framework and processing do indeed affect the transfer of information, it should be possible to change them and observe differences in an associated task, such as following a given approach path. There are three ways of changing the combination of factors, which could then result in a change in performance. These are shown in table 1, where there is a choice of aircraft or ground framework and a choice of processed or unprocessed information. Three basic types of display result from the combination of these choices.

TABLE 1.– FORMAT TYPES RESULTING FROM CHOICE OF FRAMEWORK AND INFORMATION PROCESSING

Information	Framework	
	Aircraft	Ground
Unprocessed	---	Referenced flight path (Type 2)
Processed	Unreferenced flight director (Type 1)	Referenced flight director (Type 3)

A flight director display in aircraft coordinates is a presentation of processed information in an unreferenced framework, where the external world is taken to be the reference system. This will be called a Type 1 display. A flightpath display having one-to-one correspondence with the external scene is a presentation of (theoretically) unprocessed information in a referenced framework. This will be called a Type 2 display. A flight director display in real world coordinates is a presentation of processed information in a referenced framework. This will be called a Type 3 display. It will be noted that the sequence of Types 1 and 2 corresponds with a development from the conventional kind of flight director to a less familiar kind of aircraft display, while Type 3 represents a further degree of extrapolation. The fourth possibility of an unreferenced presentation of unprocessed information is realized in supporting elements of the display such as speed, height, and ILS deviations. It has little meaning in the head-up mode for the primary symbols giving path guidance.

The present investigation deals with examples of the three types of display shown in table 1. They are implemented by computer programming and shown against a representation of the external world in an aircraft simulator cockpit. The displays are used by a group of pilots in approach tasks intended to reveal any differences due to the various combinations of factors expected to be significant. The vertical control task is taken to be of greater interest than that of lateral control because of a lack of vertical guidance information in some approach situations. Measurements of task performance are used as objective evidence of any difference between display types and pilots' evaluations are used as subjective evidence.

METHOD

Displays

Eight displays were generated for experimental purposes. They are described in detail in the briefing material of appendix A where their formats are also shown. They include one example of an unreferenced flight director, HUD 11, five examples of a referenced flightpath display, HUD 21, 22, 23, 24, 25, and two examples of a referenced flight director, HUD 31, 32, the displays being numbered in accordance with the scheme of table 1. It will be convenient to refer to the formats simply as H11, H21, etc.

The H11 format was very much the same as one used in previous tests (ref. 2) and would thus serve to provide a base level of performance. It was essentially a "fly-to" design in which the aircraft circle was flown to the movable director dot. The H21 format was derived from a Type 2 display used successfully in other previous tests (ref. 7) but with a greater distinction made here between the flightpath (direction) symbol and the fixed depression (vertical path position) symbol. This display would serve to investigate the performance of a Type 2 display in a wider range of conditions than before, and to examine the practicality of having the two moving guidance symbols.

Other Type 2 formats were included to examine variations in the method of showing the flightpath and its relation to the environmental background. In H22 the flightpath symbol was the circular form used in H21 but rotated to have its "wings" parallel with the horizon and designed to move at right angles to the horizon. Comparison of H21 and H22 might thus show whether the flightpath should be thought of as existing in aircraft or geographical coordinates. This could be revealed by user acceptance, and also by an interesting consequence of aircraft coordinates in causing the position of the runway heading on the horizon to be in error. The same difference in flightpath coordinates was used in designing H23 and H24 but in these formats the flightpath was represented by a double wing symbol.

An important characteristic of these flightpath displays was that the pilot had to decide how to place the flightpath to reduce a path error. This task may be simplified by introducing an index against which to align the flightpath symbol. For example, the index may be driven by a magnified glideslope error signal as described by Bray (ref. 8). An index of this kind was included in H25 and a comparison of this format with the other Type 2 displays should show the effect of relieving the pilot of the path placement task.

The H31 format contained only one guidance symbol in the form of a circle with wings and fin. This was to be used as a director by aligning it with a ground aim point. In IFR conditions the aim point would be the intersection of a touchdown crossbar with the runway centerline. In visual conditions it would be the touchdown zone of the real runway. The format of H32 was to be used in a similar way but without lateral guidance. A row of dots would be placed on the aim point, this symbol being driven by a "compensated" control law of the kind described by Lowe (ref. 9). A dashed line was included as supporting information to show the displacement being corrected by the compensated control, and this was simply the fixed depression symbol. Comparison of these Type 3 displays with H11 would show the effect of earth referencing.

Variations between the experimental formats were thus mainly in the guidance elements, which were intended primarily for help in vertical control, though the director displays also gave lateral guidance. There were also differences in background and peripheral elements. All displays had an artificial horizon but whereas this was shown in true scale in the Type 2 and Type 3 displays, it was shown at a reduced scale of elevation in H11 to allow comparison of effects of symbol velocity and field of view limiting. A runway centerline and an aiming crossbar were also provided in each of the displays of Types 2 and 3. These latter features would, of course, be inaccurate in a non-precision approach because their placements usually depend on having full ILS information, but this was not significant because only precision approaches were to be examined.

All formats except H25 were provided with raw ILS scales, and this difference would allow comparison of monitoring capability. Other peripherals included height information. This was a digital readout in H11, H23, H24, and a moving "tape" in H21, H22, and H31. As variations, two tapes were included in H25 to show barometric and radio altitudes, and a more elaborate digital array was given in H32. Speed error was also shown in several ways. It was shown as a peripheral scale in H11, H23, H24, H32, and as a central fin or as wing "ribbons" in the other displays. These differences between formats might serve to compare supporting elements of the HUD format.

Other display facilities included a provision for showing sideslip in Type 2 formats and a master warning symbol in all formats except H25.

Display Selection by Preliminary Experiment

The eight display formats were presented to a group of subjects comprising four test pilots, eight airline pilots, and five private pilots. Approaches were flown in simulated instrument flight and in visual flight conditions. Comments were recorded and analyzed with the following results.

1. The display symbols were generally satisfactory, except for flightpath symbols oriented with respect to the horizon, though the error in runway heading was not noted.

2. It was undesirable to show sideslip.

3. Matters evoking general comment included the relative difficulties of lateral and vertical control, workload in using flightpath guidance symbols, visibility of peripheral elements, and comparison of alternative height and speed error displays.

After reviewing these results it was decided to use only H21 and H25 of the Type 2 displays, thus eliminating the unsatisfactory flightpath symbols. Since the runway heading error was not noted, but yet appeared important on general grounds, it was decided to eliminate the error from H21 and to leave it as an alternative configuration for H25. It was also decided to abandon the attempt to show sideslip, and to cover the matters of general concern, by a questionnaire to be used in the main experiment. The formats remaining for experimental purposes are summarized in table 2, where H9 is used to designate the absence of a head-up display and the use of conventional head-down instruments (including an attitude-director indicator, or ADI). It will be seen that H32 has been excluded and this is because of insufficient time to develop the compensated control law.

TABLE 2.– EXPERIMENTAL DISPLAYS

H9	No HUD, conventional instruments (including ADI)
H11	Unreferenced flight director
H21	Referenced flightpath display, simple
H25	Referenced flightpath display, with path index
H26	As H25 but without runway heading error
H31	Referenced flight director

Apparatus

The general arrangement of experimental equipment is shown in figure 1. A Sigma 9 computer was used for the dynamics of a medium sized jet transport and for flight director and flightpath computations. The displays were generated by a PDP 11/40 computer and symbols were driven by the flight variables and guidance signals provided by the aircraft computer. Each of the displays could be shown on a monitor located in a fixed-base two-place cockpit, where they were superimposed by reflecting collimation on a simulated forward view. The flight variables of the aircraft computer were also used to drive the visual flight simulation and the conventional head-down panel instruments in the cockpit. Experimental subjects, who occupied the captain's seat, were thus exposed to a simulation of a normal airline cockpit environment, with a collimated head-up display superimposed on the external forward view. The combined visual field is shown in figures 2 and 3 for H11 and 21, respectively.

The external scene subtended approximately 45° at the pilot's eye position. The collimating lens caused distortion at the edges of the field, especially when the viewing position was changed. This effect was reduced to acceptable proportions by defining the eye position and by presenting the display within a relatively small field. And it was seen within a transparent glass plate which was used simply to simulate the reflector plate of a real optical system. The plate was mounted on the glareshield so as to maintain much the same face clearance as in a normal jet transport cockpit. Symbols were of a color (green) similar to that in a real system and the external scene was in natural colors. The cockpit layout is shown in figure 4.

For the purpose of adding a secondary task, a master warning indicator and cancel button was mounted on the cockpit glareshield. This was to be used by the pilot to remove the master warning symbol appearing in the HUD format. The pilot was also provided with a thumbswitch on the control wheel which was to be used to cancel a flashing light appearing on the control tower in the external scene. It would thus be possible to observe responses to stimuli appearing in either of the superimposed visual fields at times which could be controlled.

Driving Signals

The flight director symbols of the H11 and H31 formats were driven by signals used for the head-down attitude-director indicator without special development for HUD characteristics. Vertical commands were generated by a simple combination of glide-slope deviation and pitch attitude, with a height-dependent change of gain and command limiting. This is shown in figure 5 where it is seen that no provision was made for shaping the glide-slope input and that pitch rate was not used.

(The glideslope gain was variable in the range 22.1 to 5.35 and the time constant was 15 sec.) The present director control law was thus inferior to that used previously (ref. 2).

Vertical drives for the other guidance symbols were generated as in figure 6. The flightpath symbol was usually driven by the unfiltered ratio of vertical speed and groundspeed but with occasional use of indicated airspeed. The flightpath was stabilized by washed out pitch attitude (with a time constant of 1.6 sec) and the effect of longitudinal offset from the center of aircraft rotation was compensated by adding a pitch attitude rate term. An angle of attack drive was not used because of a dangerous tendency to indicate a rising flightpath in a downdraft situation. Turbulence was introduced as a wind component, rather than the white noise shown. The fixed depression symbol was driven by pitch attitude, with an offset of 3°, except when this was decayed to 0.8° during flare. Compensated control was generated by Lowe's method.

Calibration

The forward view was calibrated as part of the daily servicing procedure. In particular, height was checked by isogonal matching of the runway outline with a template. The overall scaling of displays was adjusted to allow freedom of operation in turbulent conditions. An effective field of view of 25° was used for formats of Types 2 and 3 but only a 12.5° field was used for the Type 1 display since this did not require alignment with the external scene (except in roll). The "real world" symbols of the Types 2 and 3 formats were calibrated by congruence observations, while applying equal deflecting signals to display and forward view. This included alignment of the fixed depression symbol with the runway touchdown zone during changes in pitch attitude. No special check was made on the accuracy of the flightpath symbol drive.

For convenience of operation in the approach, formats were lowered by about 3° while maintaining congruence conditions. Arrangements were also made to "freeze" real world symbols when they reached the limits of the central zone to show their last known positions. Gains were adjusted for H11 to keep the flight director in view. The ILS localizer scale was moved to the top of the format in Types 2 and 3 displays to reduce symbol interference.

Subjects

The choice of subjects was governed by a need to avoid bias towards any one type of display format. It was also expedient to chose subjects representative of the pilots likely to be involved in a more widespread use of HUD than previously; that is, use in the commercial rather than the military field of aviation.

The experimental subjects were 14 pilots holding commercial licenses (S20–26, 29–35). There were three captains and ten first officers from four of the major airlines and one unattached pilot. Flight experience as captain or first officer ranged from 1,000 to 20,000 hr. Subjects had heard of HUD but had no acquaintance with alternative types of format.

Procedure

Subjects were given the briefing material of appendix A for prior study. An eye test was administered as a routine check. At the experimental session the aim of the work was explained and practice runs were made for familiarization with controls and aircraft dynamics. The first display to be used by a subject was then presented while reviewing its salient features. Practice runs were made from a height of 1200 ft along a 3° approach path. The level of task difficulty was increased progressively by adding conditions of starting offset, turbulence, and wind shear (appendix G). Meanwhile the secondary task was introduced. The training was concluded when a stable level of performance was seen to have been achieved, and when the subject also felt confident of his own proficiency.

The experimental (data) runs were also 3° approaches from 1200 ft. Conditions of visibility, offset, and turbulence were varied in random order from run to run but each started in instrument flight conditions, with a breakout to visual conditions at 600 ft. There were eight conditions for each display. Visibility on breaking out was either 12,000 ft or 50,000 ft. The starting offset was either zero or 200 ft vertically, with positive and negative offsets considered equivalent as regards task difficulty. The level of turbulence was either zero or at an rms gust level of 4.5 ft/sec. Windshear was always present but it was not an experimental variable, for it was always at the same general level of severity. It was varied in detail between runs, however, to avoid its exact nature being learned. The level of severity was such that the horizontal wind component changed at a rate of 80 knots per 1000 ft of height and the vertical component at 32 knots per 1000 ft. These changes occurred together within a height band of 200 ft, and this band lay always between heights of 200 and 600 ft.

The training procedure and experimental runs were repeated for each of the six displays taken in random order. It was usually possible to complete procedures for two, and sometimes three, displays in a session of about 3 hr, with a break taken at half time. Subjects were not told the conditions for each run but were advised that shear was always to be expected. They were asked to fly the approaches as closely as possible and to land, even in conditions when a go-around would normally be made. They were also asked to respond to the master warning and control tower stimuli which were presented in random order in the visual flight sector. These visual events were also presented in automatic approaches to provide a base for comparison with responses under workload.

Measurements

For recording purposes the approach was divided into four segments. The height range was 300 ft for each segment except the last, which was terminated at 50 ft to eliminate vagaries of the flare maneuver. Two segments were thus in instrument flight and two in visual flight conditions. Of the many flight variables available in the computer printout, the most relevant was glide-slope deviation. This was a measure of success in achieving the required path (tracking accuracy), except in the first segment when there was an offset to correct. Movement of the control column was also relevant as a measure of workload. Airspeed error gave an indication of the pilot's ability to hold a reference airspeed during the approach but with the reservation that the presence of wind shear implied freedom to use a speed margin for safety. The accuracy of recorded measures was checked by the automatic approaches and by internal consistencies. Recorded measurements were obtained for all subjects except where otherwise stated.

Subjects made comments on the display formats during the course of the experiment and these were recorded. At the end of each set of display runs, subjects responded to the questionnaire which is included as appendix B. At the conclusion of the entire session, they placed displays in rank order of preference, and supported this with a detailed evaluation of the display properties defined in appendix C.

RESULTS

Tracking Accuracy

Instrument flight (1)– The first and second flight segments were used to measure beam tracking accuracy in instrument flight conditions (without any confounding effect due to the external visual field). In the first segment, from 1200 ft to 900 ft, only those runs starting on the beam could, of course, be used, but in the second segment, from 900 ft to 600 ft, all runs could be used because initial offsets had been mostly corrected.

Results of an analysis of variance (ref. 10) for rms glideslope deviation are given in appendix D. These are for displays H9, 11, 21, 25, 31, with H26 omitted because a preliminary analysis showed no significant difference between H25 and H26. Display differences (H) were found significant at the .025 level in the first segment. Means for the displays were then examined in pairs by the Tukey test (ref. 10). The results are given in table 3 where significant differences are shown for H25. Deviations for this display were smaller than for the referenced director, H31, and just smaller than for the unreferenced director, H11. Other differences were insignificant at the .05 level by this test and there were no display interactions. These results are summarized in table 12, together with those which follow.

TABLE 3.– PAIRED COMPARISON OF DISPLAY TRACKING MEANS IN INSTRUMENT FLIGHT CONDITIONS (1). [RMS Glide-slope Deviation in degrees in First Flight Segment from 1200 feet to 600 feet, offsets excluded.]

	H31 .06166	H11 .05789	H9 .05052	H21 .04052	H25 .02829
H31 .06166	---	.00377	.01114	.02114	.03337[a]
H11 .05789	---	---	.00737	.01737	.02960[a]
H9 .05052	---	---	---	.01000	.02223
H21 .04052	---	---	---	---	.01223
H25 .02829	---	---	---	---	---

[a]Greater than a 5% Tukey critical difference of .02884.

Instrument flight (2)– In the second flight segment display differences were again significant at the .025 level, and means were examined in pairs by the Tukey test. The results are shown in table 4, where only the difference between H31 and H9 is seen to be significant. There was thus no difference between HUD formats for vertical tracking, H11, 21, 25, 31. Neither was there any difference between HUD formats and head-down instruments, H9, except in the one case where H31 gave deviations which were larger by a (statistically) significant amount. But even this difference was of little practical importance because it would correspond to a displacement from the glide slope of just over 1 ft at a height of 100 ft. The means are plotted in figure 7.

The analysis of variance showed a significant interaction between displays and operating conditions at the .005 level, which is illustrated in figure 8. Glide-slope deviation is plotted vertically

TABLE 4.– PAIRED COMPARISON OF DISPLAY TRACKING MEANS IN INSTRUMENT FLIGHT CONDITIONS (2). [RMS Glide-slope Deviation in degrees in Second Flight Segment from 900 feet to 600 feet.]

	H31 .15489	H21 .14492	H25 .12774	H11 .12557	H9 .12370
H31 .15489	---	.00997	.02715	.02932	.03119[a]
H21 .14492	---	---	.01718	.01935	.02122
H25 .12774	---	---	---	.00217	.00404
H11 .12557	---	---	---	---	.00187
H9 .12370	---	---	---	---	---

[a]Greater than a 5% Tukey critical difference of .03005.

TABLE 5.– PAIRED COMPARISON OF DISPLAY TRACKING MEANS IN COMBINED INSTRUMENT AND VISUAL FLIGHT CONDITIONS AT MEDIUM ALTITUDE. [RMS Glide-slope Deviation in degrees in Third Flight Segment from 600 feet to 300 feet.]

	H9 .31457	H11 .24376	H31 .21314	H21 .19155	H25 .13856
H9 .31457	---	.07081[a]	.10143[a]	.12302[a]	.17601[a]
H11 .24376	---	---	.03062	.05221	.10520[a]
H31 .21314	---	---	---	.02159	.07458[a]
H21 .19155	---	---	---	---	.05299
H25 .13856	---	---	---	---	---

[a]Greater than a 1% Tukey critical difference of .06207.

for each display format in pairs of means, for low (L) and high (H) visibility, for calm and turbulent air, and for starts on and off the beam. It is seen that tracking was always worse in turbulent air and this was expected. It was always worse when there had been an initial offset, which showed some carry over from the first segment. There was little difference between low and high visibility in most cases and this was expected since flight was in cloud in this segment. But this was not so when turbulence was combined with offset. Then there were two cases with larger deviations in the better "visibility" and three with the opposite result. These variations appear to be chance effects and it will be noted that if the offset cases are ignored, the results are quite homogeneous. It will also be seen that in turbulence with offset the unreferenced flight directors (H9, 11) gave results better by about 0.06° than those for the referenced formats (H21, 25, 31). This appears to be the main part of the interaction.

Combined instrument and visual flight at medium altitude– Different results were obtained for glide-slope deviation in the third flight segment, from 600 ft to 300 ft, in which both display and external scene were available. The analysis of variance (appendix D) showed display differences to be significant at the .001 level and a Tukey test showed a 1% critical difference between several pairs of means, as shown in table 5. Glideslope deviations were larger for the head-down than for the head-up displays. Deviations were larger for H11 and H31 than for H25. These results suggested that the flight director formats gave larger errors (as a group) than the H25 format, and this hypothesis was found true when tested by the Scheffe method. And by comparison with the instrument flight results (where there was equality among HUD formats) it is seen that the effect of adding the visual field was to depress head-up flight director performance levels in the experimental conditions. There was no significant difference between referenced and unreferenced directors, H11, 31, nor between Type 2 formats. Display means for the third flight segment are included in figure 7.

The analysis of variance showed an interaction between displays and conditions only in the case of visibility, and that was at the .025 level. This is shown in figure 9, where it is seen that a relatively large increase in tracking error occurred with increased visibility for the unreferenced directors, H9, 11, while there was little change for the referenced formats, H21, 25, 31.

Combined instrument and visual flight at low altitude– In the fourth flight segment, from 300 ft to 50 ft, the analysis of variance showed display differences to be significant at only the .1 level (appendix D), and the results could not therefore be used with much confidence. A paired comparison of means is given in Table 6, and this shows that the only difference approaching significance was between means for H9 and H25. That is, there was nothing to choose between tracking accuracies with any of the head-up formats, and only one of these displays was better than the head-down display. The effect of the visual field in depressing the level of tracking accuracy for the head-up director formats could not be detected in the combined flight mode at low altitude.

TABLE 6.– PAIRED COMPARISON OF DISPLAY TRACKING MEANS IN COMBINED INSTRUMENT AND VISUAL FLIGHT CONDITIONS AT LOW ALTITUDE. [RMS Glide-slope deviation in degrees in Fourth Flight Segment from 300 feet to 50 feet.]

	H9 1.68403	H11 1.01687	H31 .62438	H21 .45186	H25 .30901
H9 1.68403	---	.66716	1.05965	1.23217	1.37502[a]
H11 1.01687	---	---	.39249	.56501	.70786
H31 .62438	---	---	---	.17252	.31537
H21 .45186	---	---	---	---	.14285
H25 .30901	---	---	---	---	---

[a]Almost equal to a 5% Tukey critical difference of 1.41964.

The analysis of variance showed an interaction between displays and conditions only at the .1 level.

Inertial and airmass flightpath– Tracking accuracy with the Type 2 formats was also measured with the flightpath symbol driven by either an inertial or an airmass computation. Results for 10 subjects using each drive were compared by t-test. The difference between each driving condition was found to be insignificant for each format.

Workload

Instrument flight (1)– An analysis of variance was also carried out for rms column displacements, with the results included in appendix D. In the first instrument flight segment (Segment 1) display differences were significant at the .001 level. The subsequent paired comparison of means is presented in table 7, where it is seen that the head-up flight directors, H31, 11, required larger column displacements than the Type 2 displays when tested by a Tukey 1% critical difference. No other comparisons were significant.

The analysis of variance also showed an interaction between displays and conditions of offset and turbulence at the .05 level. This is shown in figure 10, where it is seen that all director displays (H9, 11, 31) required larger column displacements under both calm conditions (on and off), but in

TABLE 7.– PAIRED COMPARISON OF DISPLAY WORKLOAD MEANS IN INSTRUMENT FLIGHT CONDITIONS (1). [RMS Column Displacement in inches in First Flight Segment from 1200 feet to 900 feet.]

	H31 .94879	H11 .86356	H9 .76433	H25 .64316	H21 .62993
H31 .94879	---	.08523	.18446	.30563[a]	.31886[a]
H11 .86356	---	---	.09923	.22040[a]	.23363[a]
H9 .76433	---	---	---	.12117	.13440
H25 .64316	---	---	---	---	.01323
H21 .62993	---	---	---	---	---

[a]Greater than a 1% Tukey critical difference of .19773.

turbulence without offset H31 displacements were largest, and in turbulence with offset the larger offsets were for H11, 31.

Instrument flight (2)– Display differences in the second instrument flight segment were significant at the .001 level and the paired comparison of means is presented in table 8. The referenced flight director, H31, required larger column displacements than the Type 2 displays. Displacements for the unreferenced director, H11, were also larger than for Type 2 displays. No other paired comparisons were significant according to the Tukey test at the .01 level.

TABLE 8.– PAIRED COMPARISON OF DISPLAY WORKLOAD MEANS IN INSTRUMENT FLIGHT CONDITIONS (2). [RMS Column Displacement in inches in Second Flight Segment from 900 feet to 600 feet.]

	H31 1.13862	H11 1.05445	H9 .96097	H25 .82973	H21 .79127
H31 1.13862	---	.08417	.17765	.30889[a]	.34735[a]
H11 1.05445	---	---	.09348	.22472[a]	.26318[a]
H9 .96097	---	---	---	.13124	.16970
H25 .82973	---	---	---	---	.03846
H21 .79127	---	---	---	---	---

[a]Greater than a 1% Tukey critical difference of .20188.

For the second flight segment there was an interaction between displays and conditions of offset and turbulence at the .005 level. This is shown in figure 11, where it is seen that column displacements were expectedly greater in turbulence than in calm air. It is also seen that displacements for the head-up directors H11, 31 were greater than for other displays in combined conditions of offset and turbulence.

Combined instrument and visual flight at medium altitude– For the third flight segment of combined instrument and visual flight, display differences were again significant at the .001 level, and a paired comparison of means is shown in table 9. In this segment the referenced flight director, H31, required larger column displacements than all the other head-up displays (H11, 21, 25) when tested by a Tukey critical difference at the 1% level. Displacements for the head-down display, H9, were also larger than for H25 but no other paired comparisons were significant at this level.

For the third flight segment the analysis showed an interaction between displays and conditions at the .05 level. This is seen in figure 12, in the larger column displacements for the directors H9, 11, 31 than for the Type 2 displays, in conditions of offset with turbulence, while

TABLE 9.– PAIRED COMPARISON OF DISPLAY WORKLOAD MEANS IN COMBINED INSTRUMENT AND VISUAL FLIGHT CONDITIONS AT MEDIUM ALTITUDE. [RMS Column Displacement in inches in Third Flight Segment from 600 feet to 300 feet.]

	H31 1.52641	H9 1.36205	H11 1.28975	H21 1.19556	H25 1.13293
H31 1.52641	---	.16436	.23666[a]	.33085[a]	.39348[a]
H9 1.36205	---	---	.07230	.16649	.22912[a]
H11 1.28975	---	---	---	.09419	.15682
H21 1.19556	---	---	---	---	.06263
H25 1.13293	---	---	---	---	---

[a]Greater than a 1% Tukey critical difference of .19521.

displacements were at the same general level for all displays in other conditions. This effect was most pronounced for the head-up directors in good visibility.

Combined instrument and visual flight at low altitude– In the fourth flight segment, from 300 ft to 50 ft, display differences were significant at the .001 level. A paired comparison of means (Table 10) showed column displacements for H31 to be larger than those for H11 and H25, by a Tukey critical difference at the .01 level. Displacements for H9 were also larger than for H25. The referenced and head-down directors thus gave rise to the larger workloads, while the unreferenced director and H25 were at the other end of the scale.

TABLE 10.– PAIRED COMPARISON OF DISPLAY WORKLOAD MEANS IN COMBINED INSTRUMENT AND VISUAL FLIGHT CONDITIONS AT LOW ALTITUDE. [RMS Column Displacement in inches in Fourth Flight Segment from 300 feet to 50 feet.]

	H31 1.89763	H9 1.81520	H21 1.72376	H11 1.62438	H25 1.50179
H31 1.89763	---	.08243	.17387	.27325[a]	.39584[a]
H9 1.81520	---	---	.09144	.19082	.31341[a]
H21 1.72376	---	---	---	.09938	.22197
H11 1.62438	---	---	---	---	.12259
H25 1.50179	---	---	---	---	---

[a]Greater than a 1% Tukey critical difference of .25350.

There was an interaction between displays and conditions of offset and visibility at the .025 level, which is shown in figure 13. In the condition of starting on the beam and in good visibility, column displacements were smallest for H11 but in other conditions the smallest displacements were for H25.

Airspeed Error

Instrument and combined flight modes– Errors with respect to a reference airspeed of 135 knots were measured for nine subjects and examined by the analysis of variance. It was found that there was no interaction between displays and flight segments. The order of goodness of the displays was thus the same for all segments, and speed errors were therefore analyzed for the complete approach, with the results given in appendix D. Display differences were significant at the .001 level. The paired comparison of means is presented in table 11, where it is found that airspeed errors for H31 were larger than for H21, 25 but no other comparisons were significant by the Tukey test at the .01 level.

TABLE 11.– PAIRED COMPARISON OF DISPLAY AIRSPEED ERROR MEANS IN INSTRUMENT AND COMBINED FLIGHT MODES. [RMS Airspeed Error in knots for All Segments, 135 knots reference speed.]

	H31 8.79610	H9 7.06381	H11 7.05204	H21 6.40748	H25 5.71163
H31 8.79610	---	1.73229	1.74406	2.38862[a]	3.08447[a]
H9 7.06381	---	---	.01177	.65633	1.35218
H11 7.05204	---	---	---	.64456	1.34041
H21 6.40748	---	---	---	---	.69585
H25 5.71163	---	---	---	---	---

[a]Greater than a 1% Tukey critical difference of 1.92847.

There were some interactions between displays (H) and conditions, the strongest being for offsets (O), turbulence (T), and flight segments (G), which was significant at the .001 level (HOTG). This is illustrated in figure 14, where it is seen that while most of the individual points in the speed error plots for H21, 25 were lower than the corresponding points in the H31 plot (as required by the main effect), there were quite different trends. For approaches starting on the beam, there was a fairly steady increase in speed error in successive flight segments (G = 1, 2, 3, 4), for all three of these displays in both calm and turbulent conditions. But for offset approaches there was a decrease in speed error with H31 in the middle segments (G = 2, 3) in calm air and a decrease in the last segment (G = 4) in turbulence, while there was a steady increase with the Type 2 displays. Figure 14 also shows that similar trends occurred with H9, 11 for offset approaches, although the general level of speed error was lower.

Subjects' Comments

The comments made by subjects were similar in content to the responses to structured enquiries and need not be given here in full. Only comments touching on matters not covered by the questionnaire or the evaluations are presented for each of the four display formats. The complete comments are given in appendix E.

TABLE 12.– SUMMARY OF RESULTS FOR TRACKING ACCURACY, WORKLOAD, AND AIRSPEED ERROR.
[Relative Values of Display Means with Interactions in Flight Segments.]

Segment	Tracking	Workload	Airspeed error (all segments)
1 (IF)	H25/H31,11	H25,21/H31,11	H21,25/H31
Inter-action	---	H21,25/9,11,31 (calm), H9,11,21,25/31 (turbulence), H9,21,25/11,31 (O,T)	Increase, G1-4 (on), H9,11,31 lower in G2,3 (calm, off)
2 (IF)	H9/H31	H25,21/31,11	See above
Inter-action	H9,11/H21,25,31 (O,T)	H9,21,25/H11,31 (O,T)	
3 (IF,VF)	H11,31,21,25/9 H25/H11,31	H11,21,25/H31 H25/H9	See above
Inter-action	H9,11(l)/9,11(h)	H21,25/9,11,31 (O,T)	
4 (IF,VF)	H25/H9(?)	H11,25/H31 H25/H9	See above
Inter-action	---	H11/9,21,25,31 (h,on), H25/9,11,21,31 (other O,L)	

Legend: Symbol / – for groups of displays (H) separated by this symbol the first entry has the more desirable value.
O,L,T,G – denote conditions of offset (on, off), visibility (h-high, l-low), turbulence, flight segment.
IF, VF – denote instrument, visual flight conditions.

HUD11– The compactness of the format was noted by S20, and S33 said that peripheral trends could easily be seen. The sensitivity of the display was noted by S22, 24. It was pointed out by S25 that there was no problem with the outside visual field, and that he tended to disregard the director and go visual for the last 100 ft. S33 also noted the tendency to go visual when near the ground, and the possibility of making a balance (of attention) between display and outside world (appendix E).

While the conventional nature of the display was noted (S32), there were some initial difficulties in distinguishing between some display elements (dots), and there was a complaint about lack of control feel. Four subjects made no comments at all.

HUD21– Comments about display sensitivity or the rapid movement of display elements were made by several subjects (S21, 22, 26, 31, 32). Two subjects said they used the outside world instead of the display. For S22, this was because the two superimposed fields did not "work together." For S25, it was because he was not concentrating on the format center (appendix E). In the context of the effect of the size of the format on the distribution of attention, S22 said that this display forced the user to scan but S23 said he had no time to look at (peripheral) raw data. One subject (S34) found the localizer line hard to interpret, and S29 found that the runway crossbar looked too much like the dashed line. An interesting comment made by S25 was that although the format was cluttered it did not matter because he understood it. Only one subject made no comment.

Additional comments were made subsequently by one subject about the motion convention being confusing, and about a lack of bank information.

HUD25– Instability of the display was reflected in comments about movement of the elements, a sense of floating, having to chase the display, and the (lateral) swing of the horizon (S20, 21, 22, 31, 32, 35). The effect of the large display field was reflected in a query whether raw data was in fact provided (S21, appendix E), and in comments about difficulties associated with attention to peripheral elements (S25, 30, 31). It was also noted by S33 that a defect of the referenced displays (H21, 25, 31) was the tendency to disorientation when symbols would go out of view, or suffer large displacements. An insufficiency of attitude information was noted by S25, 30, 32, 35 but S34 said that attitude was not needed.

A surprising comment was that this "real world" display had no relation to reality. This comment was made by only one subject (S32). Other subjects made comments of a similar nature which were less clearly expressed and could not be precisely recorded. This subject (S32) felt the movement convention to be wrong and the senses reversed. Detailed discussion of this matter revealed that the display appeared to reverse in a sense analogous to that experienced with a Necker cube. The symbols associated with the aircraft appeared to become the outside world and those associated with the external world appeared to become the aircraft. This was a dynamic effect and in direct contradiction to the manifest form of the symbols. The effect disappeared at breakout. It was stronger with this display than with the other referenced formats. It was also noted by the experimenter that apparently pilot induced bank oscillations were better controlled in visual flight conditions.

An interesting and important comment was made by S33, to the effect that it was possible to stay with this display until much closer to the ground than with H11, and that this could lead to a bad situation. The same subject exhibited a change of mind concerning clutter as he became accustomed to the format. S34 noted that the localizer line in both H21 and H25 could with advantage be made to taper towards the horizon. S35 found the lateral movement of the flightpath symbol very uncomfortable. Two subjects made no comments.

In subsequent comments one subject said he followed the flightpath index blindly. One said he found the blinking path index (at 100 ft) "too frightening." Two subjects made quite adverse comments ("bananas," "about as impossible as you can get"). One subject said that confusion could arise in a transition between head-up and head-down instruments because of the motion convention for symbols in this display. For when a gust or shear caused the flightpath to move, this subject tended to follow the flightpath itself (instead of the index) because he had made no control action to cause the movement. This led to a control reversal. Another subject noted the general tendency for movements of the localizer line to appear magnified in the Type 2 displays.

HUD31– Comments about movement sensitivity were again made by several subjects (S20, 22, 24, 25, 30, 35) and these were generally adverse. One subject (S25) made four comments of this kind. The same subject said he ignored peripheral information but it was not clear whether this was due to the relatively large scan needed or to other factors. Effects of field limiting were noted by two subjects (S22, 30). (The potential danger mentioned by S22 was due to the invisibility of the speed error symbol when the director symbol reached the lower edge of the format.) One subject found it difficult to judge bank angle (S32). There was one comment on the ease of transition between fields (S33).

In response to an incidental query about the advisability of having a reflector plate close to the pilot's face (to achieve a large field of view for a referenced display), S21 expressed concern for personal safety in an accident. (This question was not addressed to all subjects but the reply appears to be sufficiently important to warrant inclusion.) The same subject and four others made no comment about the format.

Questionnaire

Answers to the questionnaire (appendix B) are summarized in table 13. A shortened form of each question is shown in the main column. This is followed by the total number of yes and no answers. The last column gives the number of indefinite responses. Thirteen subjects responded to questions on H11, 21, and twelve to questions on H25, 31. The H25 format is taken to include H26 because these were indistinguishable to subjects.

Additional notes– The speed error worm was rated better than the ribbons (of H25) in the ratio of five to one by subjects, and the jump from above to below on change of sign was liked. Two subjects noted that the combined effect of the two moving height scales was to give a sense of aircraft motion or rotation.

Rank Ordering

Responses to the request to place the experimental displays in order of preference (or which they liked best) are shown in table 14. (S20 did not complete this evaluation at the time of the experiment.) The order is indicated by the numbers one to four for each subject. These numbers are summed over subjects, and the totals may be compared with a best possible value of 13 for a display always ranked first, and a value of 52 for one always ranked last. The rank order of displays across subjects is given by the numbers in parentheses in the totals row. The order is H11, 31, 21, 25(26).

TABLE 13.– SUBJECTS' ANSWERS TO DISPLAY QUESTIONNAIRE

Display	Question	Yes	No	?
H11	FD commands reasonable?	11	1	1
	Raw ILS monitored?	8	1	4
	Digital height OK?	8	0	5
H21	Fixed depression symbol OK?	10	2	1
	Speed error symbol OK?	12	0	1
	Vertical control difficult?	2	8	3
	Lateral control difficult?	6	5	2
	Guidance symbols harder than ILS?	3	8	2
	Flightpath placement difficult?	5	7	1
	Peripheral symbols visible?	10	1	2
	Circular path symbol preferred?	5	4	4
H25,26	Fixed depression circle OK?	6	3	3
	Vertical control difficult?	2	9	1
	Lateral control difficult?	5	5	2
	Peripheral symbols visible?	2	7	4
	Two height scales necessary?	3	8	2
H31	Hard to use?	2	10	0
All	Power indication missed?	4	7	2

TABLE 14.– ESTIMATES OF RANK ORDER OF DISPLAYS BY SUBJECTS

Subject	H11	H21	H25	H31
21	1	4	3	2
22	1	3	4	2
23	2	3	4	1
24	1	4	3	2
25	2	1	4	3
26	1	3	4	2
29	1	4	3	2
30	1	4	3	2
31	2	3	4	1
32	1	2	4	3
33	2	1	4	3
34	1	4	2	3
35	1	2	3	4
Total	17(1)	38(3)	45(4)	30(2)

Note: Kendall's coefficient of concordance (ref. 11) has a value of $W = 0.51$ for these rank orderings and this is significant at the .01 level.

Evaluation of Display Properties

The results shown in table 15 are for the evaluation of the properties given in appendix C. Each property was rated on a scale of one (very good) to nine (very bad), and this was done for each display. The total rating value for each display is shown in the table for each subject, and details of the ratings for individual properties are given in appendix F. Any of these totals may be compared with the lowest possible value of eight for an ideal display, or the highest possible value of 72 for a universally bad display. Totals across subjects are shown in the last row. These may be compared with a minimum of 104 and a maximum of 936. The rank order of displays for this evaluation is shown by the numbers in parentheses in the totals row. The order is H11, 31, 21, 25(26) which is identical with the rank order of table 14.

Response to Visual Events

Responses to the master warning symbol in manual approaches are presented in figure 15. These are for three HUD formats, H11, 21, 31, there being no warning symbol in H25. Mean reaction time for all subjects is shown for the eight experimental conditions. As the conditions were taken in random order, the sequence 1, 2, . . . 8 in the figure does not reflect learning. The baseline at 1.65 sec was the mean reaction time during automatic approaches.

It is seen that responses during manual control were close to the baseline response in the case of H21. They were fairly close for H11 and less close for H31 in most conditions. Differences were generally large in conditions of combined turbulence and low visibility (conditions 2, 7). The mean difference between responses in manual and automatic approaches for all three formats was 0.39 sec for all conditions. The biggest differences were about 1.5 sec (conditions 7, 8 in fig. 15).

Responses to the control tower signal during manual approaches are presented in figure 16. These are for the same three displays, and mean reaction time for all subjects is again shown for the eight experimental conditions. A mean reaction time of 1.33 sec for automatic approaches provided the baseline value for this external signal.

These responses were more widely separated from the baseline value than in the case of the master warning symbol. The mean difference between responses in manual and automatic approaches for all three formats was 1.33 sec for all conditions. The biggest individual differences occurred in combined turbulence and low visibility (conditions 2, 7 in fig. 15), and these were of the order of 3.5 sec.

TABLE 15.– ESTIMATES OF DISPLAY PROPERTIES BY SUBJECTS

Subject	H11	H21	H25	H31
21	24	28	27	22
22	18	42	54	27
23	18.5	39.5	43	18
24	35	37	36	31
25	25	27.5	41	28
26	16	45	54	43
29	13	41	27.5	22.5
30	24	51	42	29
31	22	26.5	24	17.5
32	13	40	69	42.5
33	17	9	27	13
34	10	33	23	26
35	8	23	65	63
Total	243.5 (1)	442.5 (3)	532.5 (4)	382.5 (2)

Note: Kendall's coefficient of concordance has a value of W = 0.52 for rank orderings of these estimates and this is significant at the .01 level. It is significant at the .001 level by the Friedman test (ref. 11).

DISCUSSION

Tracking, Workload, and Airspeed Error

What differences between displays are revealed by the experimental results, and how are they related to the factors expected to influence performance? In the capability to support an accurately flown vertical approach path, there were some differences having statistical significance but their order of magnitude was of little practical significance. This was particularly true in the instrument flight segments (1, 2) where the critical difference was about 0.03°, which amounts to a vertical error of only 1 ft at a height of 100 ft. The H25 format was better than the head-up directors (H31, 11) by an amount of this order in the first segment, but the difference disappeared in Segment 2. There was thus little to choose between all the head-up displays in vertical tracking. The pilot could mostly use the relatively unprocessed information of Type 2 formats to generate control information equivalent to the processed director information of H11, 31. So information processing in HUD evidently made no practical difference to vertical path stability, at least in general instrument flight conditions. That it may have helped a little in poor conditions is indicated by the interaction in Segment 2.

It is interesting to note that displays of Types 1, 2 were previously found equal for path stability during flight tests under good conditions in a wide-bodied jet transport, where both achieved parity with an autopilot (ref. 7). This result may therefore have some degree of generality. Another point to be noted is that the values given in table 3 showed no advantage for any of the head-up displays in instrument flight conditions. But there was a general advantage over the head-down display in the combined instrument and visual flight mode (table 5), as will be discussed.

The table 4 results also showed that the framework of the display made no difference at the test level, in general flight conditions, because tracking was the same for referenced and unreferenced directors (H11, 31). But since H11 was better than H31 in combined turbulence and offset (figure 8), the choice of framework had some effect in poor conditions for director displays. (This would perhaps have been made more apparent by using the exact configuration of the H11 format as a referenced display.) One reason for this could be the resulting degree of movement in the referenced display, which was the subject of much comment. Another reason could be the effect of field limiting noted by subjects for H31.

Different results were obtained in the combined instrument and visual flight mode of segment 3, where flight levels for directors were relatively depressed (and by amounts of greater practical importance). It is easy to see that this should be so for the head-down director because the pilot flew the approach without the help of a copilot, and therefore had to prepare to abandon panel instruments toward the end of the third flight segment. But why should levels be depressed for the head-up directors? The answer to this question may perhaps be found, for H11, in subjects' responses to questions and comments. Flight director commands were considered unreasonable in wind shear by one (perhaps two) subjects (table 13, H11). S25, 33 commented on the tendency with H11 to go "visual" close to the ground. S33 noted that he could stay with H25 until much closer to the ground than with H11. These observations suggest that subjects reviewed the information available in both of the superimposed fields, and discarded the display field in favor of the external field, under these special conditions. The result was that tracking deteriorated. This inference concerning the effect of adding the visual field is supported by the interaction of displays and conditions in this segment, which showed an increase in tracking error *with visibility* for unreferenced directors (figure 9). The increased tracking error for H31 cannot be explained in the same way because the display was referenced to the runway, but it may have been due to an inclination to reduce the effects of movement frequently noted with this display. Or it may have been due to loss of information through the field limiting observed by S22, 30.

In the fourth flight segment, there was scarcely any significant difference between the experimental displays, and none at all between those presented in the head-up mode. If the reasoning of the previous paragraph is correct, this result would indicate that all of the HUD formats were flown "loosely" when close to the ground. That is, the displays were not followed exclusively but were used in conjunction with the forward view. Another explanation is that the general level of tracking when close to the ground had deteriorated sufficiently to conceal the differences between displays found in the previous flight segments.

It should also be mentioned, in connection with the tracking errors for director displays, that the commands generated by the flight director computer were less than ideal in this simulation. This is shown by comments on display sensitivity in H11, and by comparison with previous results (table 16). For example, flight tests with airline pilots in a medium-sized jet transport using a display closely similar to H11, but with a better director control law, gave a typical mean vertical error of 0.053° in smooth air, or an estimated 0.106° in rough air, and a similar result was obtained in the corresponding (fixed base) simulation (ref. 2). Some of this difference may have been due to the effect of wind shear, although Levison (ref. 12) has shown by optimal control methods that a flight director display should be superior to a flightpath display. But the fact remains that performance with H25 stayed quite stable between Segments 2 and 3 (tables 4, 5), and this shows an advantage for the display if tracking is the main consideration.

TABLE 16.– TRACKING ACCURACIES FOR UNREFERENCED DIRECTOR (H11). [One sigma height error at 100 feet in degrees.]

Slow medium transport (ref. 13)	Medium jet transport (ref. 2)	Simulated medium jet transport (table 4) (includes shear)
0.15	0.053 to 0.106	0.244

The lack of any significant difference between the Type 2 displays (tables 3, 4, 5, 6) was not expected because there had seemed to be a definite advantage in helping the pilot aim the flightpath, and several subjects said that placement was in fact difficult. But the measurements indicate that this difficulty could be surmounted.

The choice of framework was without effect on tracking performance in any flight segment, since there was no significant difference between the head-up directors, H11, 31 (tables 3, 4, 5, 6), and this reinforced the conclusion, expected on quite general grounds, that flight director guidance is independent of framework. Another framework effect was that expected in the difference between H25, 26, which involved a change in the center of rotation of the display and a consequent heading error. The lack of any observable difference in tracking error indicated, however, that this effect was negligible in the conditions used in the experiment. It could well be that a different result would have been obtained if the approaches had required the use of larger angles of bank.

The absence of any significant difference in tracking with change in the method of computing flightpath was surprising. For it might be thought that the change in computational framework, between air mass and inertial flightpaths, would affect the ability to achieve an optimal path, especially in wind shear. But subjects were evidently able to adapt to either scheme. It must be said, however, that only one kind of wind shear was used, and that a difference might be found with other types.

The workload results showed an advantage for the Type 2 displays. They needed smaller column displacements than the head-up director displays in the instrument flight segments (1, 2). In the combined flight mode (Segments 3, 4) the advantage was less pronounced since it was shared with H11, and only H31 required the larger displacements. The interactions revealed minor variations in display order for changes in turbulence and offset, but generally with the Type 2 displays showing to advantage. As an exception, H11 required the smallest displacements for starts on the beam in good visibility in Segment 4.

If these results are compared with the tracking results, it is seen that the broad equivalence of all head-up displays for tracking accuracy in Segments 1, 2, 4 was often obtained by working harder with the directors. This would suggest that information processing was not beneficial, except that allowance should be made for the confounding effect of an inefficient director control law.

The effect of framework on workload was evident in Segments 3, 4. Column displacements were smaller for H11 than for H31. This would indicate an advantage for an unreferenced system. The advantage did not obtain, however, in the instrument flight mode (Segments 1, 2).

The results for airspeed error showed an advantage for the Type 2 displays over the referenced director, H31. But as the speed element was the same in the H21 and H31 formats, and very nearly the same in H25, the difference in performance was evidently due to the way the element was used. Since the speed element was in each case attached to a moving symbol (which was either the flightpath or the flight director), its usefulness could have depended on the movement characteristics of the host symbol except that all the displays were criticized for movement sensitivity. A more likely cause of the difference could have been the effect of field limiting. This was more prevalent with H31 than with H21, 25, because the flight director symbol could not be kept within the display field as easily as the flightpath symbol. In consequence there was a greater tendency for the speed error element to become invisible in H31.

The interaction of displays and conditions is more difficult to explain. Why was there a relatively good performance with H31 during the intermediate segments of offset approaches in calm air? This effect was also experienced with H9, 11, in which the speed element was of conventional design and was always visible. It was therefore unlikely that the form of the element was responsible. The explanation may be that in these conditions it was easier to handle a flight director than a flightpath display, or that a flight director was more familiar to subjects, so that more attention could be given to airspeed. In general, the results for airspeed were independent of information processing and choice of framework (for the guidance symbols), except as in these indirect effects.

Comments and Answers

H11– The comments and answers to questions gave further insight into the use of the display formats. The unreferenced director, H11, attracted relatively little comment. This may have been due to the conventional nature of the format, which was quite similar to an ADI, and, of course, to the fact that all pilots were very used to this type of display. One subject noted this similarity and several other pilots made the same comment in the preliminary experiment. (It was also noted by the experimenter that no control reversals occurred with this display.) The main criticism of subjects was that the director control law was poor (oversensitive). There was perhaps a need for the more advanced kind of gain development which was used previously (ref. 2).

Comments on compactness, and the ease of reading peripherals, may be taken with the ability to scan raw ILS information (table 13) as fair indications of a lack of problems due to the size of the display format. And the same scanning ability showed that fixation was not a problem with this form of flight director. This result, and the previously mentioned ability to abandon the display when close to the ground in adverse conditions, may help to dissipate the criticism of a tendency to tunnel vision, which is sometimes leveled against flight directors.

H21– There were more comments made about the H21 display. This was perhaps to be expected in view of the unfamiliar nature of the information content, but not all comments could be considered naive reactions. Movement sensitivity was quite frequently criticized, and it became clear that the large angular velocities of symbols deployed in an external framework would always be a likely feature of this display. But the relatively large size of this "real-world" display did not lead to difficulties of peripheral scanning (table 13), and there was no need to increase the size of outlying elements.

Effects of computing errors in generating a mismatch between the superimposed fields were not often noted by subjects. They were frequently observed by the experimenter, however, and an example is shown in figure 3 where it can be seen that the localizer line is not aligned with the runway centerline. Mismatches (due to source errors) were also observed in previous flight tests (ref. 7), and it may be that this kind of error has to be accepted as a feature of a ground referenced display. A lateral mismatch is more of a nuisance than a source of danger because it is often plainly visible. A vertical mismatch may be more serious because it may be less evident.

Symbols were generally satisfactory with H21. The fact that lateral control was more difficult for many subjects (table 13) than vertical control was expected, because the display did not provide much lateral guidance information. This difficulty might have been avoided by not using the display, but rather the visual background for lateral control (as some subjects did). There was some difficulty in knowing how to place the flightpath (table 13) and this was at variance with the lack of any measurable performance difference between H21, 25. The skill of placement could evidently be learned but it required conscious mental effort on the part of subjects trained only to the level recommended for a similar display (ref. 1).

Since use of the outside world instead of the display was not too frequently noted, it is not definitely clear whether a state of continuous transition was achieved by all participants. The comment about clutter being acceptable in a well understood display may even indicate a lack of external scan in the case of one subject. But the responses to the control tower light (fig. 16) were much the same as when using H11, for which the continuous transition has been established (ref. 14). It may well be that a similar property is available with H21, after due practice, but this cannot be considered proven.

H25– Comments about H25 were quite numerous, and this was again to be expected with an unfamiliar display, but many of the comments were critical of the features associated with a ground referenced display. The movement characteristics of symbols were far from ideal and resulted in a sense of instability. Field limiting was criticized as inducing disorientation. There was more difficulty in seeing peripheral elements than with H21 (table 13). But H21, 25 were of the same size and had the moving height scale as a common component, so the difference in visibility may have been due to a greater difficulty in leaving the central elements of the H25 format, possibly because it was more difficult attending to the three guidance symbols than the two in H21.

Symbols were again generally satisfactory but the fixed depression circle was not as well received as the fixed depression symbol of H21 (table 13). Lateral control was again more difficult than vertical control for the same reason of a lack of lateral guidance in the format. Because of difficulties experienced with use of a laterally movable flightpath symbol, it seems that strict conformity of the flightpath has to be sacrificed, and that such guidance would best be provided by means of a director symbol as used by Bray (ref. 8).

The experience of one subject, in finding unreality and a sense of reversal in this real-world display, is important because it may indicate the existence of a class of subject tending to think in a different coordinate framework during instrument flight. It was nevertheless reassuring (and perhaps significant) that the sense of reversal should disappear on breakout, and this pointed to a measure of transition between fields. But there was little direct evidence of the essential quality of a continuous transition, and there was the comment on the possibility of staying too long with this display when about to land. While this comment was rare, it cannot be dismissed lightly because the consequences could be dangerous. It needs to be determined whether there is a significant risk of becoming engrossed with this type of display when close to the ground, or in other critical circumstances.

H31– The H31 format was another display attracting little comment and this also may have been due to familiarity with the flight director concept. The main comment was a criticism of the movement sensitivity inevitably associated with a ground referenced display. Another drawback was the field limiting and consequent loss of vital information, which included speed error. It would obviously have been desirable to have eliminated both of these defects, but this could scarcely be done without loss of conformity which was an essential quality of the display.

There was limited evidence of the transition between fields in a comment of one subject. This was supported by responses to the control tower light, which were similar to, and perhaps better than, responses when using H11, 21 (fig. 16). It would nevertheless be premature to conclude that the display allowed continuous transition, especially because of the distracting effect of movement sensitivity.

Form of symbols, including peripherals– As the circular flightpath symbol was only preferred to the double wing symbol by a slim majority (with several users uncertain), it has to be concluded that either symbol may be acceptable. A more decisive result was obtained in the case of the speed error symbols, and the worm rising or falling from the path circle was a very successful form. This must be qualified, however, by the reservation (applicable to either worm or ribbons) that this error symbol cannot safely be attached to a moving symbol, unless the movement is limited to keep the error indication visible.

The chief variation among peripherals was in the height elements. The digital height readout was quite well received (table 13) but the moving height scale was less successful (appendix E, H21). The use of two height scales was not accepted as a necessary feature (table 13), and their combined effect was to suggest a false motion of the aircraft. On balance, it seemed that a digital readout was preferable in the experimental situation, though a different provision would obviously be needed for other phases of flight.

Other peripheral symbols were generally satisfactory, and this was not surprising in view of the incorporation of many of the ideas found successful in the course of the development of panel instruments. There was evidently sufficient feeling for the need of a power indication to justify its inclusion in a HUD format (at least in the absence of information of similar type such as potential flightpath). A comment about the frightening nature of a blinking path index symbol may have been an indication that this device was too powerful for a not absolutely vital warning. It suggests the need for a balanced approach to the whole subject of cautionary or warning indications, with the degree of prominence of symbols matching their importance.

No unsolicited comments were made about the reflector plate and this evidently gave no problems to subjects, apart from safety.

Rank Order and Properties

The rank ordering of displays placed the flight directors ahead of the Type 2 formats, with a clear lead for the unreferenced director and H25 unambiguously last (table 14). While this result is definite, it is not very informative by itself. For example, a particular display characteristic might have had an overriding effect. But the estimation of display properties (table 15) placed the displays in the same definite order, and it may thus be inferred that the rank ordering depended on an appreciation of most of the properties listed in appendix C. In other words, there was a careful evaluation of the formats for quite a large range of useful qualities.

It had been expected that H11 would do well for simplicity, disorientation resistance, and fixation resistance, because these qualities were already quite well established (ref. 15). It was expected to do well for interference resistance because there was no gross movement of symbols through each other, as in the other formats. It had not been expected that it would do so well for conformity because it did not show features of position conformity, as did the other displays, and it was only conformal in motion, although this was evidently sufficient. Nor was it expected that it would do better than the others for monitoring and situation visibility because the raw ILS scales were common to H11, 21, 31 (though not to H25), and this information plays an important part in judging the long term quality of an approach, and the overall position. It was not clear in advance how the displays would be judged for wind shear capability. For some gave more position information than others, and some had speed information in a preferred form (worm). So the outcome would be governed by the way subjects estimated shear, whether by position or speed.

These results should be considered, however, in the light of the following facts. Subjects were naive and trained only to a level found satisfactory elsewhere. On the other hand, they were familiar with flight directors. Their subjective responses may therefore have been influenced in favor of the director displays. They may also conceivably have been influenced by the experimenters, although no opinion on any of the displays was offered at any time, and indoctrination was limited to the briefing material given in full in appendix A.

Visual Events

The responses to the master warning symbol showed simply that the pilot was able to acquire information from the display when the external field was visible, with a reaction time closely similar to that under no-load conditions. Conversely, the responses to the tower signal showed that the external field was seen while attending to the display (on the evidence of tracking accuracy), though with a delay of about 2.5 sec, which included response times for poor visibility. It would obviously be desirable to find a relation between responses to the tower signal and the transition between instrument and external fields of information. But this is not a straightforward matter because several kinds of transition can be distinguished, especially when HUD is involved. The various kinds are shown in table 17 together with times for the transition.

The usual meaning of the transition is that the pilot changes the field of information, on which his control actions are based, from the head-down instrument panel to the external forward view, which may be clear or only dimly perceived. The time required for the transition can be measured if it is possible to identify control actions which are associated unambiguously with each of the two fields of information. It is usually difficult to do this because of the complex nature of the external

TABLE 17.– TRANSITIONS BETWEEN INFORMATION FIELDS

Type	Transition	External stimulus	Time	Notes
1	HD-visual	Complex, clear	---	---
2	HD-visual	Complex, dim	---	---
3	HD-visual	Simple, clear	3.45 3.86	ref. 16 ref. 14
4	HD-visual	Simple, dim	---	---
5	HD-HUD	---	---	---
6	HUD-visual	Complex, clear	---	---
7	HUD-visual	Complex, dim	---	ref. 6
8	HUD-visual	Simple, clear	0.88	ref. 14
9	HUD-visual	Simple, dim	2.66	fig. 16 (mean)

Legend: HD – head-down panel instruments
Visual – external visual field
Complex – pilot's forward view
Simple – discrete signal
Clear – good visibility
Dim – poor visibility

field and because the sequence of control actions is generally required to be smooth. Another difficulty is that the external field visibility may affect acquisition time, so that transition time will vary with conditions. This suggests the distinction made between Types 1, 2 in table 17. It is not known whether measurements have ever been made for these kinds of transition, or whether they can in fact be made with precision. Other aspects of these transitions have been investigated by Haines in recent unpublished work.

If the external stimulus is simple and discrete a measurement can be made. Gabriel used a Landolt ring and found a response time of 3.45 sec (ref. 16). This agrees with earlier measurements of 3.86 sec for a single patch of white light (ref. 14). These times are for the Type 3 transition in table 17. The case of a simple dim stimulus (Type 4) does not seem to have been investigated. Nor do measurements appear to have been made of the transition from panel instruments to HUD (Type 5).

The same difficulty of measurement occurs in the transition from HUD to the forward view. Only qualitative results have been obtained and these were for dim stimuli (Type 7). But a value of 0.88 sec was obtained with a simple clear stimulus (Type 8, ref. 14), and the present results (fig. 11) yield a mean value of 2.66 sec for a simple dim stimulus (Type 9). While Types 3, 8 transitions can be compared to show an advantage of about 3 sec for HUD when the stimulus was clear, it is not possible to compare the present experimental result with other data (i.e., Types 4, 9), although it would be expected that the time for a Type 4 transition would exceed 4 sec and thus show some advantage for HUD.

It must nevertheless be pointed out that the value of 2.66 sec was the average of mostly quite small values and relatively large values arising in conditions of turbulence and low visibility. The experimental method did not show whether the larger times were simply due to the difficulty of making control responses in high workload conditions, or whether they indicated a real delay in seeing the external world. It needs to be more carefully determined in these circumstances whether attention to one of the superimposed fields precludes attention to the other (ref. 17). This may be particularly important for the H25 format in view of the previously discussed possibility of staying too long with the display.

CONCLUSIONS

1. In the pure tracking mode (instrument flight) and in good conditions the relatively unprocessed information of the Type 2 displays could be used to give a path stability slightly better than that obtained with the processed information of director displays (Types 1, 3). This result appears to have some degree of generality, except for a caveat about having used a poor director control law.

2. The frame of reference made no difference to tracking accuracy in instrument flight and in the combined mode, except that the unreferenced head-up flight director display was better in poor instrument flight conditions. This display also had a lower workload in the combined flight mode.

3. In the general tracking mode of combined instrument and visual flight, there was at first a relative degradation in performance with the head-up director displays. In the case of H11 this appears to have been due to a reluctance to follow director commands in a strong wind shear situation. The difference disappeared at low altitude.

4. Workload (as shown by control activity) was greater for the director displays especially the referenced director (Type 3). This effect may also have been confounded by a poor director control law.

5. There was no difference in tracking performance between the referenced displays of unprocessed information (Type 2 formats), despite the addition in one of them of means to help placement of the flightpath.

6. There was no difference in tracking performance with Type 2 displays when the flightpath computation was changed from an air mass to an inertial framework. It was evidently possible to make sufficient adjustment for the change even in wind shear conditions.

7. The referenced displays of unprocessed information attracted the most comment. This may have been partly due to the novelty of the formats but it may also have been due to some unsatisfactory features of the specific displays tested, since expected effects of movement sensitivity and field limiting were criticized. Peripheral symbols were hard to see in one format (H25), and this was possibly due to preoccupation with guidance symbols, rather than the large size of the display format. Lateral control was difficult because of lack of information in the display.

8. The referenced director display was criticized for movement sensitivity and field limiting. These effects were disadvantageous.

9. Results for individual elements of the displays showed the digital height readout and the speed error worm to be successful providing they are not allowed to disappear from view.

10. The display formats were placed in a clear order of preference, which was substantiated by a detailed evaluation of display properties, such as fixation resistance and monitoring capability. The unreferenced director (H11) was placed first. The referenced director (H31) was second. The referenced display of unprocessed information (H21) was third. And the referenced display having an added path index (H25) was fourth. These subjective results were for pilots more familiar with flight director displays.

11. Responses to the visual events showed some degree of division of attention between the superimposed visual fields in high workload wind shear conditions but further effort is needed to evaluate the supposed risk of staying too long with the H25 format when close to the ground.

12. There was a general advantage in tracking for head-up formats in the first part of the combined instrument and visual flight mode.

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APPENDIX A

DESCRIPTION OF DISPLAYS USED AS BRIEFING MATERIAL

HUD11. Unreferenced Flight Director

Concept– The display provides guidance without the need for stabilization with respect to a ground object. It makes use of processed information. It is a fly-to display in geographical coordinates, but true angular relationships are not preserved. It provides protection against fixation, or undue concentration, on the guiding elements.

Implementation– Guidance is provided by the relation between a fixed circle with "wings" (1) and a movable dot symbol at the apex of a stack of crossbars (3), as shown in figure 17. The circle represents the aircraft and its wings are parallel with the lateral axis of the aircraft. It is "flown" to the dot, which moves parallel to the horizon for heading (azimuth) commands, and perpendicular to the horizon for height (elevation) commands.

The stack of crossbars has each member parallel to the horizon at all times, and it is enclosed by an (invisible) envelope terminating in the dot symbol. The lowest crossbar (which is always nearest the ground) rotates in bank at a fixed distance from the aircraft circle, so that when the dot is displaced the envelope becomes distorted. The purpose of the crossbar stack is two-fold: to indicate where the dot symbol is located without the user having to fixate on it, and to show bank attitude in the absence of an artificial horizon (at large angles of elevation).

Supporting elements– An artificial horizon (2) is provided in the form of a bar with a gap spanning the aircraft circle. It shows bank angles in the usual way and elevation ("pitch attitude") at reduced scale, which is a convenient device for keeping the symbol within the display field and is sufficient to indicate the nature of the maneuver required by the flight director. Another supporting element is a digital readout of radio height (4) which changes in intervals of ten feet, as is convenient for a stabilized approach. Peripheral elements include a "fast-slow" speed indicator (5) showing departures in 10 knot intervals from a set speed (positive upward), and scales showing "raw" (unprocessed) glideslope (6) and localizer (7) deviations which are also conventional in interpretation (e.g., if the scale center is above the movable "bug" in the glide-slope indicator the aircraft is high). Finally, a square symbol (8) is provided as a master warning. It may be noted in passing that the ILS scales are the only elements of the display which are not uniquely identifiable by shape alone.

Driving signals– The flight director index is driven by azimuth and elevation commands furnished by the scheme of figure 5, in which ILS deviations are processed with attitude terms. As a special case, an alternative elevation command is generated for the Non-Precision Approach, when glide-slope deviation is unknown. In this case, the command signal is designed to achieve a constant rate of change of height and to become operative at the outer marker. Driving signals for the other elements of the display follow standard practice as far as possible. The artificial horizon, however, is scaled to move vertically at a reduction in angle of five to one, and the master warning symbol is blinked at a rate of 2 cycles/sec until canceled by pressing the conventional master warning indicator in the instrument panel.

HUD21–24. Referenced Flightpath Displays

Concept– In these four displays flightpath information is referred to an aimpoint on the runway. The information is essentially elementary in nature (unprocessed) and is of two kinds: the *position* of the flightpath, whether displaced above or below an ideal path (usually a 3° path through the glide slope origin at the touchdown zone), and the *direction* of the flightpath, expressed as a point of eventual impact with the ground. They are all fly-to displays, in the sense that path displacement and direction symbols have to be brought to the runway aimpoint. In each display, lateral guidance is confirmed by the appearance of the runway itself.

The displays differ in the shape and orientation of the flightpath (direction) symbol and in its coordinate frame of motion. There are also differences in peripheral elements of the formats. They are essentially true angle displays.

General implementation– In these Type 2 displays, which are shown in figures 18–21, the aimpoint is the touchdown zone on the runway seen in visual flight or, in instrument flight conditions, it is at the intersection of a short crossbar symbol (15), which is parallel with the horizon, and a runway centerline, or localizer line, symbol (14). The localizer line is drawn downward from a runway heading symbol (16) located on the artificial horizon. When the localizer line is perpendicular to the horizon the aircraft is on the (extended) runway centerline.

HUD21. Implementation– In this format, figure 18, the artificial horizon (12) is a line with a small gap which is always above the display center on a line parallel to aircraft vertical. The artificial horizon is, of course, displaced from the visible horizon because of the earth's curvature.

Guidance is provided in this display partly by the relation between the displacement symbol (13) and the aimpoint. The symbol is a series of dashes, with a central gap, and is parallel to the horizon at an angular distance of, say, 3° (γ_k). When it is below aim the aircraft is below the ideal (3°) path, and when it is above aim the aircraft is above this path. Guidance is also provided by the relation between the flightpath symbol (1A) and the aimpoint. This symbol is moved beyond aim by the pilot's control action, to the side remote from the displacement symbol (13). The amount of movement is chosen to reduce displacement at a suitable rate, and as the displacement becomes less the flightpath symbol is brought closer to aim, so as to reduce the rate of closure. The two symbols (1A, 13) eventually converge on aim unless there is a wind effect, which may require the flightpath to be maintained at an offset. The flightpath symbol is the aircraft symbol (1) of HUD11, figure 17, with a fin added. It is oriented and moved (at true angular scaling) in aircraft coordinates, so that guidance, horizon, and aimpoint symbols form a hybrid (geographical-aircraft) system.

Supporting elements– The other elements follow the layout of HUD11 and include the same ILS glideslope (6) and localizer (7) scales but the fast-slow speed element is replaced by the vertical fin (11) of the flightpath symbol, which shows positive and negative departures from a set speed by upward and downward extension, respectively. There is no digital readout of height: instead, there is a moving scale with intervals of 100 ft (17) which moves through a "window" in the format. The master warning symbol (8) is the same as in HUD11, and it is again true that the ILS scales are the only elements not uniquely distinguished by form.

Driving signals– The horizon symbol is driven by angles of elevation (θ) and bank (ϕ) in true scale. The runway heading marker is displaced from the horizon gap by the difference between runway and aircraft headings ($\Delta\psi$), and is thus in error when the aircraft is banked. The localizer line is inclined to the horizon at an angle whose cotangent is the ratio of localizer deviation (α') and the algebraic sum of the fixed depression angle and glide-slope deviation ($\gamma_k \pm\beta'$), while the denominator of this ratio is the signal used to locate the aimpoint crossbar. It is significant, in the operational context, that if glide-slope deviation is unknown (as in the Non-Precision Approach) the inclination of the localizer line and the position of the aimpoint are in error.

The fixed depression symbol (13) is driven by pitch attitude with a constant angular offset ($\gamma_k = 3°$, say). The flightpath symbol is driven vertically, in aircraft axes, by the flightpath angle, the reference point being the gap in the horizon bar. It is driven laterally in the same axis system by the sideslip angle, from the same reference point. Driving signals for the other elements of the display are similar to those used in HUD11 but the height scale is, of course, driven by an analog signal.

HUD22. Implementation– The HUD22 format is shown in figure 19. The artificial horizon (18) in this case has a gap which is always above the display center in the geographical vertical, so as to provide a heading reference point which is itself in true angle.

Guidance is again provided by the relation of the fixed depression (13) and flightpath (19) symbols to the aimpoint, but in this case the flightpath symbol is oriented and moved in geographical coordinates. The horizon, aimpoint, and guidance symbols thus form a pure geographical system.

Supporting elements– Other elements are the same as in HUD21, figure 18. The ILS scales (6, 7) and the master warning symbol (8) are carried forward from HUD11, figure 17, the moving height scale (17) replaces the digital height readout, and speed error is shown by a fin (11) on the flightpath symbol. Also, a similar degree of uniqueness in symbol form is available.

Driving signals– The symbols in HUD22 are driven by the same signals as in 21. The horizon is thus true in elevation and bank but the new (true) position of the horizon gap affects the positions of the heading marker (at $\Delta\psi$), localizer line, and crossbar. However, the inclination of the localizer line ($\alpha'/(\gamma_k \pm\beta')$) and the depression of the crossbar ($\gamma_k \pm\beta'$) remain the same, so that relative positions are preserved. The fixed depression symbol is again driven by offset pitch attitude ($\theta + \gamma_k$), and the flightpath symbol by flightpath angle and sideslip, but these signals are applied in geographical axes from the (true) reference point. As before, the slope of the localizer line and the position of the crossbar are in error during a Non-Precision Approach. Driving signals for other elements are similar to those used in HUD11 but with an analog drive to the height scale.

HUD23. Implementation– The HUD23 format is shown in figure 20, where it can be seen that elements of the central zone are closely similar to corresponding elements in the HUD21 format, figure 18. The horizon (12) is the same symbol with its gap again located on the aircraft vertical. The fixed depression symbol (13) is the same symbol and is used in the same way, by observing its displacement from the intersection of localizer line (14) and crossbar (15) symbols, which are also the same as in 21. The main difference is in the shape of the flightpath symbol, which is in the form of two aircraft wing sections (21). This symbol is oriented and moved, at true angular scaling, in aircraft coordinates. It is used in the same way as the HUD21 flightpath symbol, and guidance, horizon, and aimpoint symbols again form a hybrid system.

Supporting elements– The other elements of the format are exactly the same as in HUD11, figure 17. In other words, the digital height readout (4), the fast-slow indicator (5), glide slope (6) and localizer (7) scales, and the master warning symbol (8) have the same forms, positions, and orientations as in the Type 1 format, while the moving height scale and "fin" speed error are not used. As before, all symbols except the ILS scales are distinguishable by form alone.

Driving signals– The horizon is true in elevation and bank (θ, ϕ). The runway heading marker is displaced (by $\Delta\psi$) from the gap and the absolute positions of localizer line and crossbar symbols are thus in error. Inclination of the localizer line ($\alpha'/(\gamma_k \pm\beta')$) and crossbar depression ($\gamma_k \pm\beta'$) are nevertheless correct, except in a Non-Precision Approach, and relative positions are preserved. As usual, the displacement symbol is driven by offset pitch attitude ($\theta + \gamma_k$), and the flightpath symbol is driven in aircraft axes by flightpath and sideslip signals, which are referred to the horizon gap. Other elements are, of course, driven by the same signals used in HUD11.

HUD24. Implementation– The HUD24 format, which is shown in figure 21, is derived from the HUD23 format, figure 20, by modifying the flightpath symbol. The difference lies in orienting and moving this symbol in geographical coordinates, in true angle (22). It follows that the relation between the HUD23 and HUD24 formats, which includes a shift in horizon gap, is the same as the relation between HUD21 and HUD22 formats, figures 18 and 19. Thus, the artificial horizon is changed from symbol (12) to symbol (18), with dependent changes in position for the heading marker (16), localizer line (14), and crossbar (15), which are otherwise unchanged. The fixed depression symbol (13), which is entirely unchanged, together with the flightpath (22) and "background" (14, 15, 16) symbols form a pure geographical system similar to that of the HUD22 format and are used in a similar way.

Supporting elements– Digital height (4), speed error (5), ILS scale (6, 7), and master warning (8) elements are the same as in HUD11, figure 17, with the same degree of individual uniqueness among all the symbols.

Driving signals– The driving signals remain the same as in other Type 2 formats. The horizon is true in elevation and bank, the heading marker is driven by heading error ($\Delta\psi$), the crossbar is offset by the fixed depression angle and glide-slope deviation ($\gamma_k \pm\beta'$), inclination of the localizer line is defined in the usual way ($\alpha'/(\gamma_k \pm\beta')$), and the fixed depression symbol is driven by offset pitch attitude ($\theta + \gamma_k$). The flightpath symbol is driven by flightpath angle and sideslip from a true reference point (the horizon gap), in geographical coordinates. As with other Type 2 formats, localizer line inclination and crossbar position are in error during a Non-Precision Approach. Driving signals for the other elements are the same as in HUD11.

HUD25. Referenced Flightpath Display with Flightpath Index

Concept– This format is a special case of the Type 2 display. Guidance is again provided through unprocessed information about the position and direction of the flightpath in relation to the horizon and runway but the directional aspect is managed with the help of a flightpath index, instead of a runway aimpoint. This leads to some loss of conformity but the display is otherwise in true angle and is still of the "fly-to" kind. Besides these changes, there are modifications to the supporting elements to provide more height information, while removing the ILS scales.

Implementation– The format is shown in figure 22. Background symbols include an artificial horizon (28), which is an unbroken bar with an enlarged runway heading marker (27) and smaller markers (29) at regular intervals (such as 5°). The localizer line (14) is drawn in the usual way from the runway heading marker, and guidance is confirmed by the apparent perpendicularity of this line. The background symbols either reinforce or replace corresponding features of the external visual world.

The flightpath symbol (21) has the same form and orientation as the corresponding symbol of the HUD23 format, figure 20, and it is also moved in the vertical axis of the aircraft but it remains with its center on this axis; that is, sideslip is not shown. The fixed depression symbol of the other Type 2 formats (13) is replaced by a circle (34) which is at the same angle below the horizon (γ_k) but remains on the geographical vertical through the runway heading marker (27). This symbol is no longer the primary means used to decide how to place the flightpath symbol. Its function is taken over by the flightpath index (35) which is a thin line of dashes, each longer than in symbol (13). The flightpath index is parallel with the horizon and it is depressed by an angle calculated to secure an optimum rate of reducing displacement when the flightpath symbol is aligned with it. The index represents no physical feature of the real world and is conformal only in its coordinate system. When the flightpath symbol is held on the index the two symbols (21, 35) tend to converge on the fixed depression circle (34). The situation is complicated, however, by the presence of a longitudinal wind component, especially if this is unknown. The background and guidance symbols form a hybrid system.

Supporting elements– The display is flanked by two vertical scales. Altitude is shown on the left hand scale (31), with the mean sea level altitude of the runway indicated by the top of a bar symbol. Radio height is shown on the right hand scale (17), the zero value corresponding with landing. These scales are similar to the moving height scale of the HUD21 format, figure 18, but a three-dot symbol is added to each of them to show decision heights (32, 36). Speed error is shown by fins extending from the flightpath symbol, rising upward from the upper surfaces for a positive error (33) and falling from the lower surfaces for a negative error. A digital readout of airspeed is provided in support of the speed error symbol and this is seen at the upper left corner of the format (30). The master warning symbol and ILS scales are omitted from the format, and there is a reasonable degree of uniqueness among symbols except for the similarity of height scales.

Driving signals– The background symbols have drives similar to those used in the other hybrid systems (HUD21, 23). The horizon is in true angle (θ, ϕ) and the localizer line is correctly inclined ($\alpha'/(\gamma_k \pm\beta')$) but this line is drawn from a runway heading marker which is displaced (by $\Delta\psi$) from a point on the vertical aircraft axis, and is thus slightly out of position when the aircraft is banked. As with all Type 2 systems, the localizer inclination is in error during a Non-Precision Approach.

The fixed depression circle is driven by offset pitch attitude ($\theta + \gamma_k$), and the flightpath symbol is driven along the aircraft vertical by the flightpath angle. The flightpath angle index is driven by the algebraic sum of the fixed depression angle and a multiple of the glide-slope deviation angle ($\gamma_k \pm N\beta'$). In the simplest case ($N = 2$), the index lies *beyond* aim (on the side remote from the fixed depression symbol) by the glide-slope deviation angle. With larger values of N, it is possible to augment the effect of path direction in reducing path displacement.

Driving signals for other elements of the display include analog height drives, a digital speed drive, an analog speed error signal for a set airspeed, and a set decision height. Arrangements are made for blinking the decision height symbols when height is reduced to within 100 ft of the decision height. The flightpath index is made to blink from a height of 100 ft until flare.

HUD31, 32. Referenced Flight Directors

Concept– The displays make use of processed information in providing guidance with respect to a ground object. They are "fly-to" displays in the sense of requiring action to move a guiding symbol to an aimpoint. The background elements are in true angle, in geographical coordinates. The guiding element is not in true angle but is moved in geographical axes. The two displays differ in the configuration of guiding elements and the provision of displacement information. There are also differences in supporting elements.

General implementation– The displays are shown in figures 23 and 24, where it is seen that each has the same background elements. These include the runway heading marker (16), the localizer line (14) and crossbar (15) symbols of types 21–24, together with a horizon (18) having a true reference gap, as in types 22 and 24 (figs. 19 and 21). As before, the localizer line can be used to confirm, or effect, lateral guidance by its perpendicularity, and it is used to provide an aimpoint by its intersection with the crossbar.

HUD31. Implementation– Guidance is provided by the relation between the flight director symbol (20, fig. 23) and the aimpoint, which may be indicated by symbols (14, 15) or it may be the touchdown zone on the real runway. The director symbol is the flightpath symbol of HUD21 (fig. 18), which is moved in geographical axes for azimuth and elevation commands. No displacement information is provided and, as with HUD11, the user is not *required* to interpret unprocessed information in order to surmount a difficult (wind) situation, though he may use supporting elements for monitoring purposes. The background and guiding elements together form a pure geographical system, as far as the coordinate framework is concerned, but the director symbol has no one-to-one correspondence with any feature of the real world. Also, it is oriented in aircraft axes to provide an attitude reference.

Supporting elements– The ILS glide slope (6) and localizer (7) scales, and the master warning symbol (8) of HUD11 (fig. 17) are provided, together with the moving height scale (17) of HUD21 (fig. 18). Speed error is shown by a fin (11) added to the director symbol, as in HUD21. Once again, the ILS scales are the only elements not distinguishable by form alone.

Driving signals– The horizon is true in elevation and bank (θ, ϕ) and the runway heading marker is correctly placed on the horizon (at $\Delta\psi$). Inclination of the localizer line ($\alpha'/(\gamma_k \pm\beta')$) and depression of the crossbar ($\gamma_k \pm\beta'$) are also correct, except in the Non-Precision Approach. The flight director symbol is displaced from the intersection of localizer line and crossbar symbols by command signals, azimuth command being parallel with, and elevation command perpendicular to the horizon. With the exception of an analog drive for the moving height scale, the other elements are driven by the same signals as in HUD11.

HUD32. Implementation– In this display, (processed) guidance information is only available in the true vertical plane. It is again referred to the symbolic aimpoint (14, 15) or the real world runway. Displacement is shown by the position of the fixed depression symbol (13) in relation to aim, as in most Type 2 displays. Information of command type is shown by the relation between a row of dots (26) and the aimpoint. These dots move out from nesting positions in the fixed depression symbol as a result of control action. The amount of control required is shown by the angle through which the dots have to be moved for them to become aligned with the aimpoint. The pilot is thus assisted in using the processed (command) guidance information by knowing the reason (displacement) for the action required of him. Background and guidance elements form a pure geographical system, except that the line of dots corresponds to no feature of the visible external world.

Supporting elements– The periphery of the format is occupied by the fast-slow display (5), ILS scales (6, 7), and master warning symbol (8) of HUD11 (fig. 17). A change is made, however, by introducing a digital display showing the relation of present height to decision height. The value set for the decision height is labeled DH and appears always in the same position, in the upper right corner of the format (24). Above it is a digital readout of present height (23) which appears only when the aircraft is above decision height. Below it is a similar readout (25) which appears only when below decision height. As before, all elements of the display have unique forms except the ILS scales.

Driving signals– The background symbols are again driven by signals ensuring that the horizon is true in elevation and bank, with the heading marker properly located, while the localizer line is correctly inclined and the crossbar properly placed, except in the Non-Precision Approach. The displacement symbol is always depressed from the horizon by the selected path angle (γ_k) and the row of dots is driven from this position by a "compensated" signal designed to reduce optimally the observed glide-slope deviation (β'), which is the angular separation of crossbar and displacement symbols (as may be seen in fig. 18). The compensated signal is generated from an attitude input which is processed together with attitude rate, height rate, and acceleration inputs. Driving signals for other elements are as in HUD11, with the addition of a decision height input.

APPENDIX B

QUESTIONNAIRE

The questionnaire was designed to cover aspects not dealt with in other parts of the investigation. For example, the method of applying the same questions to all formats was used in evaluating display properties. And free comment was recorded separately. Instead, the questions here were mainly related to features peculiar to individual formats.

As stated in the main text, the questions were based on matters of general concern to 17 pilots taking part in the preliminary experiment for the selection of displays and, as such, were not intended to be a balanced set of questions. These matters were few in number for the director displays and quite numerous for the Type 2 displays.

H11

a. Did the flight director commands seem reasonable to follow in a wind shear (assuming that passenger comfort was not a consideration)?

b. In the high workload, wind shear situation, were you able to monitor raw ILS information?

c. Was the Digital Height readout a good, usable symbol (assuming that height information was necessary to the pilot)?

H21 and/or H25

a. Was the Fixed Depression symbol a good, usable symbol?

b. Was the Speed Error Worm a good, usable symbol?

c. Was vertical control difficult?

d. Was lateral control difficult?

e. Were the central, guiding elements harder to use than the raw ILS scales?

f. Was the circular Flightpath symbol better or worse than the winged Flightpath symbol?

g. Was it hard knowing how to place the Flightpath symbol to reduce displacement?

h. Were peripheral elements of the display sufficiently visible?

i. Were two height scales necessary?

H31 and/or H32

a. Was this type of display hard to use?

General

a. Did you miss having an indication of power?

b. Which display did you consider the best?

c. Do you have any other comments?

APPENDIX C

DISPLAY PROPERTIES

Each of the experimental displays was evaluated subjectively for the properties defined in the following notes. Each property was defined in a positive sense, as in the Cooper-Harper scale. A rating of one was given for excellence, a rating of nine for the worst case, and a rating of five for an average state of affairs.

Properties

Simplicity– In a simple display, the number of elements is reduced to the smallest practical value, and the form of each element is free of complexity or elaboration. The result is that the forward view is cluttered to the least extent, and this is the criterion used in evaluating the degree of simplicity for a given display.

Conformity– This property resides in the similarity between elements of the display and corresponding features of the pilot's forward view. In the present context, only the symbols in the central zone are likely to be conformal elements. The criterion for conformity is the extent to which these elements show similarities of orientation, position, and motion with their real world counterparts.

Situation visibility– A display provides situation visibility when it allows an understanding of the situation in which the aircraft is found. The criterion is an unambiguous description of attitude, position, and velocity, which may be assimilated easily at any time.

Disorientation resistance– A display with disorientation resistance has the capability of preventing the pilot from becoming disoriented, especially at breakout. This property is related to, but not a necessary consequence of, situation visibility because a situation display could be understandable in its own right, without reference to the external scene, but the pilot might become disoriented when observing display and real world together. The criterion for disorientation resistance is the absence of any tendency to disorientation or vertigo during combined use of display and forward view.

Monitoring capability– A display has monitoring capability when it enables the performance of a pilot, or an aircraft system, to be related to operating limits; for example, when it shows if glide-slope deviation exceeds a specified value. This property is a consequence of situation visibility when operating limits are shown but it may not be necessary for the situation to be *fully* represented; for example, it may be sufficient to show only glide-slope deviation. Also, a complete situation display may give information which changes too rapidly for monitoring purposes. The criterion for monitoring capability is that monitored functions, such as path and speed, can be related to the appropriate limits with ease, at any time.

Interference resistance– A display has the property of resisting interference when there is no tendency for any one symbol to inhibit the flow of information from another. The criterion for interference resistance is that no symbol ever occupies the same position as another, or is prominent to a degree inconsistent with its importance.

Fixation resistance– The property of resisting fixation exists when there is no tendency for the pilot to become engrossed with particular symbols, to the exclusion of other sources of information. The criterion for fixation resistance is that the pilot should not find difficulty in detaching himself from, say, a guidance symbol in order to attend to another element of the display, or the external forward view.

Wind shear capability– A capability for dealing with wind shear exists when the pilot is able to understand the airmass situation well enough to fly his aircraft safely through changing winds by means of the display. The criterion (for subjective evaluation) is that the pilot should have confidence in the ability of the display to allow this result.

APPENDIX D

ANALYSIS OF VARIANCE

ANALYSIS OF VARIANCE FOR GLIDE-SLOPE DEVIATION, SEGMENT 1

(H – display format, O – offset, L – visibility, T – turbulence. Only significant effects shown.)

Source	Error term	F	df	Mean square	Significance
Mean	S	139.13	1	.639	—
H	HS	3.53	4	.010	.025
T	TS	21.45	1	.115	.001

Note: runs with initial offsets excluded from this analysis (see text).

ANALYSIS OF VARIANCE FOR GLIDE-SLOPE DEVIATION, SEGMENT 2

Source	Error term	F	df	Mean square	Significance
Mean	S	675.08	1	10.261	—
H	HS	3.38	4	.021	.025
O	OS	152.89	1	1.785	.001
T	TS	122.06	1	1.275	.001
OT	OTS	27.47	1	.195	.001
HOL	HOLS	2.36	4	.008	.1
HLT	HLTS	4.50	4	.014	.005
OLT	OLTS	4.85	1	.014	.005
HOLT	HOLTS	5.02	4	.013	.005

ANALYSIS OF VARIANCE FOR GLIDE-SLOPE DEVIATION, SEGMENT 3

Source	Error term	F	df	Mean square	Significance
Mean	S	382.69	1	27.181	—
H	HS	26.09	4	.476	.001
O	OS	3.70	1	.018	.01
L	LS	13.60	1	.203	.005
T	TS	61.97	1	.582	.001
HL	HLS	3.52	4	.038	.025
OT	OTS	33.99	1	.433	.001
LT	LTS	5.99	1	.030	.05

ANALYSIS OF VARIANCE FOR GLIDE-SLOPE DEVIATION, SEGMENT 4

Source	Error term	F	df	Mean square	Significance
Mean	S	22.94	1	373.936	–
H	HS	2.42	4	34.165	.1
T	TS	5.94	1	49.138	.05
HOL	HOLS	2.20	4	16.380	.1
HOT	HOTS	2.43	4	20.901	.1

ANALYSIS OF VARIANCE FOR COLUMN DISPLACEMENT, SEGMENT 1

Source	Error term	F	df	Mean square	Significance
Mean	S	218.07	1	331.944	–
H	HS	11.57	4	2.141	.001
O	OS	10.21	1	1.962	.01
T	TS	67.74	1	11.774	.001
HO	HOS	8.44	4	.801	.001
HL	HLS	2.28	4	.203	.1
HT	HTS	2.26	4	.468	.1
OT	OTS	9.09	1	.982	.01
HOT	HOTS	2.96	4	.205	.05

ANALYSIS OF VARIANCE FOR COLUMN DISPLACEMENT, SEGMENT 2

Source	Error term	F	df	Mean square	Significance
Mean	S	309.25	1	510.675	–
H	HS	12.50	4	2.412	.001
O	OS	57.14	1	6.211	.001
T	TS	83.50	1	33.565	.001
HO	HOS	12.51	4	1.063	.001
OL	OLS	11.83	1	.448	.005
HT	HTS	4.24	4	.567	.005
HOT	HOTS	4.95	4	.386	.005

ANALYSIS OF VARIANCE FOR COLUMN DISPLACEMENT, SEGMENT 3

Source	Error term	F	df	Mean square	Significance
Mean	S	565.79	1	948.243	–
H	HS	14.59	4	2.633	.001
O	OS	37.24	1	3.764	.001
L	LS	9.86	1	1.746	.01
T	TS	162.43	1	21.817	.001
HO	HOS	4.88	4	.494	.005
HL	HLS	2.60	4	.439	.05

ANALYSIS OF VARIANCE FOR COLUMN DISPLACEMENT, SEGMENT 3 (Concluded)

Source	Error term	F	df	Mean square	Significance
OL	OLS	26.16	1	2.257	.001
HT	HTS	4.22	4	.444	.005
OT	OTS	18.00	1	8.816	.001
LT	LTS	3.92	1	.831	.1
HOL	HOLS	2.13	4	.187	.1
HOT	HOTS	2.21	4	.429	.1
HOLT	HOLTS	2.59	4	.396	.05

ANALYSIS OF VARIANCE FOR COLUMN DISPLACEMENT, SEGMENT 4

Source	Error term	F	df	Mean square	Significance
Mean	S	154.54	1	1642.215	—
H	HS	8.94	4	2.719	.001
L	LS	35.53	1	5.514	.001
T	TS	64.08	1	13.337	.001
OT	OTS	30.47	1	8.162	.001
HOL	HOLS	3.11	4	.408	.025

ANALYSIS OF VARIANCE FOR AIRSPEED ERROR, ALL SEGMENTS

Source	Error term	F	df	Mean square	Significance
Mean	S	737.13	1	70662.75	—
H	HS	8.90	4	377.54	.001
O	OS	116.90	1	806.34	.001
L	LS	4.37	1	69.06	.1
T	TS	37.83	1	1263.14	.001
G	SG	155.52	3	4552.43	.001
HO	HOS	7.90	4	124.47	.001
OG	OSG	8.05	3	82.16	.001
LG	LSG	49.74	3	340.63	.001
TG	TSG	20.62	3	259.35	.001
HOL	HOLS	2.37	4	18.90	.1
HOT	HOTS	2.76	4	47.89	.05
OLG	OLSG	9.14	3	31.32	.001
HTG	HTSG	6.27	12	35.41	.001
OTG	OTSG	45.24	3	768.36	.001
LTG	LTSG	4.06	3	19.05	.025
HOTG	HOTSG	3.18	12	24.68	.001
HLTG	HLTSG	1.94	12	7.23	.05
OLTG	OLTSG	33.56	3	130.91	.001
HOLTG	HOLTSG	1.86	12	6.58	.1

APPENDIX E

SUBJECTS' COMMENTS ON DISPLAYS

(Parentheses are used to denote editorial additions, dots are used to separate individual comments.)

HUD11

SUBJECT 20 – ". . . like compactness of this display . . . more useful . . ."

SUBJECT 21 – ". . . think this is my favorite display . . ."

SUBJECT 22 – ". . . very sensitive . . . easy to confuse horizon with glide slope . . . speed is easier to see than on (H)25 . . ."

SUBJECT 23 – (no comment)

SUBJECT 24 – ". . . sensitive . . . end up with high sink rate . . . unrealistic because have no feel . . . need extended speed error scale, more dots . . ."

SUBJECT 25 – ". . . like better than (H)25 on pitch, it is less sensitive . . . dot easier to control . . . more accuracy . . . from the diagrams I thought the bar would be easier to control but the dot is easier . . . like controllability of it all . . . can get fixated on dot close to the ground . . . I don't pay any attention to localizer on the bottom, may not be worth it . . . no problem with outside visual field . . . digital readout is nice . . . don't have the pitch problems I had on (H)25, may not be moving controls as much . . . tended to disregard dot on last 100 ft and go visual . . . HUD much easier to fly than existing (brand name) flight director . . ."

SUBJECT 26 – ". . . this is nice . . ."

SUBJECT 29 – (no comment)

SUBJECT 30 – (no comment)

SUBJECT 31 – (no comment)

SUBJECT 32 – ". . . lot nicer display than (H)21, 31 . . . more conventional . . . confusion with so many dots . . . confused between speed and glide slope . . . like bars . . . speed ribbon bothersome . . . lots easier to work with than (H)21, 31 . . . don't use raw localizer data . . . do use glideslope. . ."

SUBJECT 33 – ". . . really like this . . . could fixate, forces you to do instrument scan . . . can see peripheral trends at all times without lots of eye movement . . . easier scan pattern than with panel instruments . . . can see cues a lot faster because no transition from panel to outside . . . when in close hesitate to overcorrect so tend to go visual . . . makes a balance between HUD and visual, works smoothly . . . see trends much faster on display than head-down . . . didn't pay much attention to digital speed (sic) . . ."

SUBJECT 34 – ". . . looks like a good display to recover from unusual position . . ."

SUBJECT 35 – ". . . lot of scanning to do . . . really like stability of dot . . . I love that . . . seems so simple . . . use raw data to eliminate chasing the dot during transition, especially at night the approach tends to deteriorate, hopefully any HUD will eliminate this . . . this makes workload much lower . . . using all raw data . . . digital readout of altitude is beautiful, especially down low . . . was as easy as flying visual approach . . ."

HUD21

SUBJECT 20 – (no comment)

SUBJECT 21 – ". . . have tendency to overcontrol . . . very sensitive display . . ."

SUBJECT 22 – ". . . airspeed very accurate . . . used raw scales more than central elements . . . using visual scene rather than display because can't get rapidly moving display and outside world working together . . . flightpath moves around too much, can't tell where to place it . . . working harder on lateral than on vertical . . . can't use drift information received from horizontal indicator . . . must be ready for lag in movement and not overcontrol . . . forces scan . . ."

SUBJECT 23 – ". . . like speed worm . . . no time to look at raw data . . ."

SUBJECT 24 – ". . . readout on altitude not precise enough after 100 ft . . . doesn't have as much realism as (H)11, this is more mechanical . . . more difficult to cope with because you have to interpolate where to put the symbol . . ."

SUBJECT 25 – ". . . initially, from reading (briefing material), thought would be harder to fly but was easier in last 100 ft, not erratic, more accurate (than H11, 25) . . . looking through this one more than (H)11, not concentrating as much on the center . . . tend to look at raw data, glide slope, on left more than on (H)25, 11, to check meaning of central symbols . . . easier to fly in wind . . . easier to fly in lateral . . . used localizer more than in (H)25, 11 . . . has a lot of clutter but it doesn't bother me because I understand it . . . like digital height rather than scale . . ."

SUBJECT 26 – ". . . tend to use conventional glide slope and localizer . . . lots of movement is distracting . . ."

SUBJECT 29 – ". . . more difficult than (H)25, 11 . . . center bar looks too much like dashed line . . ."

SUBJECT 30 – ". . . like dashed line, is a good indicator . . . good relation of flightpath versus touchdown zone, makes situation clear . . ."

SUBJECT 31 – ". . . had to chase a bit . . ."

SUBJECT 32 – ". . . would like power readout . . . overcontrolling on speed because thought ribbon higher in speed than it really was . . . used raw data quite a bit . . . rarely looked at altimeter . . . localizer too sensitive . . . like presentation but it moves too fast laterally . . . easier flying raw data . . . prefer digital readout of speed . . ."

SUBJECT 33 – ". . . nice, each display has its good points . . . flare mode is good . . . didn't watch raw data like should have . . ."

SUBJECT 34 – ". . . it is easier if you think of center vertical line as runway instead of localizer (which is) difficult to interpret . . . if vertical line were wider at the bottom could use better . . . have to think bottom is closer to me than the top . . ."

SUBJECT 35 – ". . . this is much more like display I am used to laterally . . . can do this naturally without thinking about it because I am used to it . . ."

HUD25

SUBJECT 20 – ". . . degree of movement is greater than actual situation . . ."

SUBJECT 21 – ". . . wasn't sure of where to put what . . . was there any raw data? . . . more things moving in display make it harder to control . . . simplicity of (H)11 with flying circle to dot is better than lots of movement as in (H)21, 25 . . . digital speed is distracting in present position, didn't react to wind shear because had to go up to see it, don't need it if you have speed worms . . . when hit wind shear got a floating sensation because display seemed to be sinking down, so was able to react faster . . ."

SUBJECT 22 – ". . . display is sensitive to all movements, certainly laterally . . . so sensitive on horizontal plane . . . because of fixed base I get sliding motion horizontally . . ."

SUBJECT 23 – ". . . like digital readout on airspeed, you can gauge change a little quicker, need that in shears . . . can see digital readout before ribbon change . . ."

SUBJECT 24 – ". . . flare seems very sensitive at end, abrupt pitch moves . . . would help me to have power setting . . . need simple thrust indication . . ."

SUBJECT 25 – ". . . enjoyable presentation . . . easy to understand and follow . . . like ribbons (fast-slow) used them especially on turbulence and shears, can adjust throttle . . . if I flew ILS like that in real world would be in tough shape . . . HUD25 easier to learn on than (brand name) . . . can use numerical bank information that HUD doesn't supply, have to wait for display to start to move . . . HUD makes it easier . . . peripheral glances causes (sic) loss of lateral control . . ."

SUBJECT 26 – (no comment)

SUBJECT 29 – (no comment)

SUBJECT 30 – ". . . strange display . . . doesn't give strong cues . . . harder to fly than (H)11 . . . doesn't give attitude information . . . raw data on periphery takes too much time to deal with . . ."

SUBJECT 31 – ". . . don't pay much attention to raw data, more concerned with center . . . really chased that one, right down to runway . . ."

SUBJECT 32 – ". . . don't like this one, can't even find myself on it . . . confusing, crossbar is confusing . . . when I get lost it is extremely difficult to decide what to do . . . speed ribbons on wings add to clutter . . . has no relation to reality for me . . . miss raw data, can't refer to anything when lost . . . movement convention seems wrong . . . swing horizon very distracting, all this movement very distracting . . . senses reversed on what is actually happening, this wasn't so on (H)11, really liked that one . . . a confusing thing, constant movement between circle and "fly-to" line is too confusing because of too much movement . . . am sure it would take too much training to learn this but even after it is learned could be confusing because of clutter . . . displays 21, 31, 25 all have same defect: when the symbols go out of view or are displaced a lot it is hard to regain orientation . . . not using localizer . . . at breakout display appears to reverse (like a Necker cube) . . . it looks unnatural to push over and see display go up and not the outside world when I am visual . . . tendency for (cube) reversal is stronger with (H)25 than 21 or 31 . . . in (H)21, 31 had raw data to fall back on . . . roll a problem . . . pushing wings in wrong direction for pitch . . ."

SUBJECT 33 – ". . . lots of clutter . . . prefer (H)11 to this one because of clutter . . . like digital readout to support speed error . . . like flare mode, it really helps . . . more clutter but like better than (H)11 . . . like airspeed controls better . . . can keep on glidepath better . . . handles better in turbulence . . . all information is centralized, especially for approach . . . am staying on this display till much closer to the ground before going completely visual than on HUD11 . . . the fact that you can stay with (H)25 longer may lead you into a bad situation if you fall behind and need large corrections close in . . . speed ribbons make you think you are going faster than you really are, forces you to check speed constantly . . . on (H)25 my input response is much faster . . ."

SUBJECT 34 – ". . . more like real horizon . . . flare works well by following circle . . . circle and flare would solve depth perception problems on low visibility landing when coming head-up from head-down . . . would be easier if vertical line was two lines and tapered, if tied in with DME would spread apart as came in close . . . confusion when going head-down then coming up and seeing dashed line as display horizon . . . display horizon is superfluous, do not need attitude . . ."

SUBJECT 35 – ". . . like speed error . . . can't establish a pitch . . . control reversals . . . have inadequate information as to bank angle . . . distracting to be floating about target point when aircraft is actually on track . . . any time the wings move from the center laterally I am very uncomfortable, it interrupts my correction because the wings displacement distracting and moves too much . . ."

HUD31

SUBJECT 20 – ". . . localizer line is jerking about, gain much too great . . ."

SUBJECT 21 – ". . . (in response to an unrelated query about the possibility of having to use a reflector plate close to the face) I'd really rather have it farther away, especially in accident could tear your face away . . ."

SUBJECT 22 – ". . . may be lazy, like (H)11 . . . seems extreme movement of displacement of display . . . when below glidepath and flying up to it the display goes out of view, went head-down this time and saw speed drop below 120, potentially dangerous had (I) stayed head-up . . . like all symbology but extreme movement down is not good, this would completely destroy pilot loyalty . . ."

SUBJECT 23 – ". . . I like this one, seems easy to understand . . ."

SUBJECT 24 – ". . . seems awful sensitive . . ."

SUBJECT 25 – ". . . much more sensitive laterally, vertically and pitch (than H11, 21, 25) . . . extremely accurate close down, at T-zone . . . have feeling of lots of vertical movement in horizon, distracting, gives strange sensation . . . more sensitive to lateral than others . . . seemed to make greater corrections . . . easy to fly but don't like all the movement . . . tends to bring concentration to center, except localizer . . . ignore peripheral information . . . sensitive laterally . . . movement is distracting . . ."

SUBJECT 26 – (no comment)

SUBJECT 29 – (no comment)

SUBJECT 30 – ". . . odd to see whole display move up and down . . . capturing localizer hard once symbols move over to a side . . . swinging localizer line tends to cause vertigo . . . it is easier when visual . . . easy to get confused, as long as I am on the beam it is not difficult but when difficulties arise it is hard to get things back together . . . T-down (zone), both visual and display, tend to get lost when on horizon line . . . HUD11 was easy, HUD25 more difficult, and this one much more difficult . . ."

SUBJECT 31 – (no comment)

SUBJECT 32 – ". . . think master warning should be in center because it is so critical . . . very difficult to judge bank angle . . ."

SUBJECT 33 – ". . . like this display better than (H)25 or 11 . . . pretty interesting . . . nicest display . . . minimum clutter . . . like airspeed . . . easy to transition . . . speed error needs increments for faster reference . . ."

SUBJECT 34 – (no comment)

SUBJECT 35 – ". . . rapid movement is quite distracting . . . difficult to relate horizon, glide slope, and attitude . . . all circle type displays seem to eliminate error, especially laterally . . . when have positive controls to add seems to make workload heavier . . . reversed controls . . ."

APPENDIX F

DETAILED EVALUATION OF DISPLAY PROPERTIES

DISPLAY H11

Subject	A	B	C	D	E	F	G	H
	Property evaluated							
21	1	7	2	2	2	2	4	4
22	1	3	1	1	2	2	6	2
23	2	2.5	3	1	4	1	1	4
24	3	4	6	5	–	4	8	5
25	4	5	2	1.5	1	2	6	3.5
26	1	3	2	3	2	1	2	2
29	2	1	2	1	1	2	1	3
30	2	4	3	2	4	3	2	4
31	2	6.5	2.5	2.5	3	2.5	2	1
32	2	1	2	1	2	1	2	2
33	3	1	2	1	3	1	2	4
34	1	1	1	1	2	1	1	2
35	1	1	1	1	1	1	1	1

DISPLAY H21

Subject	A	B	C	D	E	F	G	H
	Property evaluated							
21	4	3	4	4	5	5	2	1
22	7	7	7	3	5	6	3	4
23	5.5	5	5	5	2	6	7	4
24	6	8	4	5	–	5	4	5
25	4	3	2.5	5.5	2	3	4	3.5
26	6	5	4	5	7	7	6	5
29	7	5	6	5	7	2	6	3
30	8	6	5	7	6	8	9	2
31	6.5	5	2.5	2.5	4	2.5	3.5	3
32	6	6	6	3.5	5	4	5	4.5
33	2	1	1	1	1	1	1	1
34	4	6	5	5	2	5	5	1
35	3	3	5	3	2	3	2	2

Key
- A Simplicity
- B Conformity
- C Situation visibility
- D Disorientation resistance
- E Monitoring capability
- F Interference resistance
- G Fixation resistance
- H Windshear capability

DISPLAY H25

Subject	A	B	C	D	E	F	G	H
	Property evaluated							
21	4	3	4	3	4	4	3	2
22	9	9	9	4	7	8	3	5
23	8	4	7	6	1	6	6	5
24	5	6	6	5	–	7	4	3
25	6.5	6	6	2	6	6	1.5	7
26	8	5	7	6	8	7	6	7
29	5	5	4	2.5	5	2	1	3
30	5	5	4	6	5	6	7	4
31	5	3	2.5	2.5	5	2.5	3.5	3
32	9	9	9	8	8	9	9	8
33	4	4	4	1	4	4	4	2
34	5	3	3	3	2	2	2	3
35	9	8	7	9	8	9	9	6

DISPLAY H31

Subject	A	B	C	D	E	F	G	H
	Property evaluated							
21	2	6	3	2	3	2	3	1
22	4	5	3	2	3	3	4	3
23	1	5	1	2	5	1	2	1
24	4	3	4	5	–	3	7	5
25	5	3	4.5	2	2	6	4	1.5
26	5	4	6	5	6	5	7	5
29	3	5	4	2.5	2	2	1	3
30	4	5	3	3	5	3	2	4
31	1	1	2.5	2.5	2	2.5	1	5
32	5	6	7	5	5	5	5	4.5
33	1	3	1	1	2	1	1	3
34	3	5	4	5	2	3	3	1
35	7	8	9	8	8	8	8	7

Key
- A Simplicity
- B Conformity
- C Situation visibility
- D Disorientation resistance
- E Monitoring capability
- F Interference resistance
- G Fixation resistance
- H Wind shear capability

APPENDIX G

TRAINING RUN SCHEDULE

3° approaches from 1200 ft height. Breakout at 600 ft. Visibility 12,000 ft.
Visual events (Task 2) presented in alternate order (1, 2).

Run	Offset, ft	Turbulence, f/s rms	Shear, wind no.	Task 2
1	+200	—	—	1
2	+200	—	—	2
3	-200	—	—	1
4	-200	—	—	2
5	—	1.5	—	1
6	—	4.5	—	2
7	—	4.5	W32	1

Note: after each run the subject was asked if he was satisfied with his performance and understanding of the format. If not, the run would be repeated. Finally, the subject was considered to have become familiarized with the display when it was seen that he made no reversals, and recorded no large tracking errors.

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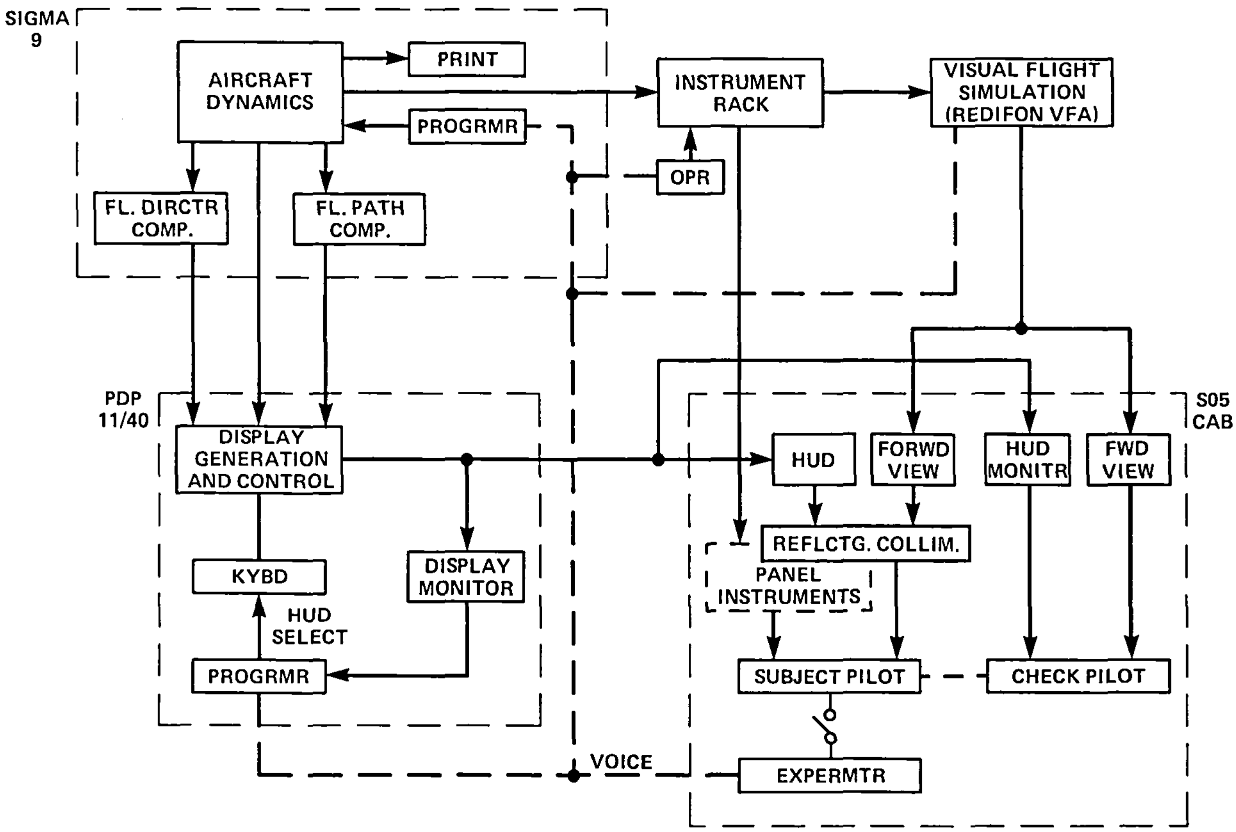

Figure 1.– Arrangement of experimental equipment.

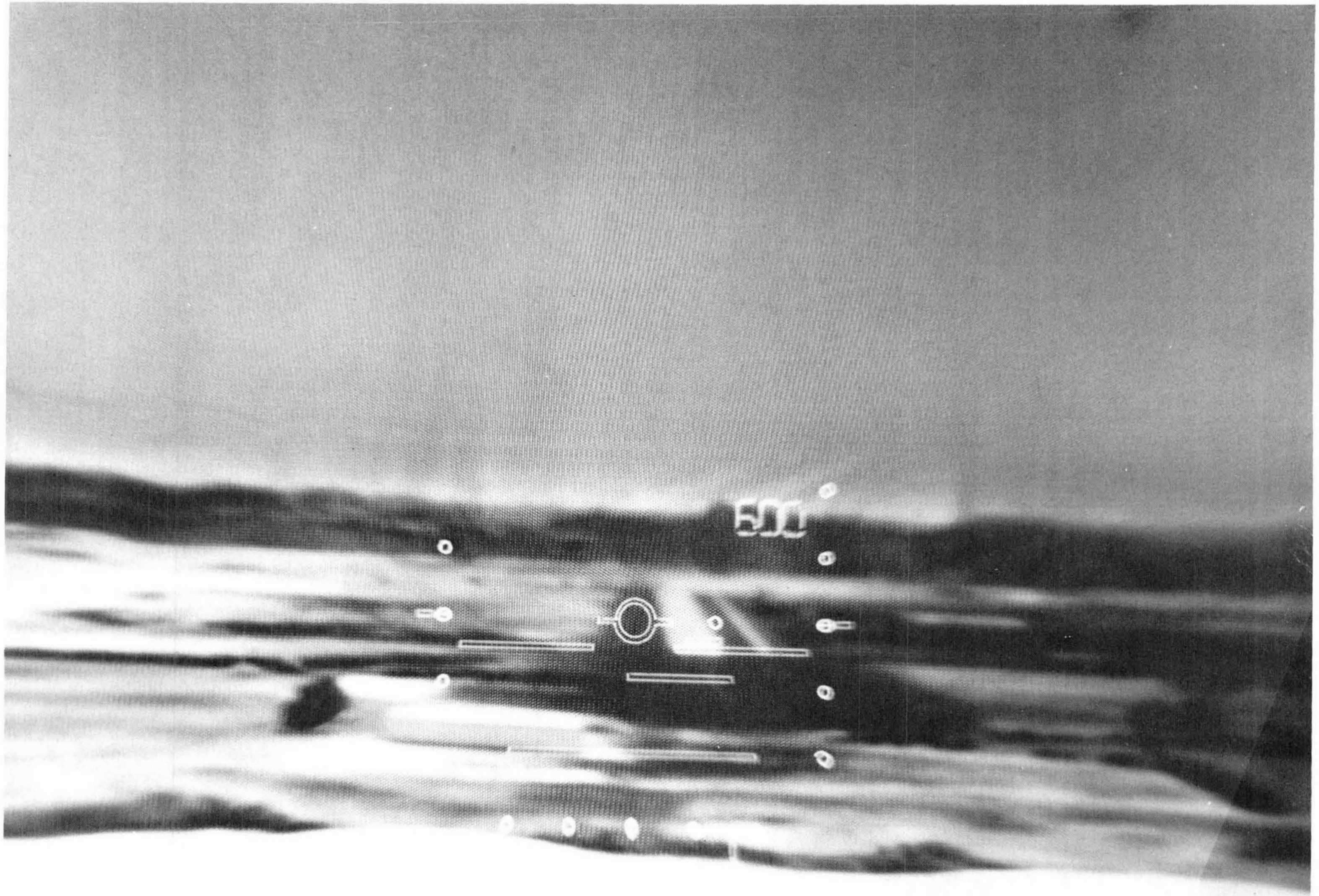

Figure 2.– H11 format and forward view.

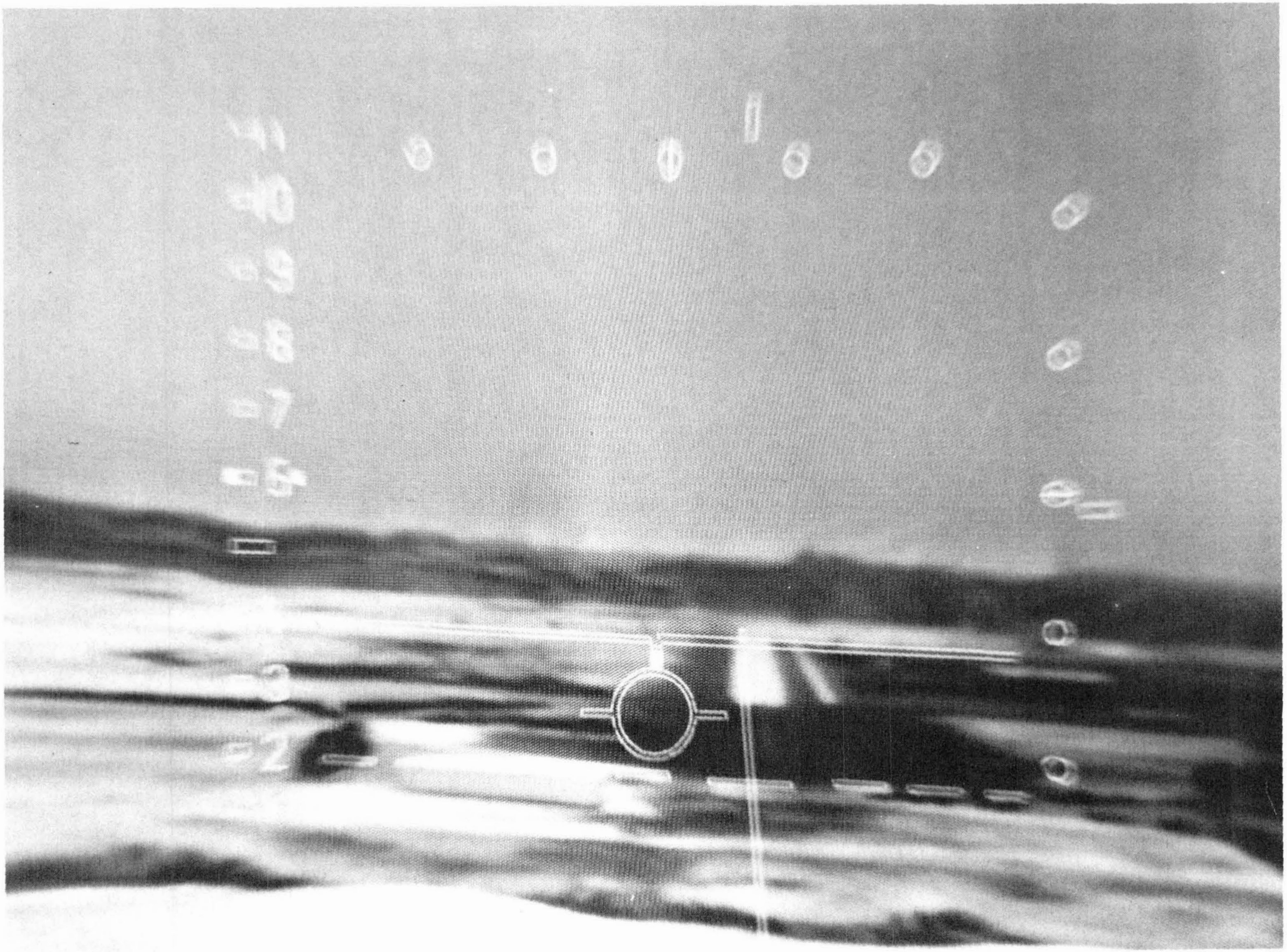

Figure 3.– H21 format and forward view.

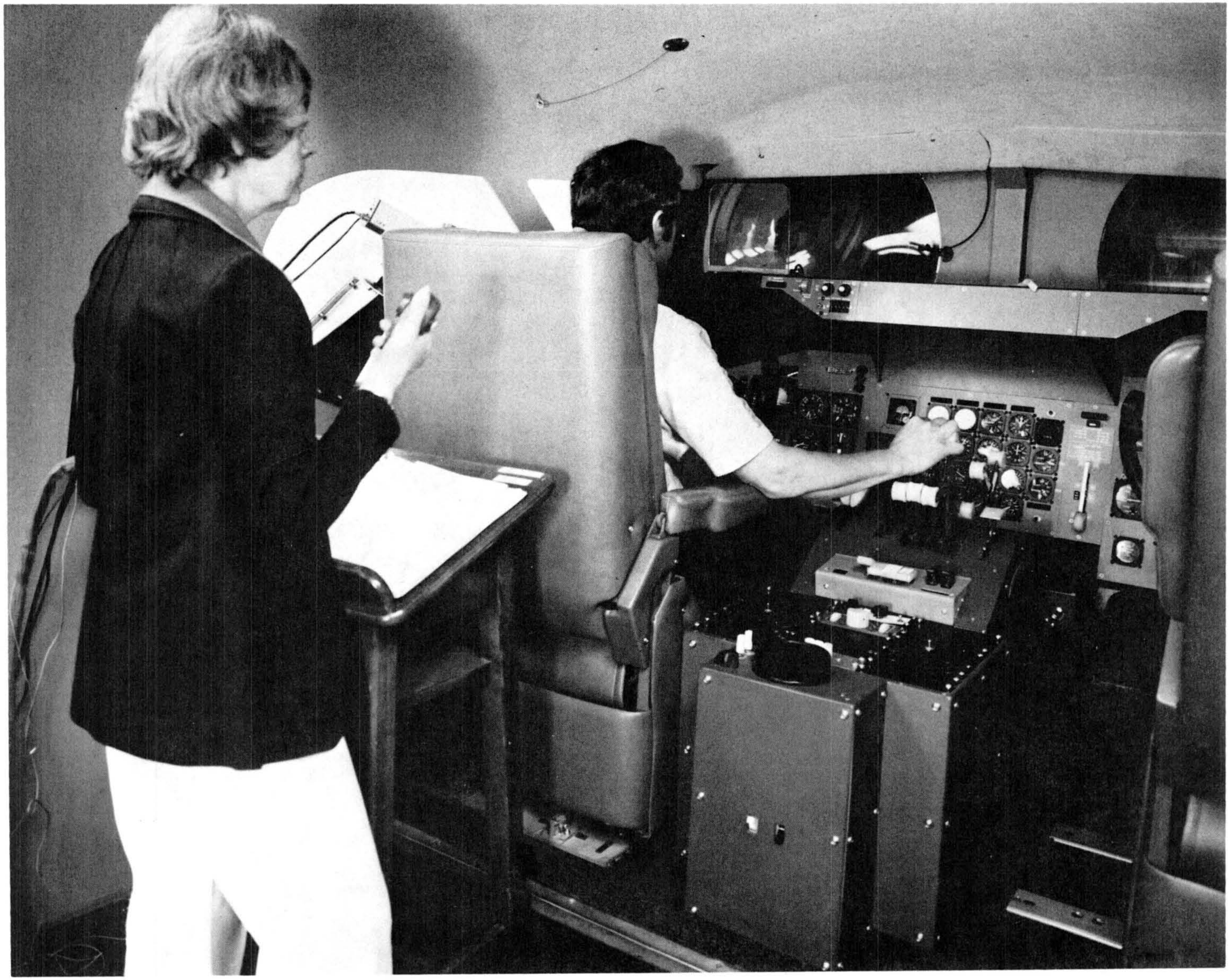

Figure 4.– Cockpit layout.

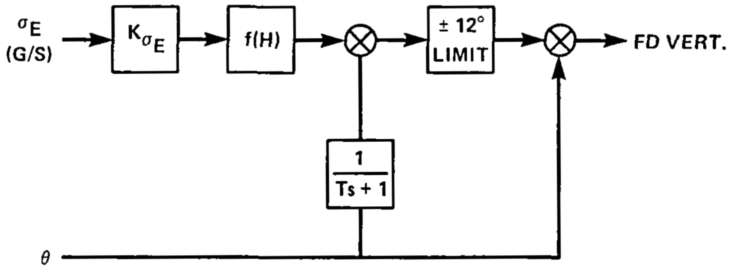

Figure 5.– Vertical flight director drive.

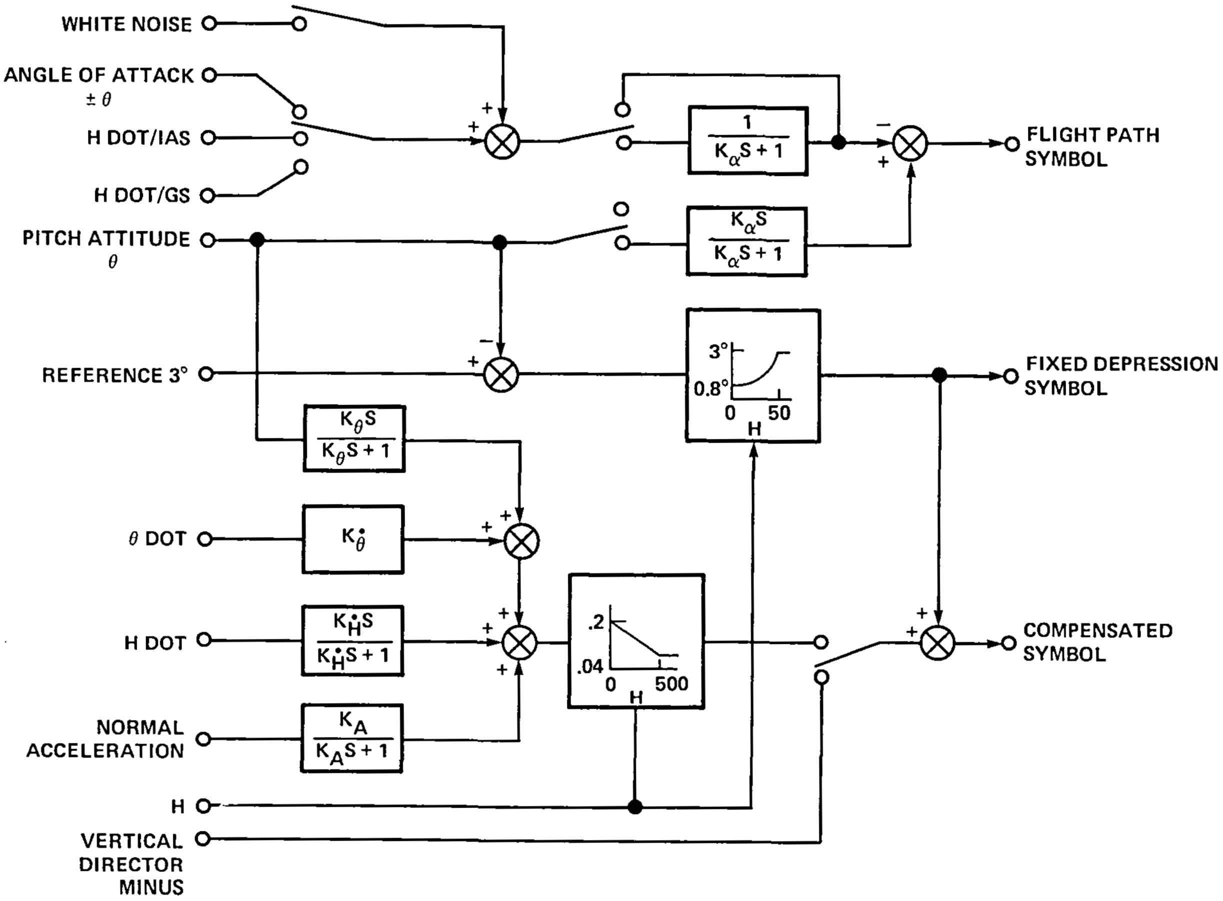

Figure 6.– Vertical drives for flightpath displays.

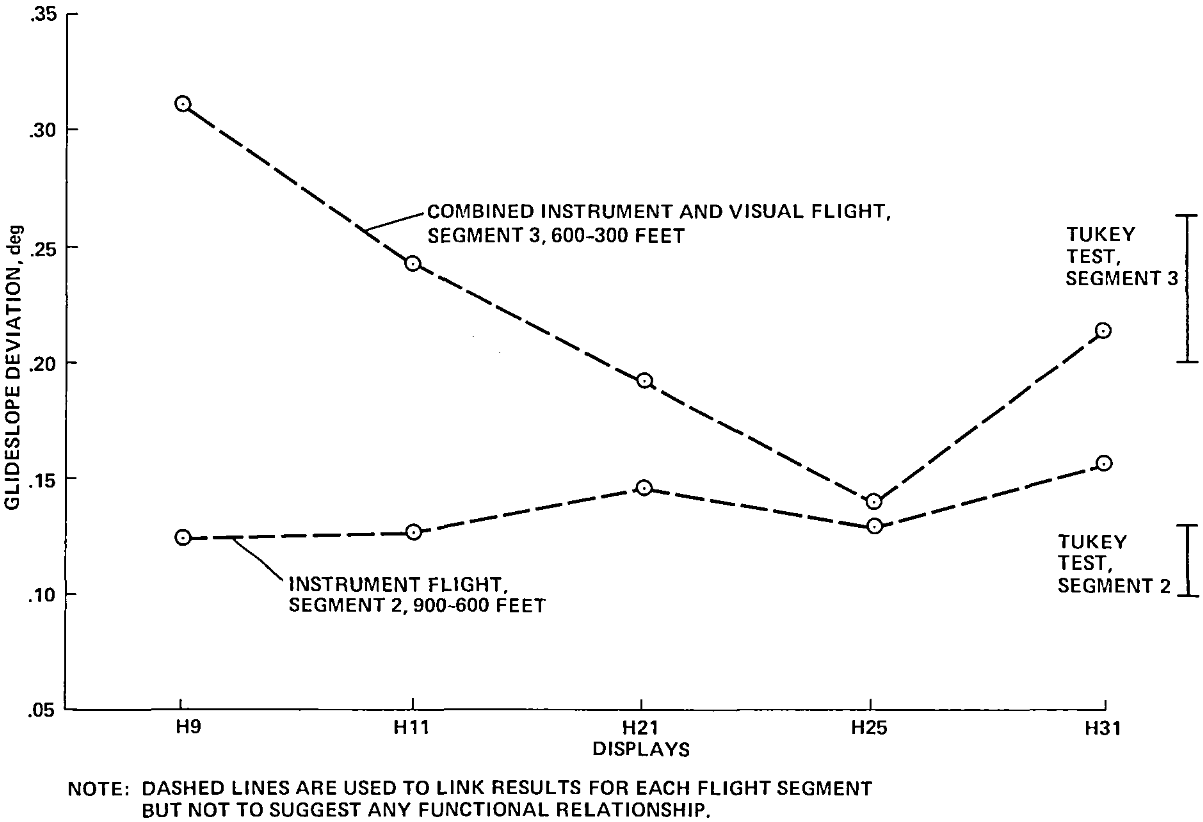

Figure 7.– Tracking means for second and third flight segments.

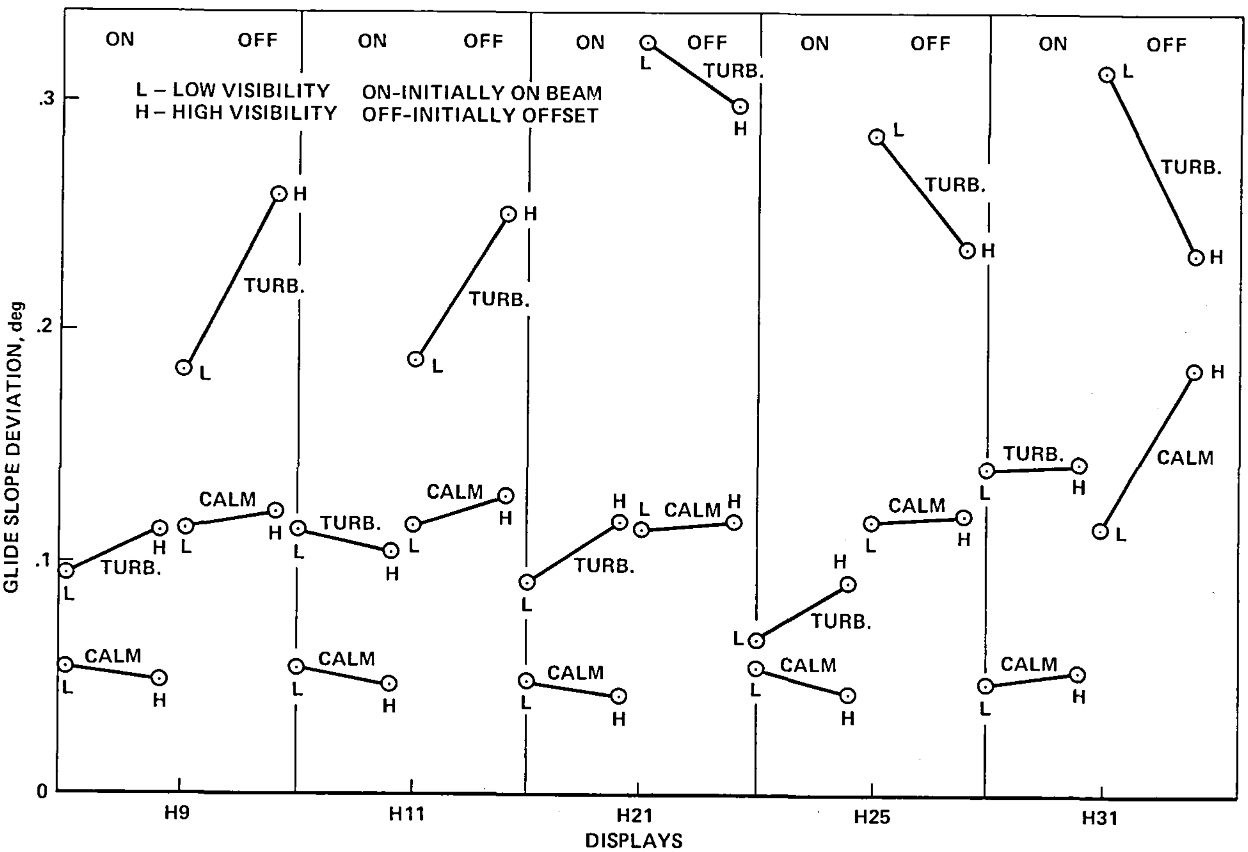

Figure 8.– Tracking interaction of displays and conditions in instrument flight, Segment 2.

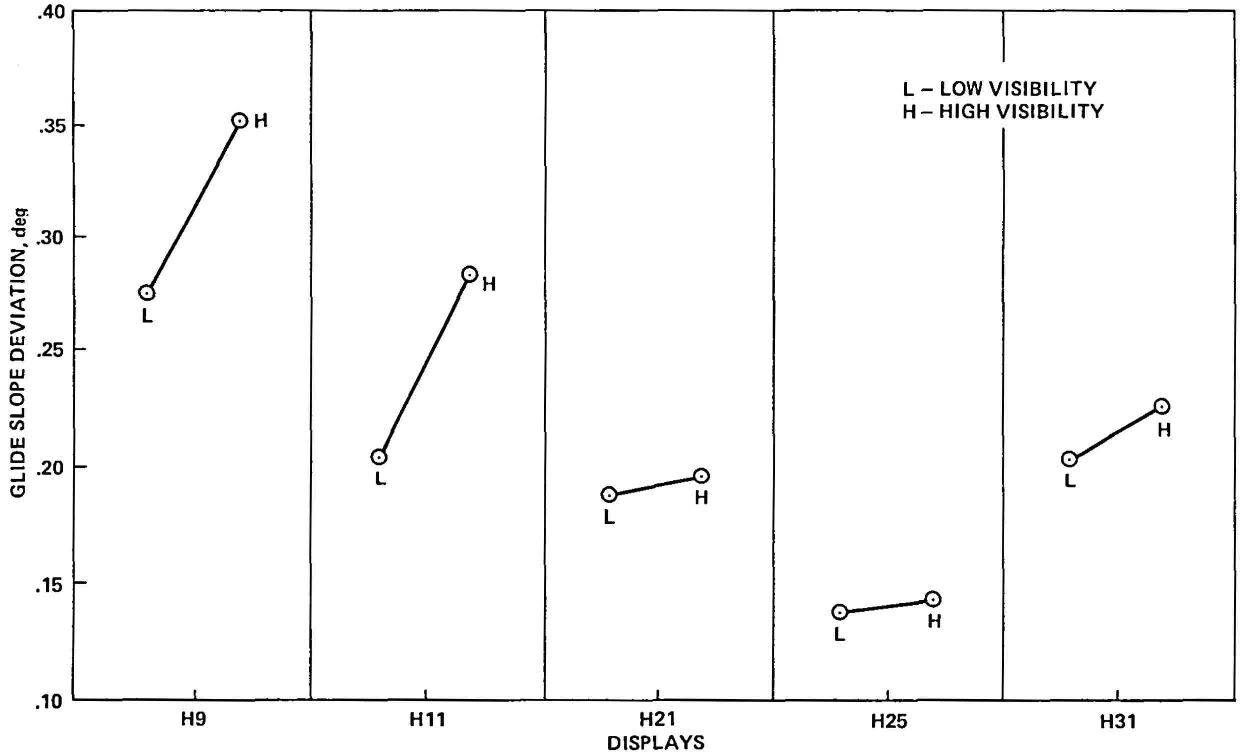

Figure 9.– Tracking interaction of displays and visibility in combined instrument and visual flight, Segment 3.

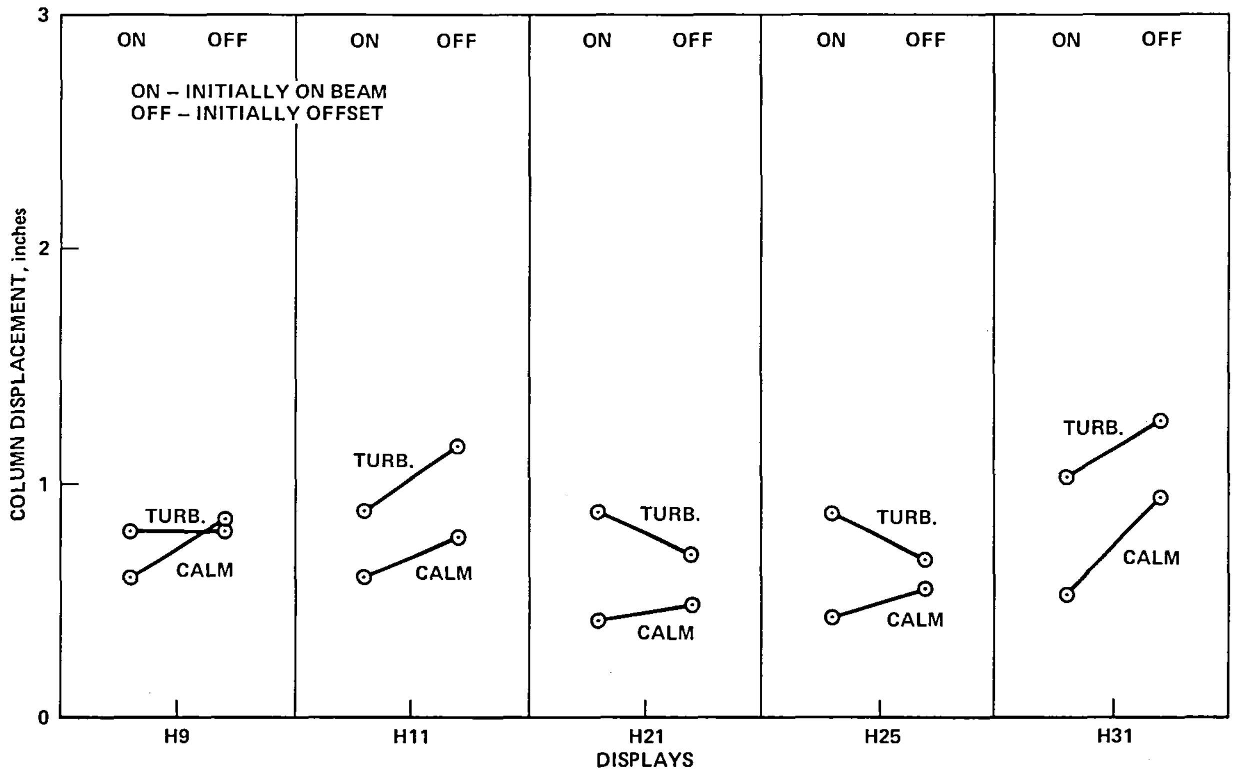

Figure 10.– Workload interaction of displays and conditions in instrument flight, Segment 1.

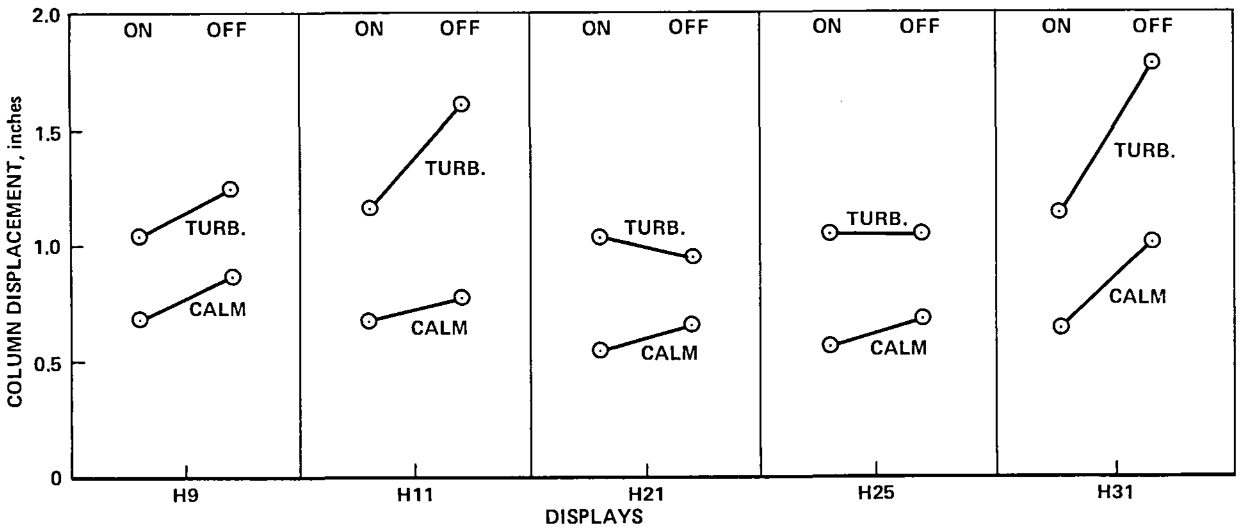

Figure 11.– Workload interaction of displays and conditions in instrument flight, Segment 2.

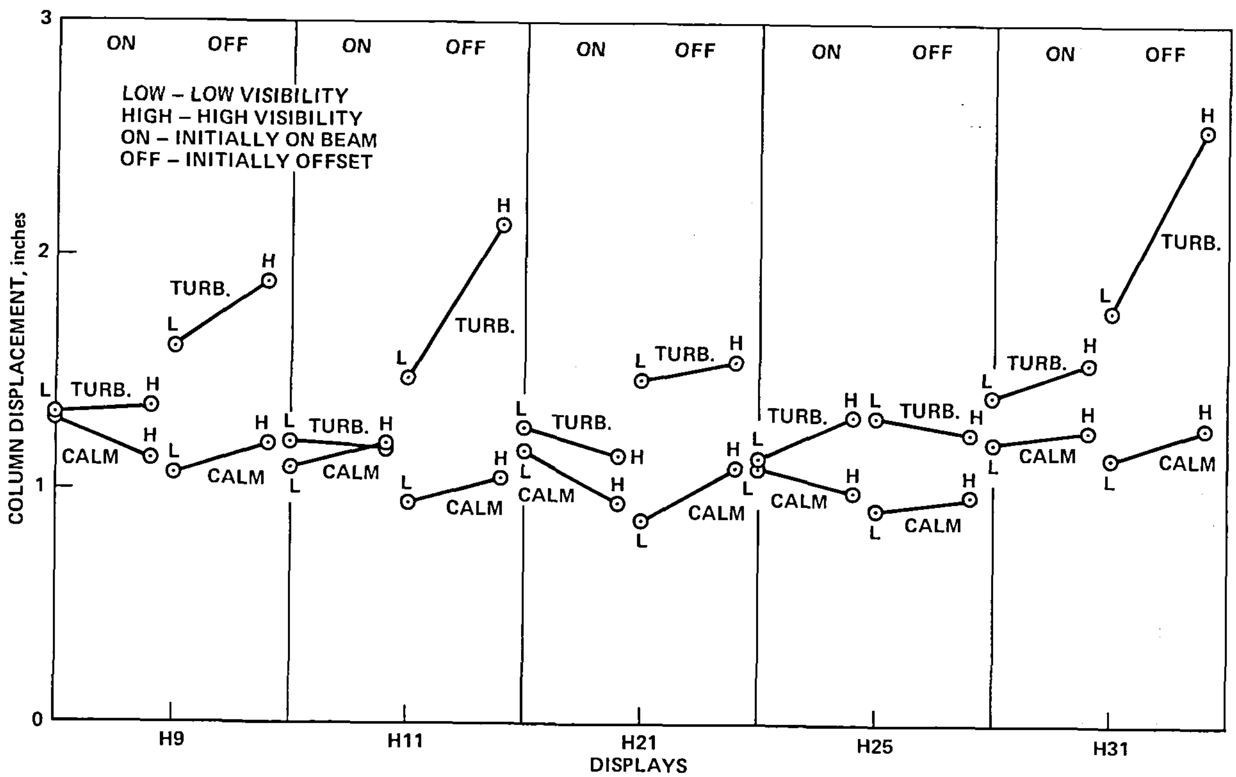

Figure 12.– Workload interaction of displays and conditions in combined instrument and visual flight, Segment 3.

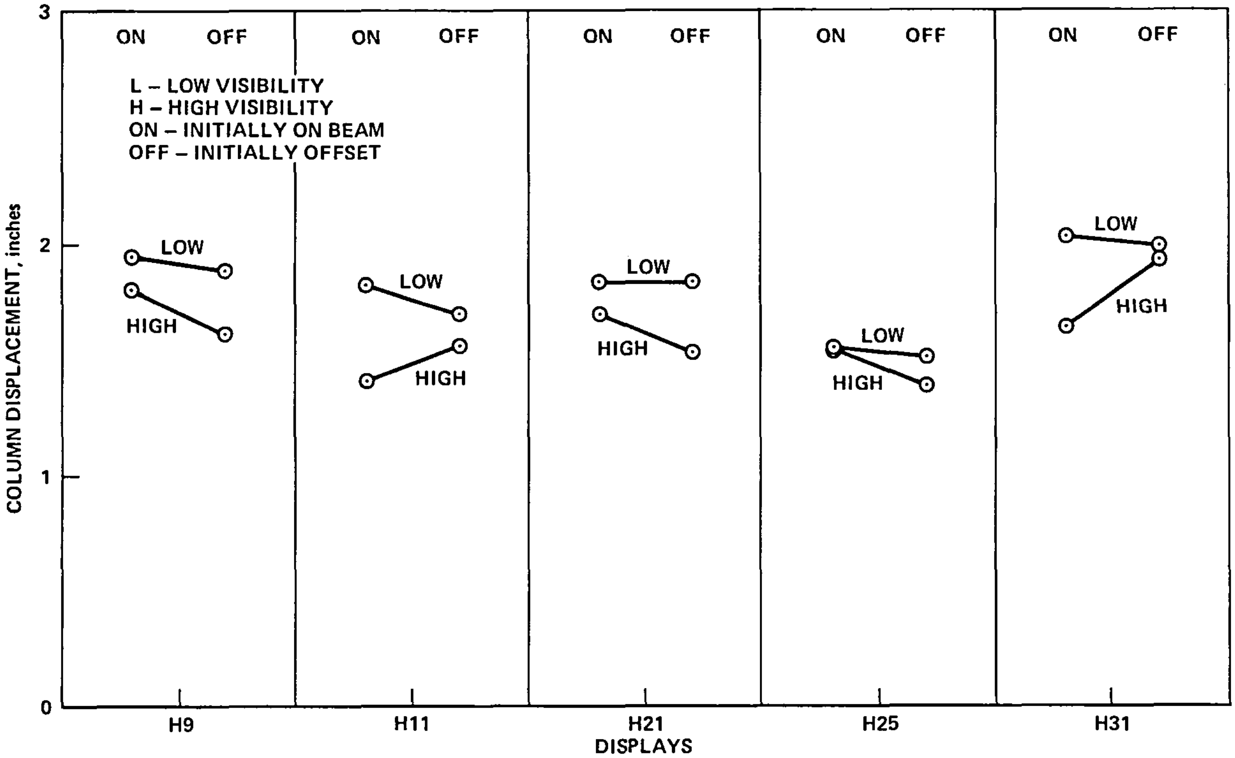

Figure 13.– Workload interaction of displays and conditions in combined instrument and visual flight, Segment 4.

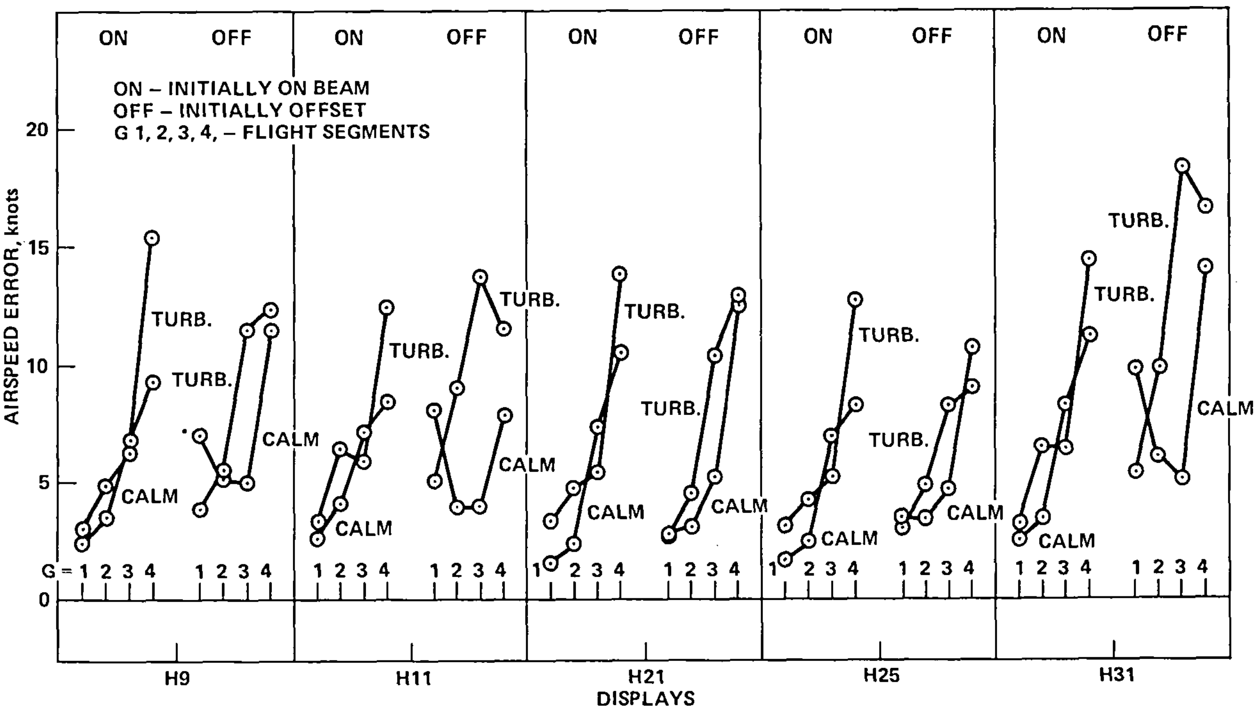

Figure 14.– Airspeed error interaction of displays and conditions and flight segments.

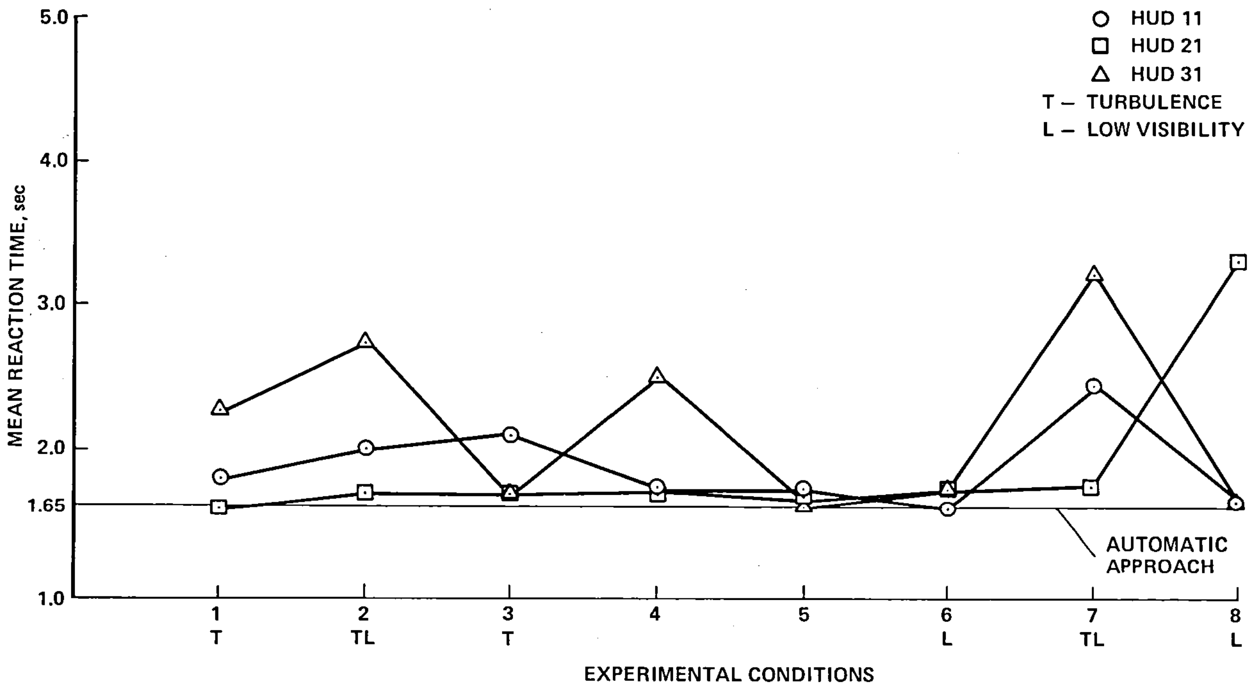

Figure 15.– Response to HUD warning symbol.

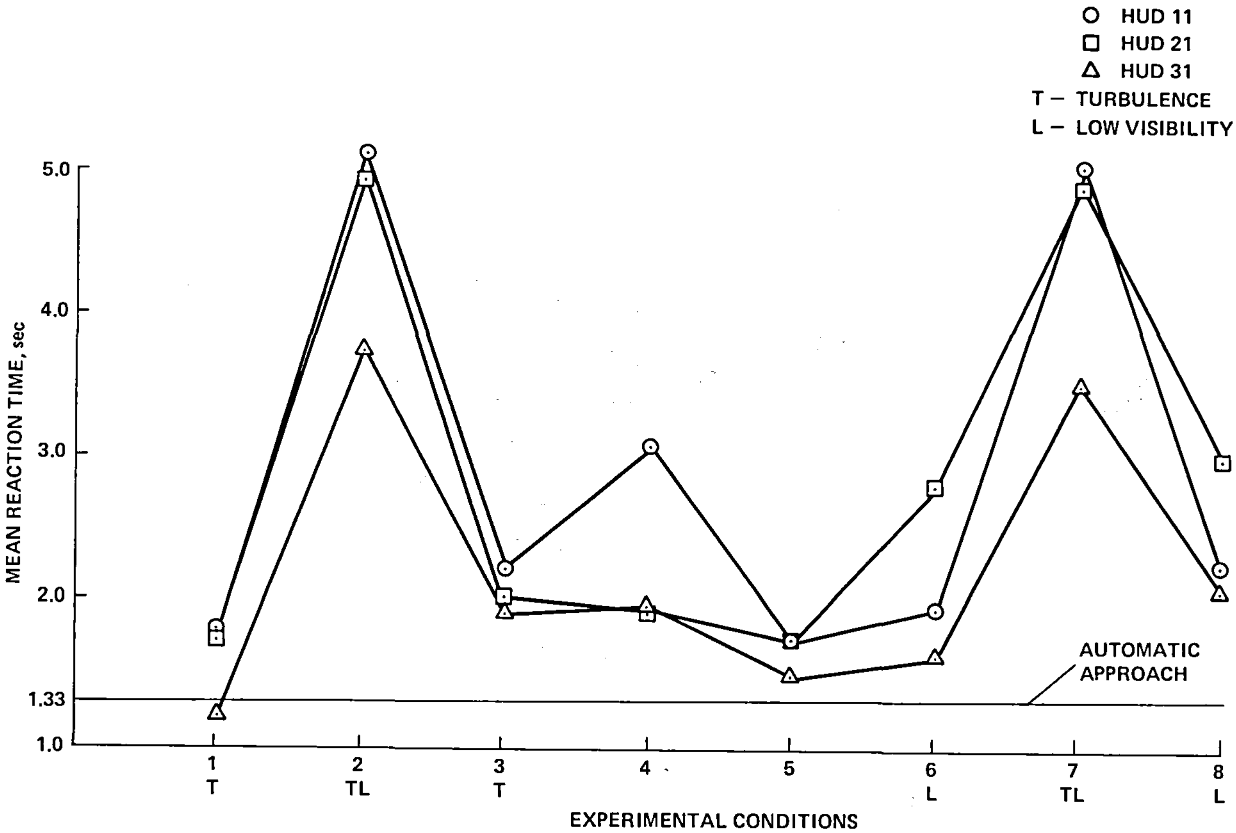

Figure 16.– Response to external stimulus.

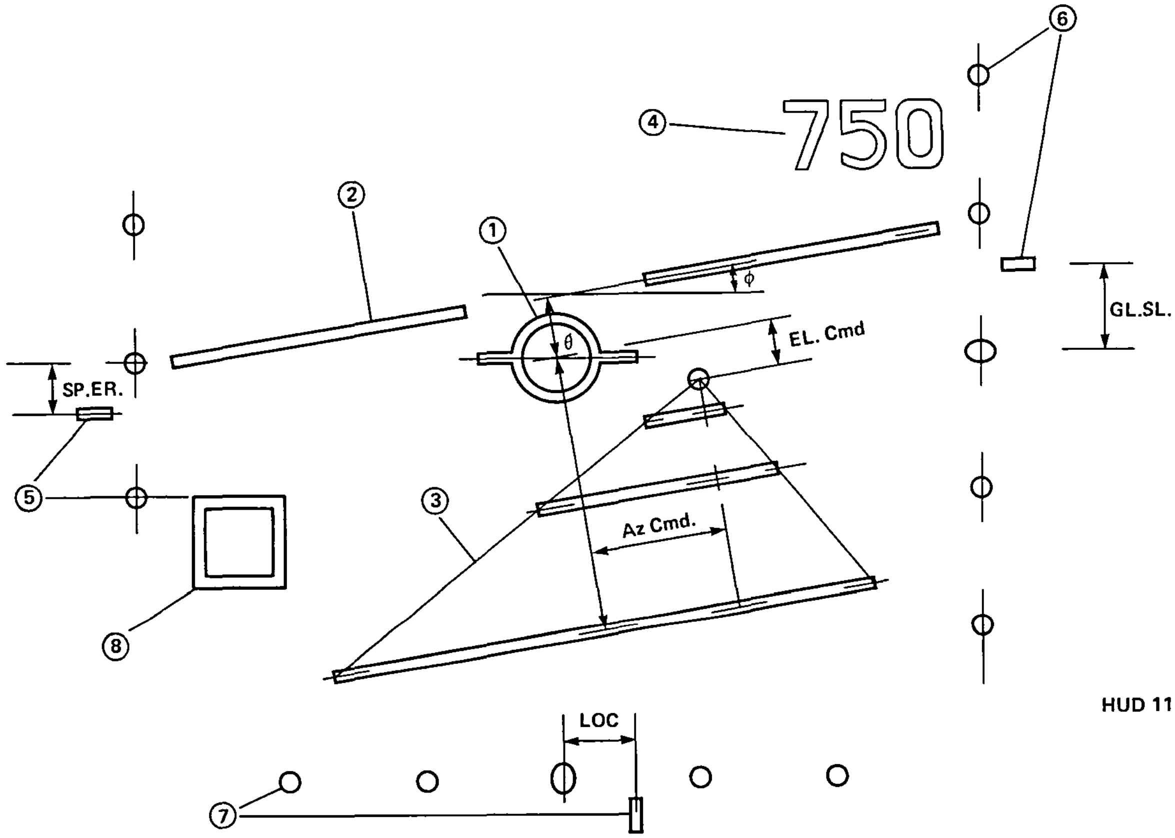

Figure 17.–HUD11 format.

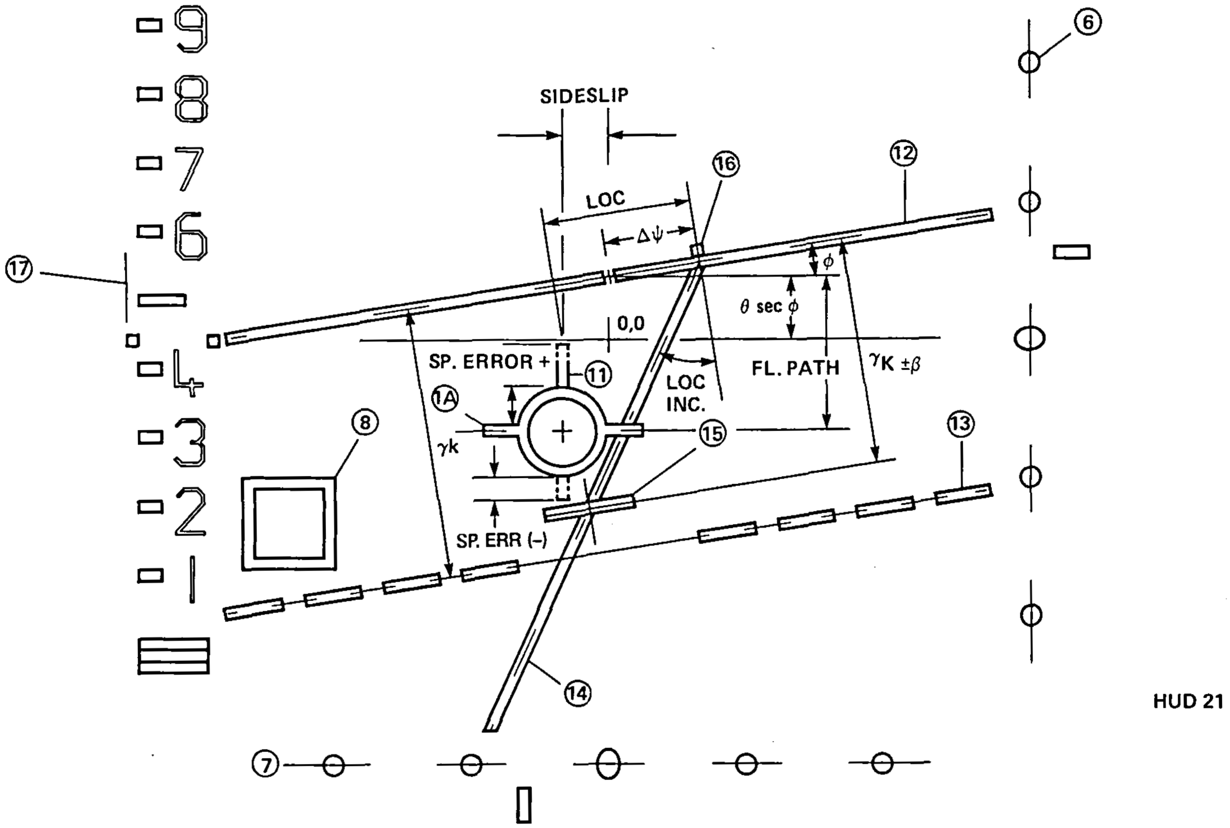

Figure 18.– HUD21 format.

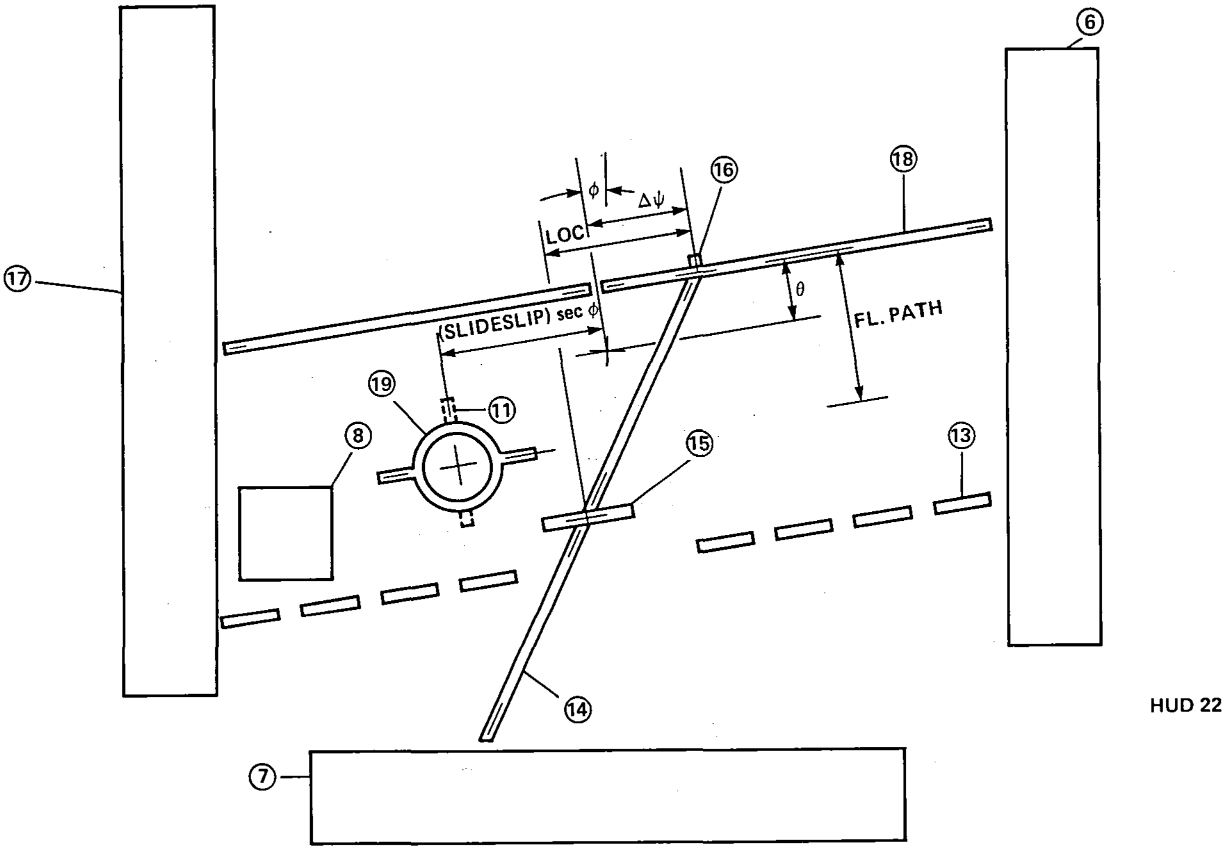

Figure 19.– HUD22 format.

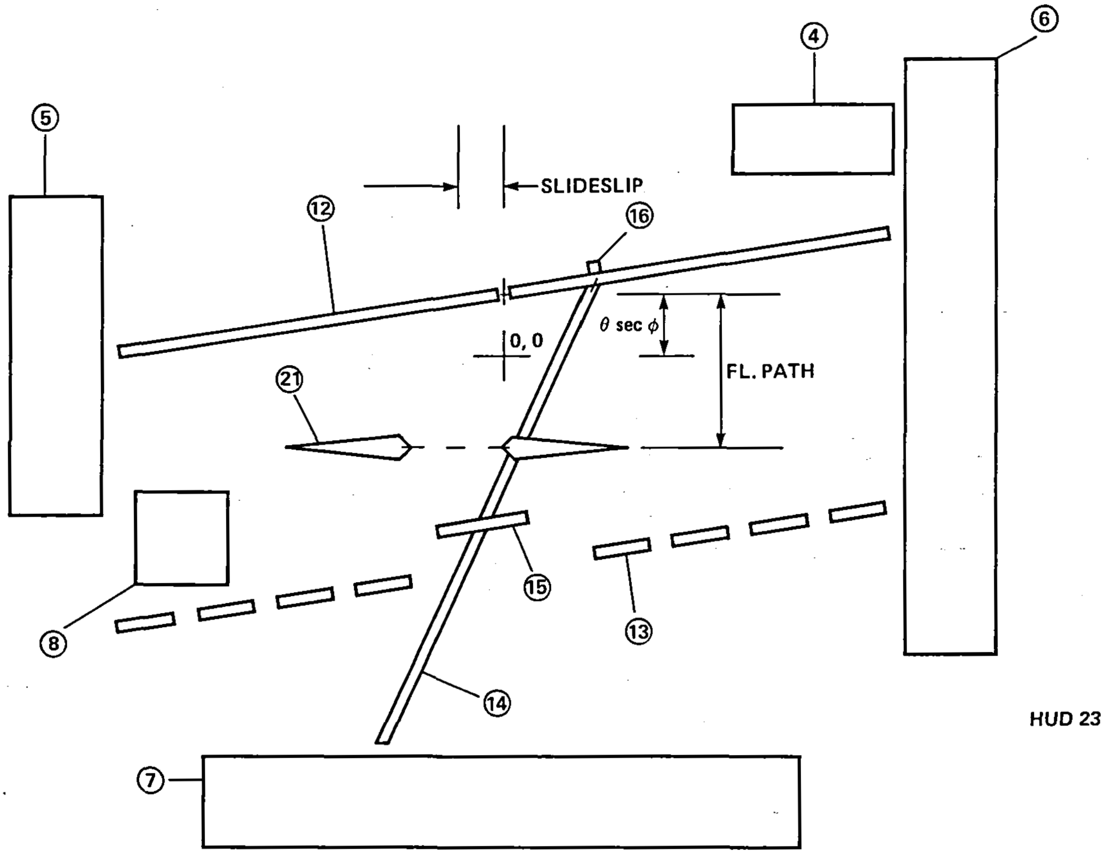

Figure 20.– HUD23 format.

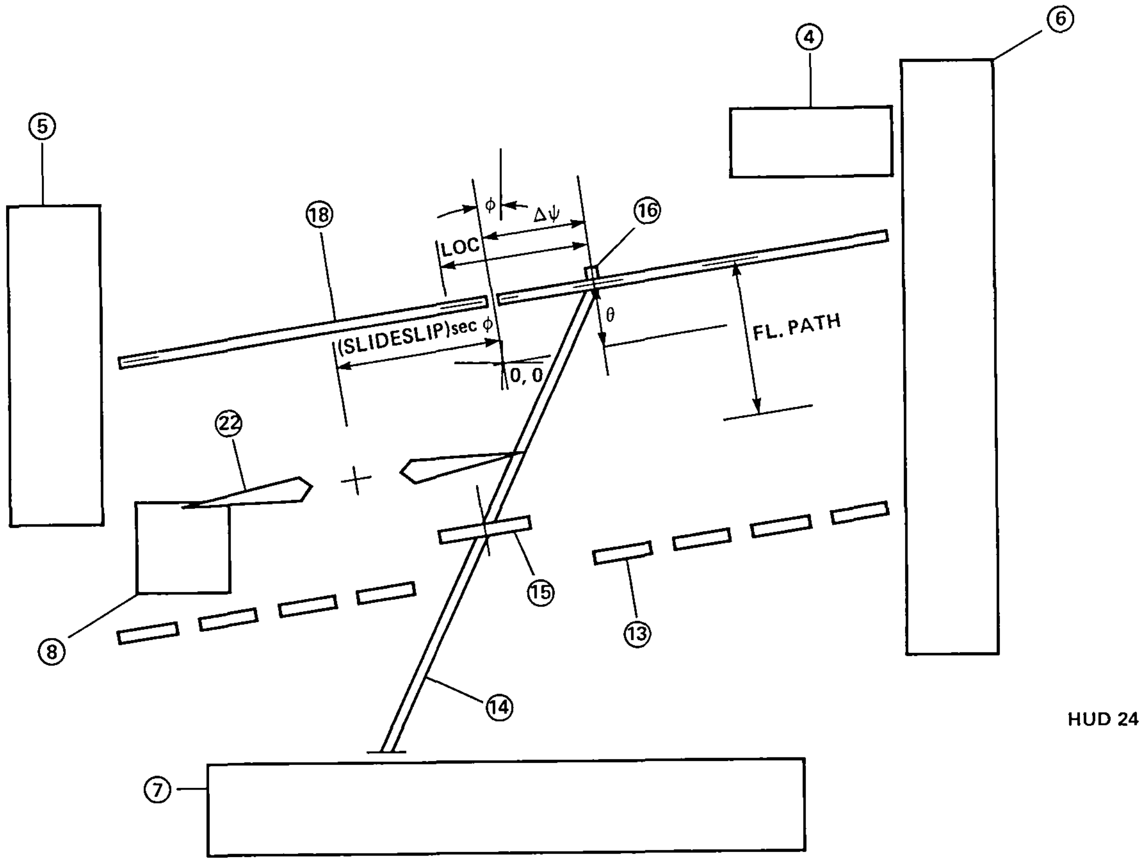

Figure 21.– HUD24 format.

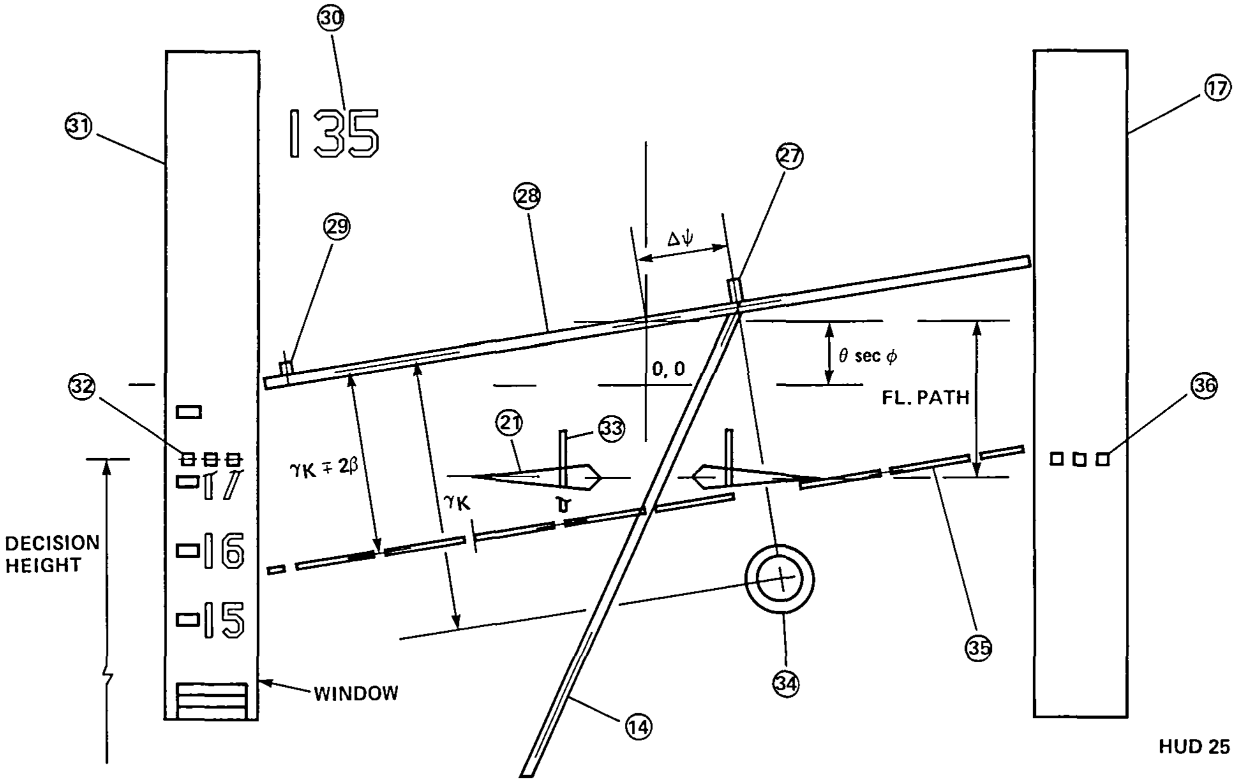

Figure 22.– HUD25 format.

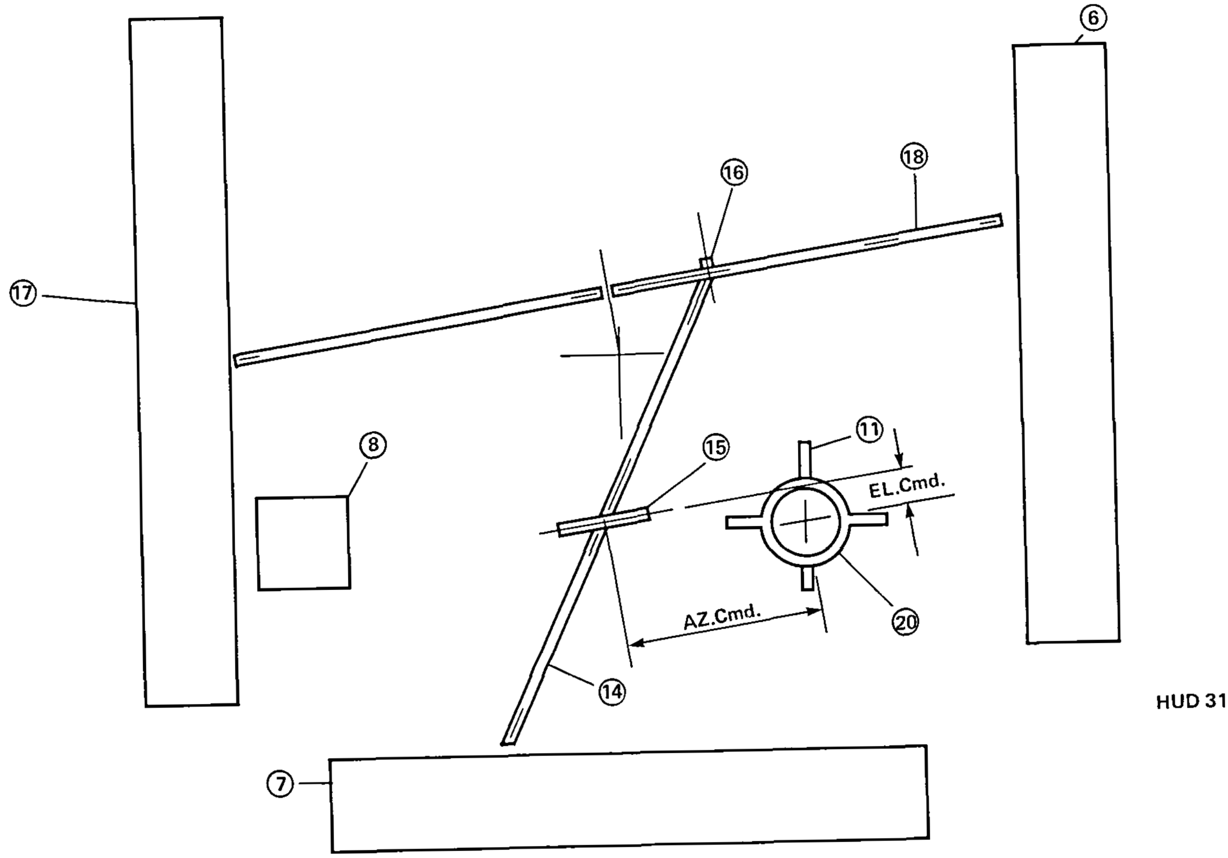

Figure 23.– HUD31 format.

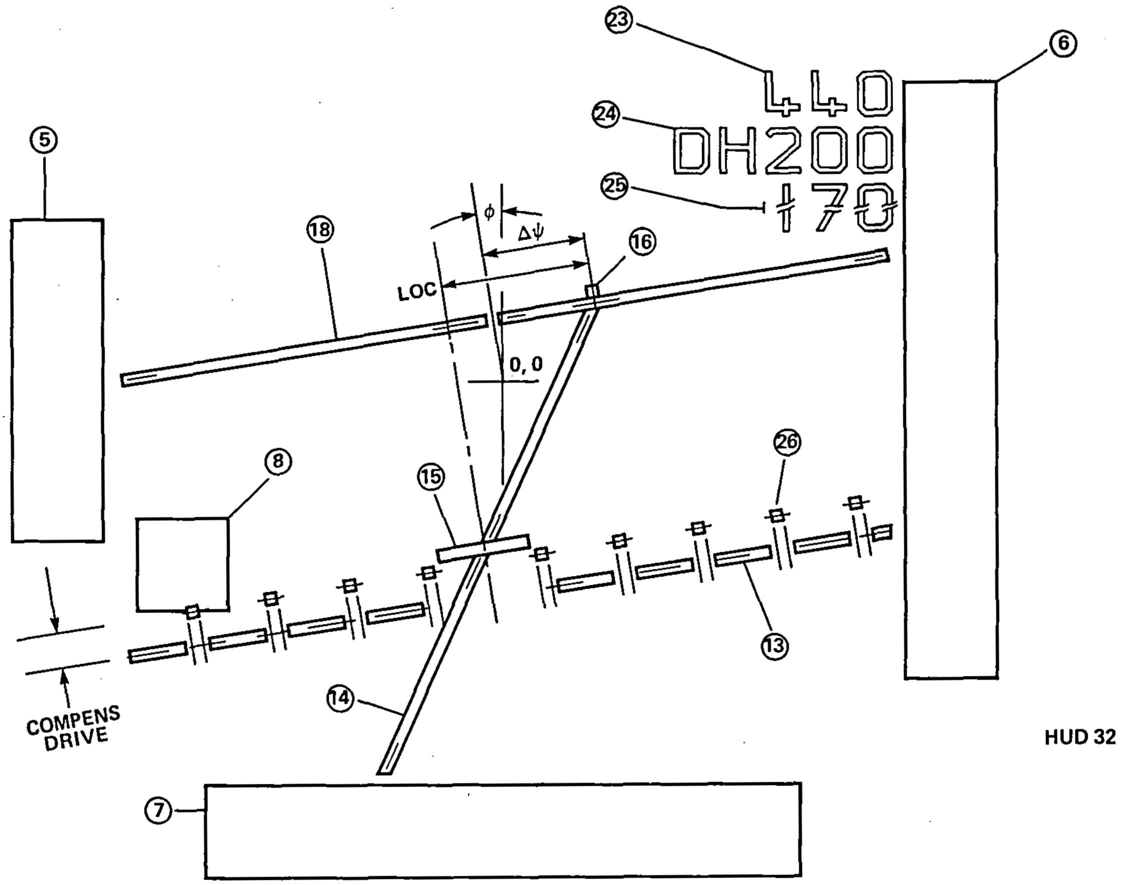

Figure 24.– HUD32 format.

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16. Abstract
The investigation deals with three types of head-up display format in which there are differences in the choice of framework and in the kind of information processing used to form driving signals. Type 1 is an unreferenced (conventional) flight director. Type 2 is a ground referenced flightpath display. Type 3 is a ground referenced director. Formats are generated by computer and presented by reflecting collimation against a simulated forward view in flight. The subjects are pilots holding commercial licenses, who fly approaches in the instrument flight mode and in a combined instrument and visual flight mode. The approaches are in wind shear with varied conditions of visibility, offset, and turbulence. Tracking accuracy is measured as vertical path error and workload as column displacement. Speed error is also measured. Comments and answers to a questionnaire are recorded. Displays are placed in rank order by subjects and display properties are evaluated. As a secondary task subjects respond to visual events in HUD and in the external scene to illustrate transition between these two fields.

To all practical purposes, displays are equivalent in pure tracking but there is a slight advantage for the unreferenced director in poor conditions. Flightpath displays are better for tracking in the combined flight mode, possibly because of poor director control laws and the division of attention between superimposed fields. Workload is better for the Type 2 displays. The flightpath and referenced director displays are criticized for effects of symbol motion and field limiting. In the subjective judgment of pilots familiar with the director displays, they are rated clearly better than path displays, with a preference for the unreferenced director. There is a fair division of attention between superimposed fields.

17. Key Words (Suggested by Author(s))
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Symbol format
Human factors
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