A HEAD-UP DISPLAY FORMAT FOR TRANSPORT AIRCRAFT APPROACH AND LANDING

Richard S. Bray
Ames Research Center

Barry C. Scott
Federal Aviation Administration

SUMMARY

An electronic flight-guidance display format was designed for use in evaluations of the collimated head-up display concept applied to transport aircraft landing. In the design process of iterative evaluation and modification, some general principles, or guidelines, applicable to electronic flight displays were suggested. The usefulness of an indication of instantaneous inertial flightpath was clearly demonstrated. Evaluator pilot acceptance of the unfamiliar display concepts was very positive when careful attention was given to indoctrination and training.

INTRODUCTION

The electronic flight-guidance display discussed in this paper was developed for use in a NASA/FAA program studying the potential benefits and problems associated with the application of head-up displays (HUD) to landing operations of civil-transport aircraft. Another paper in these proceedings (ref. 1) reports the reactions and performances of airline pilots using this display in flight-simulation experiments. It is the purpose of this paper to describe the display and its development and to point out the factors that influenced its design. The display format evolved over a period of several years in a process that included iterative evaluations in flight simulators. Initial formats borrowed significantly from military HUD experience and from the very limited experience with HUD in transport-category aircraft. Experience with these formats in flight simulation inspired many modifications, and in the process some basic "design principles" were suggested. The experimental displays were designed to function as the pilot's primary instrumentation in a broad range of operational situations, not just the final approach; thus, it is probable that many observations discussed are appropriate to forms of integrated electronic flight-guidance displays other than HUD.

After a brief description of the simulator facilities and procedures used in the development process, this paper addresses the HUD symbology content as influenced by the flight modes in which it is to be used. The logic employed in the dynamics of some of the display elements is described, and the pilot's use of the full display in several types of approaches is demonstrated. The design of selected display elements is discussed to substantiate suggested HUD design principles. The paper concludes with observations regarding a few unresolved questions exposed in the simulator exercises and the training requirements associated with new display concepts.

TEST FACILITIES AND PROCEDURES

Simulation

Equipment- Most of the simulator tests were conducted in the Ames Flight Simulator for Advanced Aircraft (FSAA), which incorporates a transport-type cockpit on a larger amplitude six-degree-of-freedom cockpit motion system. In this simulator, a *Redifon* TV-model board visual simulation system provides a 46° by 34° representation of the forward view of the terrain from the cockpit.

The optical collimating system of the cockpit visual simulation display was used to provide the collimated head-up instrumentation display superimposed upon the outside scene. The physical arrangement is illustrated in figure 1. In a flight installation, the display system must place the optical combiner relatively close to the pilot's eyes to present a satisfactory field of view with equipment of practical size. For some of the simulator tests, a dummy combiner having typical combiner transmissivity was mounted as shown in figure 1. With or without the dummy combiner, the binocular field of view of the HUD was 24° wide and 18° high and it was not affected by head motion. The HUD display written on the cockpit cathode ray tube (CRT) was generated by a general purpose computer-graphics system linked to the similator computer. An example of the pilot's visual scene, including the HUD, is illustrated in figure 2.

Aircraft models- The initial simulator tests utilized a dynamic model of the Boeing 737 airplane, but the more recent work was conducted with a simulation that incorporates the flight dynamics of the Boeing 727-200 airplane. The simulations were optimized for dynamic fidelity in approach and landing maneuvers. Instrument landing system (ILS) approach-coupling and autoland capability were provided with the 727 model.

Simulation of landing environments- The objectives of the display development called for efforts to simulate with some fidelity the reduced-visibility conditions accompanying low clouds and fog. Appropriate selective electronic occlusion of the simulated visual scene provided constant or varying visual conditions to as low as a 150-m (~500-ft) runway visual range (RVR). In addition to standard wind, wind-gradient, and turbulence models, a library of discrete atmospheric disturbances (shears and downdrafts) was utilized. In some instances, shear and downdraft profiles were combined with intermittent visibility conditions to simulate conditions known to be associated with specific aircraft accidents.

Evaluation Procedures

In general, the evaluation procedures during the development of display formats were considerably less formal than those of the "operational evaluation" reported in reference 1. After an experimental display format had been assembled and tested by the Ames project staff, engineering pilots from the air transport industry and the Federal Aviation Administration (FAA) were invited to participate in the simulations and offer their evaluations and suggestions for improvements. In all the evaluations, a variety of approach types and environmental situations were experienced with and without the HUD. Without the HUD, approaches were conducted with instrument panel displays including an attitude-director indicator (ADI) and a horizontal situation indicator (HSI) typical for the aircraft and operation categories. Performance of the simulated aircraft and comments of the evaluator pilot were recorded. Over the past several years, about 250 hr of piloted simulation have been devoted to development of the subject display. At least 20 industry and government-agency pilots have participated in the extended evaluation sessions, and more than twice that number have experienced less extended exposure to the HUD simulations.

HUD DESIGN CONSIDERATIONS

Introduction

Two interrelated design objectives characterize the evolution of a head-up display. The first involves the *superposition* of displayed information on the outside scene to form unique flight-guidance information in visual meteorological conditions (VMC). The allied objective is the optimal *integration* of attitude, energy, and guidance information, taking advantage of the electronic medium and modern sensors to provide the pilot with the means for improved precision of control in low-visibility approach and landing. The following discussion uses the particular details of the subject HUD to demonstrate how these objectives can be met. It should be pointed out that the individual logics and symbology details utilized in the display are not claimed to be unique to this display nor are they claimed to be uniquely effective, but simulation experience to date indicates that they do meet the design objectives. A complete technical description of the display is the subject of reference 2.

Military experience (particularly with the Viggen in Sweden), experimental work with head-up displays in transport-category aircraft in France, and experience with the panel-mounted electronic display of the Terminally Configured Vehicle (TCV) program at the Langley Research Center have demonstrated the virtues of a representation of the instantaneous direction of flight of the airplane (flightpath symbol) relative to visible earth references. To provide this "conformality," attitude information of a quality normally associated with inertial navigation systems (INS) is desired. The following discussion assumes the availability of such information, as well as inertial velocity and acceleration data sufficient to determine vertical flightpath angle and ground-track angle relative to heading. A later discussion addresses the options available when inertial velocity information is nonexistent.

Approach Guidance

VMC glidepath control- The most obvious method of providing precise VMC glidepath guidance with a conformal display of flightpath is illustrated in figure 3. A "fixed-depression" line below the horizon is utilized to determine whether the aircraft is above or below the intended glidepath. In figure 3(a) the aircraft is above the intended glidepath of -3° and is in level flight. In figure 3(b) the flightpath of the aircraft is being directed at a point short of the runway, thus descending toward the desired glidepath. As the -3° line lowers to the intended touchdown point, the flightpath symbol is raised to aim at the touchdown point (fig. 3(c)). If necessary the flightpath is adjusted further to maintain the -3° line on the touchdown point. The effectiveness of this scheme has been thoroughly demonstrated in flight by G. Klopfstein of the French Air Force (ref. 3) and more recently in the Calspan T-33 airplane associated with the Air Force/Navy Display Evaluation Flight Test (DEFT) program in this country. With the visible runway, lateral lineup is assumed to be straightforward, requiring no additional aids. However, the indication of track does offer increased precision in the lateral steering mode.

IMC guidance- As might be deduced from figure 3, instrument meteorological conditions (IMC) guidance can be provided by a symbolic representation (in true perspective and location) of the runway. Such a symbol can be constructed from the ILS glide-slope and localizer error measurements, together with range-to-runway information either measured directly or deduced from the altitude above the runway and the ILS error. In fact, Klopfstein's display functions in just this manner in the IMC mode.

With the subject display, however, it was desired to explore a more explicit form of guidance, one that did not depend on the symbolic runway remaining in the display field of view. The guidance concept chosen is illustrated in figure 4. ILS localizer error is indicated by the lateral displacement of a display element with respect to the approach course heading reference, as shown in figure 4(a). Glide-slope error is indicated by the vertical displacement of another element with respect to the horizontal elements 3° below the horizon (or the path angle of the ILS system in use). These error indications are gained so that they combine to define a point in the visual field that corresponds to a position of an object on the ILS glidepath approximately one-fifth of the distance from the aircraft to the runway. The explicit guidance principle inherent in this error-display concept is illustrated in figure 4(b). By directing the flightpath of the aircraft at the combined error indication (i.e., flying a "pursuit course" at the symbolic moving point on the approach path) a convergence to the path is effected, and the aircraft falls in trail "behind" the ILS symbology on the desired path (fig. 4(c)). The same guidance principle appears in a newer French HUD development (ref. 4). A symbolic runway is shown in these figures to assist in illustrating the guidance principle, but it is not essential to the pilot's control task. It was retained in the display for its contribution to "situation awareness."

Energy Management

To this point, the basic-approach guidance functions of the display in IMC and VMC have been defined. Displays of energy state are now required in order to provide the desired independence of instrument panel information while using the head-up display. As shown in figure 5, four separate items of information, three of which are normally found on the instrument panel, are added in association with the flightpath symbol, moving with it to form a single major element of the display. A digital readout of indicated airspeed appears to the left and below the flightpath reference. A "tape" extends vertically above or below the left "wing" of the flightpath symbol to indicate fast or slow relative to a reference speed. A small chevron-shaped symbol moving vertically with respect to the left wing indicates acceleration along the flightpath. With the appropriate scaling, the position of this symbol indicates the constant-speed flightpath for the current thrust and airplane configuration. Other mechanizations of this concept have been termed "potential flightpath." A digital display of altitude, of definition appropriate to the flight regime, is located below and to the right of the flightpath symbol. A separate vertical rate indication is deemed unnecessary since the vertical flightpath presentation provides that function.

Additional Display References

The format of figure 5, with the addition of the ILS symbology discussed earlier, contains the information desired for the final IMC approach. However, additional symbology is added (fig. 6) to accommodate the more generalized maneuvering of approach-path intercept or go-around. Additional pitch and heading references are provided, together with a fixed symbol relating the longitudinal reference of the aircraft ("boresight") to the other display elements. It can be noted that the lateral position of the flightpath symbol relative to the "aircraft" symbol defines the drift angle of the airplane, and the vertical relationship of these two symbols is an approximate indication of angle of attack. The latter relationships suggested another symbol, intended as a warning of approach to limit angle of attack. As the angle of attack is increased, as indicated by increasing deflection of the flightpath symbol downward in the display field, a flashing line is displayed at a vertical position representative of the angle of attack associated with the primary stall-warning device of the airplane. When appropriate, a distance-measuring-equipment (DME) measure and a marker-beacon annunciation appear near the aircraft reference symbol. All these features are illustrated in figure 6, which depicts the display as it might appear if the aircraft were recovering from a sudden severe wind shear at low altitude.

Two elements in the display provide altitude references. Radio altitude of the main gear above the runway is indicated by the deflection of a two-line-segment symbol below the horizon. A satisfactory landing flare is effected if this symbol is tracked with the flightpath symbol. In the absence of an ILS glide-slope signal, a similar symbol is used to provide an altitude "command" or capture function.

This display did include the means for localizer intercept in duplication of the basic function of the horizontal situation indicator (HSI) of the panel. A line symbolic of the runway centerline extended, in perspective, defines whether the aircraft is left or right of course and whether the aircraft is on a converging or diverging track relative to the approach course. An approach to course from a left-of-course position is illustrated in figure 7. When the approach course heading is outside the field of view, as in this case, the point of intersection of the symbol with the horizon is constrained to remain at the edge of the field, and the approach course heading is defined beneath the flightpath symbol. In figure 7, the localizer-error symbol and the 1° pitch marks are used to designate the desired intercept heading (135°). At "localizer capture," these symbols assume their localizer-error function, indicating a turn toward the approach course.

OPERATIONAL PROCEDURES

The operational use of the display in an ILS approach is demonstrated in figures 8(a) through 8(h), which are photographs taken during simulator tests of the display. Prior to the approach, the pilot has entered into his guidance-display computer the runway heading and altitude, ILS glide-slope descent angle, decision height, speed reference, and desired ILS course-intercept heading. In figure 8(a), the pilot is maintaining an altitude of 1500 ft by flying the flightpath symbol on the horizon. He is tracking an intercept heading of 155° toward the ILS localizer associated with a runway having a heading of 090°. The DME reading indicates that he is 15 km (9.3 mi) from station, which in this case is at the airport. Acceleration and speed-error indications show a steady speed about 10 knots above the reference. For this series of photographs, the option to use angle of attack as the speed-error reference is being exercised, and the extension of the tape represents a negative angle-of-attack increment corresponding to a 10-knot speed surplus. The glide-slope signal is being received, as indicated by the presence of the symbol near the top of the display. It should be pointed out that the runway is at sea-level elevation; thus, the barometric altitude shown corresponds to altitude above the runway.

In figure 8(b), the airplane is in a localizer-intercept turn. As the localizer error is reduced below 2.5°, the localizer symbol moves left from its preset intercept heading position. The pilot pursues the localizer symbol while maintaining his desired altitude. His acceleration symbol shows speed to be decreasing at about 0.5 knots/sec.

In figure 8(c), convergence on the localizer is nearing completion and the runway symbol is in the field of view. The glide-slope symbol is descending, indicating an imminent crossing of the glide slope.

Figure 8(d) shows the aircraft on localizer, on course, in level flight just slightly below the ILS glide slope. This is the optimum moment to initiate the pushover to the 3° descent path. The flaps have been lowered to final-approach configuration, resulting in the reduction of the target speed to that corresponding to the reference angle of attack.

Figure 8(e) is a configuration of the display representing the stabilized on-localizer, on-glide-slope situation that is sought and effected by directing the flightpath symbol to the localizer and glide-slope symbols. The aircraft is "in trail" behind the intersection circle. Note that the aircraft heading is left of the aircraft track, in this case the result of a crosswind component from the left.

In figure 8(f), the airplane has just passed the middle-marker position 900 m (0.5 mi) short of the runway threshold. The runway symbol overlays the runway, which is just becoming visible. Within a second after this situation, the runway symbol disappears, indicating descent through "decision height." For the remainder of this approach, radio altitude is indicated.

Figure 8(g) shows the airplane descending toward flare-initiation altitude and shows the ground-proximity symbol rising in the display, while in figure 8(h) the ground-proximity symbol is being tracked in the landing flare.

In figures 9(a) through 9(e), a localizer-only "nonprecision" approach (NPA) is demonstrated. From the approach fix (in this case, the outer marker beacon), a 5° descent is flown to minimum descent altitude (MDA), which in this approach was set at 135 m (440 ft). In figure 9(a), the target-altitude symbol is shown rising toward the flightpath symbol. Tracking the line pair produces the convergence on the MDA shown in figure 9(b). Level flight is continued until the intended touchdown area is nearly 3° below the display horizon, as shown in figure 9(c). A descent is initiated with the flightpath symbol aimed at the touchdown area (fig. 9(d)). Adjustments are made in the flightpath as necessary to maintain the touchdown point on the runway depressed 3° below the horizon. Again, flare altitude is being approached in figure 9(e).

The go-around maneuver requires no unique symbology or procedure relative to the approach modes of use. The flightpath is expeditiously raised to a modest positive value (2°-3°) as the thrust is increased to climb power. When the desired climb speed is attained, the flightpath is elevated to correspond to the position of the acceleration symbol, assuring a constant-speed climb-out. If climb performance is threatened by engine malfunction or atmospheric disturbance, optimum action can be effected with the closely integrated displays of altitude, speed, flightpath, and acceleration. Speed decay is avoided by matching the flightpath with the acceleration indication. If terrain clearance is temporarily critical, intelligent trade-offs between speed and altitude are aided because the pilot is directly controlling an indication proportional to vertical velocity, and he has speed and acceleration indications in close visual proximity.

DISCUSSION OF DESIGN DETAILS

The previous sections of this report have described a display format developed over a period of time that reflects experience with a variety of individual display-element concepts. The following discussions of individual features are offered with the hope that they suggest design principles applicable to head-up displays and to integrated electronic displays generally.

Symbol Form

Airspeed and altitude display- The first display format evaluated in the program nearly 3 years ago is illustrated in figure 10. Its design borrowed heavily from military experience in general layout, with airspeed and altitude scales, or "thermometer readings," boldly evident. At that time, the display was designed with the assumption that ground track was not available, and lateral guidance was aided by a symbol which duplicated the function of a flight director "steering bar." The only features of this display that are retained in the final display configuration are the ILS glide-slope guidance scheme and the fast-slow tape.

The speed and altitude scales were quickly assessed as awkward and cluttered in the landing approach. In fact, they were often ignored because the fast-slow tape and an expanding runway representation at least partially met the immediate demands of the pilot. The first major revision of the display presented digital readouts of speed and altitude fixed in the lower portion of the display frame (fig. 11). These were retained through the next-to-final configuration, illustrated in figure 12. Efforts to move these indications closer to the flightpath symbol for easier scanning resulted in undesirable dynamic "conflicts" until McDonnell-Douglas Corp., in the development of their DC9 HUD, demonstrated the virtue of tying the digits directly to the flightpath symbol. On no occasion have evaluation pilots cited a desire to return to scales or electronic representations of their panel airspeed and altitude instruments. Several pilots missed a vertical rate indication until they recognized that the displayed flightpath angle provided that function.

Symbol "weight"- The state of current technology discourages the use of color to improve discrimination between symbols in head-up displays; and to minimize obscuration of the outside scene, as well as to minimize display-writing time, line or outline symbols are favored over solid opaque symbols. Simulator experience with the display of figure 11 pointed out the hazard resulting from inadequate differentiation between a controlled element (flightpath symbol) and the display element to which it is being referenced (glide-slope error line). On a number of occasions, under stressful, dynamic conditions, pilots suffered abrupt divergences of flightpath because they momentarily reversed the roles of these two symbols. With the current display format, which features a return of the flightpath circle and the attachment of the speed and altitude digits to form a relatively massive array, such occurrences have been rare. A "reversal" tendency was noted with the energy-control symbology of a foreign experimental head-up format in which the controlled and reference elements were similar in type and size.

Pitch scales- The earlier versions of the display included the traditional pitch "ladder," with references at 5° intervals, that moved in pitch and roll with respect to the aircraft reference symbol. It was found that such clutter can be satisfactorily avoided by limiting the pitch references to those required for the nominal approach tasks, except in cases of severe nosedown upset where additional references can be programed to appear. The final display format reflects this finding, and in addition gives a heading degree of freedom to the pitch references. This latter feature is visually gratifying. All major earth-oriented symbols have the full three-degrees of angular freedom, reducing the slight tendencies toward disorientation that were experienced with the earlier configurations under conditions of combined high pitch and yaw rates.

Speed control- The fast-slow tape, attached directly to the primary symbol, was derived from earlier electronic display experience and received consistently favorable reviews throughout the course of the subject development. The attachment of the symbol to its reference may be as important to its success as is its easily scanned location. Even under the most dynamic circumstances, it does not have to be sought, and its size is a direct indication of the error to be nulled. Selection of upward extension to indicate "fast" reflects the decision to remain consistent with the usual ADI fast-slow indication.

The acceleration (or "potential flightpath") symbol did not appear in the first format. Among the criticisms of that design was lack of a thrust reference. The acceleration symbol satisfied most evaluators, although some observed that an indication of overboost would be valuable. The weight of the symbol was kept low in accordance with its role as an aid or guide, not as a measure that was continuously monitored and controlled to a specific reference.

The acceleration indication was probably the single most unfamiliar feature in the display to those pilots who had not been previously exposed to electronic flight displays; however, its acceptance was unanimous, as it has been in other flightpath display mechanizations. Because of its novelty, pilots varied in their techniques and skill in using the measure, and their appreciation of its usefulness grew with their experience. No obvious, systematic misuses of the symbol were noted.

Symbol Dynamics

Flightpath- With the subject display, the pilot's primary task is direct control of the flightpath symbol to what are normally considered attitude references, or to guidance elements. The dynamic behavior of the flightpath of the center of gravity of the airplane in response to pitch-control inputs lags that of pitch attitude by more than 1.5 sec at approach speeds. Thus, without some form of compensation, precise control of an indication of the vertical flightpath of the aircraft c.g. location is quite difficult. However, if the flightpath is measured or computed to be that of the cockpit area of a large aircraft (25.9 m (85 ft) forward of the c.g. in the 727-200), the dynamics of the symbol are very good. A small amount of additional pitch-attitude "lead" can be used to optimize the response without producing any undesirable consequences. Vertical flightpath angle in the subject display is defined as

$$\tan^{-1}\left(\frac{\text{vertical velocity of cockpit}}{\text{velocity along track}}\right) + \theta\left(\frac{0.4s}{0.4s + 1}\right)$$

where θ is pitch attitude and s is Laplace operator.

In the simulation exercises, direct control of this "augmented" flightpath indication was seen to be analogous to that of pitch attitude, and it substituted completely and gracefully for that normal mode. When the significance of the flightpath indication is fully appreciated by the pilot, control of vertical flightpath in the presence of speed or configuration changes, as well as atmospheric disturbances, is instinctive and precise. A unique virtue is seen in the response of the flightpath indication to the vertical gust component of turbulence. As configured, the indication represents the flightpath of a point forward of the cockpit, in the vicinity of the center of the natural rotational response as the airplane heaves and "weathercocks" in response to vertical gusts; thus, the flightpath indication is stabilized relative to pitch attitude, and the need for higher frequency pitch-control inputs is minimized. While the indication of pitch attitude provided in the display by the aircraft reference symbol becomes of secondary importance, the relationship of this symbol to the flightpath symbol, reflecting angle of attack, strongly complements the speed indications of the display.

Acceleration along the flightpath- The definition of the acceleration indicated by the deflection of the chevron relative to the flightpath symbol reflects the objective of providing for improved energy management in severe atmospheric disturbances. To provide wind-shear sensing attributes while also assisting in routine thrust management, a combination of inertial acceleration and rate of change of indicated airspeed was derived in a complementary filter of the form

$$\text{indicated acceleration} = \left(\frac{\text{airspeed}}{\tau} + \text{inertial acceleration}\right)\left(\frac{\tau s}{\tau s + 1}\right)$$

where τ is a time constant (3 to 5 sec). This logic prevents the masking of continuing shear indications by inertial acceleration, while sufficiently filtering the noise inherent in the derivative of airspeed in turbulence.

Lateral flightpath dynamics- As indicated earlier, the final format, and the one immediately preceding it, were configured and evaluated with the assumption that INS-derived ground-track information was available. The pilot's task in the ILS approach was to direct his track (flightpath symbol) at a particular instantaneous heading reference indicated by the localizer-error symbol. Some difficulties were anticipated because of the unfamiliar response of the track indication in lateral maneuvering (it is almost decoupled from heading in short period motions) and because the "track command" relationship of the localizer-error symbol to the flightpath symbol resembles that of the roll-command vertical needle in a conventional flight director. No major difficulty was encountered, although the pilots demonstrated a need for some familiarization with the new control mode. A few of the pilots experienced undesirably persistent tendencies to oscillate slightly in roll when tracking the localizer. Some of these pilots felt that their behavior was the result of inadequate bank-angle references in the display. It is possible that these pilots possessed styles of control that did not accommodate readily to the unfamiliar tracking dynamics, or they may have carried into the task some of their flight director habits. These oscillatory tendencies diminished with increased exposure to the display.

Some of the most recent experience with the final configuration has utilized a display mode that again assumes the unavailability of INS-derived ground speed or track. In this mode, the flightpath symbol remains associated laterally with aircraft reference (indicated track the same as heading) until a valid localizer error of less than 3° is sensed. Localizer-error rate is then used, in the manner of a flight-director computer, to deduce an approximation to ground track which is used to position the flightpath symbol. This technique is effective in the simulator for localizer-guided approaches; however, a fully satisfactory mechanization of the lateral behavior of the flightpath symbol for approaches without track measures or localizer has not yet been identified.

Symbol excursion limits- If the guidance elements of the display, which are referenced to the approach course heading, were to remain strictly conformal with the outside world, they would leave the limited field of view of the display in many situations when they are most needed. The same fact is true of the flightpath symbol itself; a very strong crosswind can produce a drift (or crab) angle that will place the flightpath outside the display field. Excursions of these symbols must be limited to the display field in a manner that does not produce ambiguities or irritating dynamic behavior and does not require a significantly revised mode of operation. In the subject display, when the flightpath symbol is against a lateral excursion limit, the positioning of the guidance elements reflects that condition so as to continue the same dynamic relationships. The experience with the subject display suggests that these excursion-limiting considerations are among the most challenging in the design of a conformal head-up display.

Unresolved Issues

Localizer-intercept display- The attempt to include in the display format indications adequate for intercept of a localizer course may have been more appropriate for panel instrumentation than for a head-up display, but the opportunity to address the question of combining ADI and HSI functions in one format could not be ignored. The "runway centerline" mechanization described in figure 7 is as technically unambiguous and descriptive of the flight situation as the conventional HSI; however, it consistently inspired criticism from pilots, especially in their early experience. Resistance to acceptance of the runway-centerline perspective interpretation is probably caused by confusion with the error indication in the familiar HSI. As illustrated in figure 13, the angular relationship of the error symbol to the "frame" of the HSI is a measure of the difference between localizer course and aircraft headings, while in the HUD the angle is a measure of lateral displacement from course and is independent of aircraft heading. The disorientations experienced by the pilots with this feature of the display argue strongly for avoidance of such perceptual conflicts with conventional display logic, or at least for indoctrination and training to effect full familiarity with the new logic.

Flare guidance- The provision for continuous vertical guidance in the landing flare was included in all the formats and was effectively utilized by most of the evaluating pilots. However, it is the personal observation of the author, supported by solicited views of pilots similarly experienced with the display, that the use of the flare guidance to touchdown in manually controlled landing is accomplished at the expense of reduced perception and use of the cues normally derived from visual scanning of the runway. This is understandable if one accepts the reasonable assumption that in normal landings, without HUD, pilots fully saturate their visual perception capabilities in support of their conduct of the flare maneuver. In a pilot's early experience with the display, presentation of a second field of information inspires an either/or decision, conscious or subconscious. The development of a scan that includes both fields of information to effect optimal control of the flare seems to require much practice. The possibility is raised that the willingness to concentrate on the display in the flare is exaggerated in simulation, where outside visual cues are somewhat degraded relative to those of flight. Thus a question still remains regarding the value of a continuous flare cue in the manual landing, but very recent experiences with simulations of very-low-visibility automatic landings support its presence as a performance monitoring aid.

Provisions for display simplification- All versions of the format were accompanied by one or more submodes, suitable for the final VMC portion of the approach, that contained considerably less symbology than the all-up display. A "decluttered" version of the final display is illustrated in figure 14. These modes were acquired by depression of a sequencer button on the pilot's control wheel. When introduced to this feature, all the evaluator pilots reacted favorably; however, in the total simulator experience, only a few of the pilots actually adopted the procedure of simplifying the display late in the approach. Apparently either the full display did not constitute a significant visual burden to most pilots, or the declutter option was simply forgotten in the high work load of low final approach.

PILOT ACCEPTANCE AND LEARNING

To most of the evaluator pilots, the HUD format represented an arrangement of information radically different from any they had used in flight. The rapidity of acceptance of most of these unfamiliar forms is considered a measure of their effectiveness. The designation of the flightpath symbol as the primary controlled element of the display presented no problems to the pilots in the aircraft control modes used in this development (full manual or ILS-coupled autoland). Its use was dynamically comfortable, and sufficiently analogous to that of their conventional instruments to require a minimum of familiarization prior to the conduct of precise instrument approaches, at least in nominal conditions. The observation is offered that many pilots tended initially to demonstrate more confidence in than technical comprehension of the display, and thus were sometimes slow to appreciate and employ the full potential of the flightpath information offered them. Continued instruction and practice past the first several hours of experience proved rewarding in terms of demonstrated performance in high-workload situations posed by turbulence and shears. It should be expected that the development of scan patterns and control strategies with a completely new layout of flight information requires practice. The simulator experience associated with this display development very strongly points out the advisability of exposing pilots to thorough indoctrination, practice, and testing as part of their evaluation procedure.

CONCLUDING REMARKS

The display development program described in this paper enjoyed the periodic availability of sophisticated flight simulation in which demanding piloting tasks could be realistically represented. The experience suggests that there is no rational alternative; the evaluator must get into the control loops, with ample time to develop a performance plateau. However, the program would have benefited from the availability of a simpler simulator in which a greater variety of display concepts could have been given preliminary inspection. Such improved flexibility in the design process might protect against the natural tendency to concentrate on, and overrefine, a single concept.

The subject conformal flightpath-based head-up display format was developed and evaluated under the assumption that in the aircraft it would, under the most favorable circumstances, be supplied precise attitude, velocity, and acceleration data from modern sensors, including INS. A quite different display concept might result if assumed sensors remained limited to those found on most of our presently operating domestic-transport aircraft.

Most of the air-transport-community pilots exposed to the HUD formats demonstrated an encouraging acceptance of unfamiliar concepts when effectiveness was demonstrated in high-quality flight simulation. However, from this design and evaluation experience comes the warning that with radically new displays pilot performance can precede pilot understanding, with the result that inadequate emphasis is placed on instruction, testing, and practice.

REFERENCES

1. Lauber, John K.; Bray, Richard S.; and Scott, Barry C.: An Evaluation of Head-Up Displays in Civil Transport Operations. 1980 Aircraft Safety and Operating Problems, NASA CP-2170, 1981. (Paper 10 of this compilation.)

2. Bray, Richard S.: A Head-Up Display Format for Application to Transport Aircraft Approach and Landing. NASA TM-81199, 1980.

3. Head-Up Display Systems Evaluated. Aviation Week and Space Technology, Jan. 10, 1977, pp. 70-79.

4. Mirage 2000 Head-Up Display. Flight International, April 12, 1980, p. 1124.

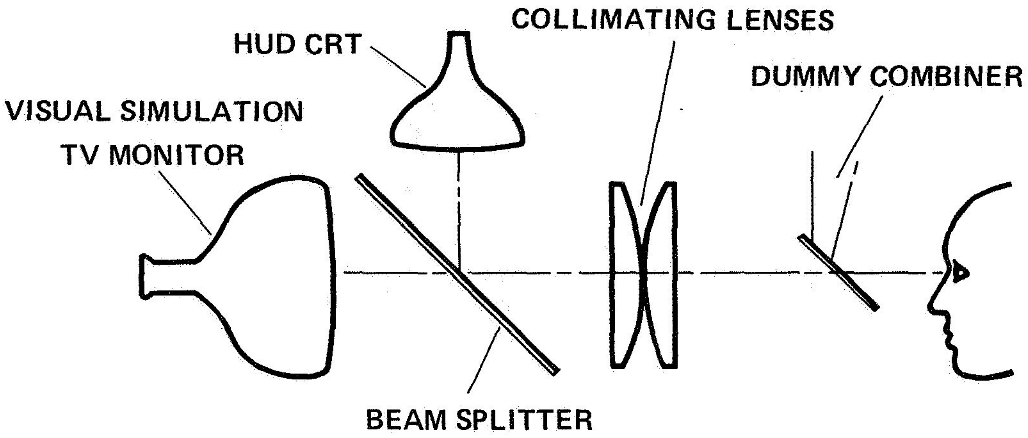


Figure 1.- Optical combining of HUD with visual scene in simulator.

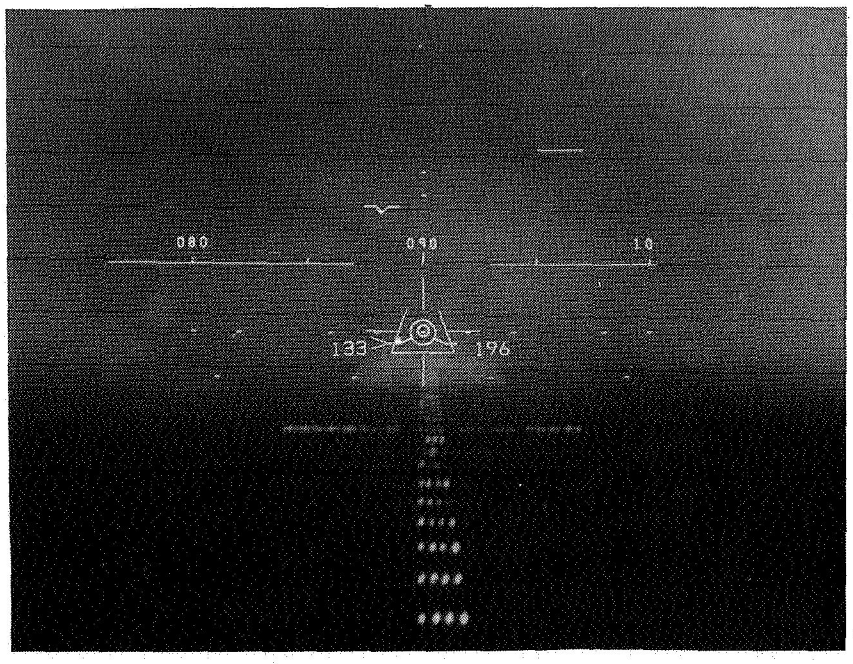
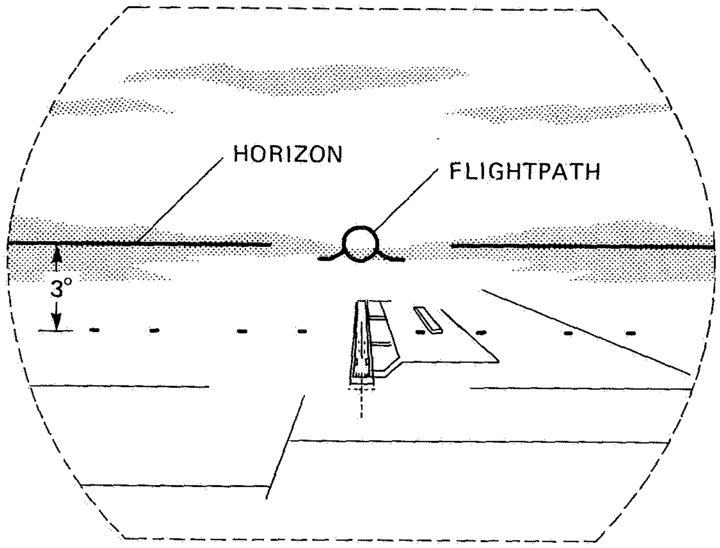
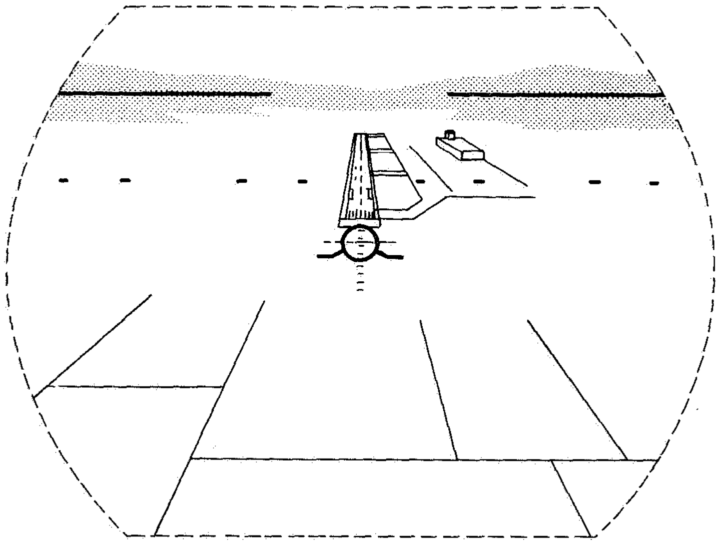


Figure 2.- Head-up display in simulated low-visibility approach.

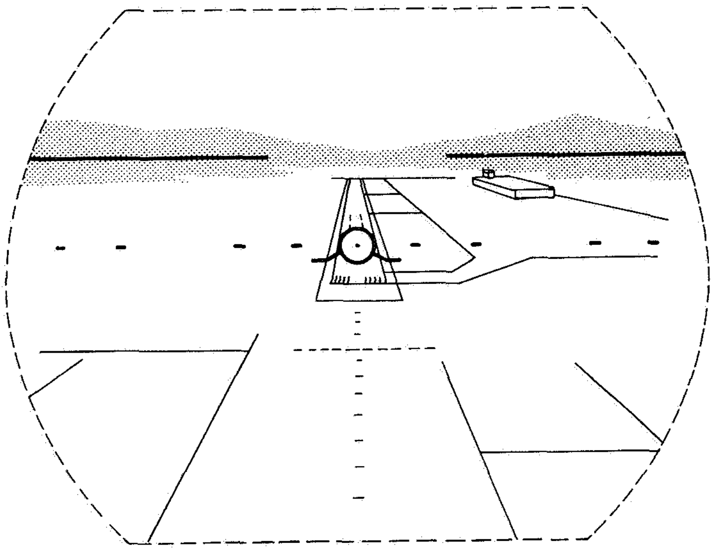


(a) Level flight, above 3° path to touchdown point.



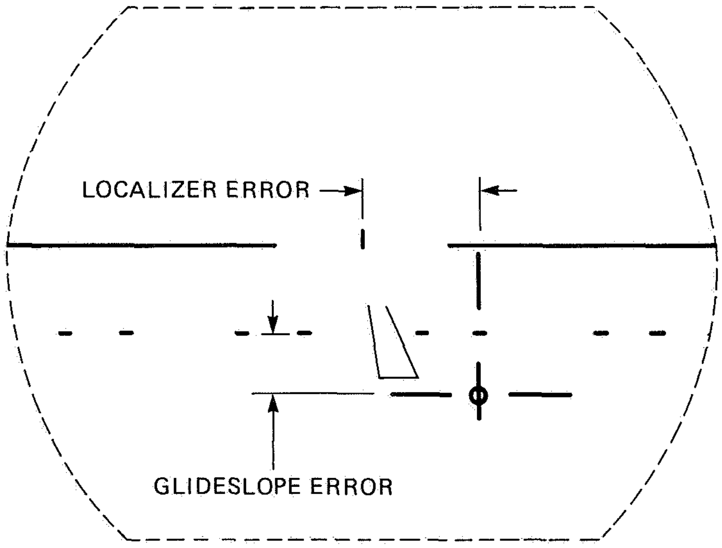
(b) Descending at 5° to establish 3° approach flightpath.

Figure 3.- Approach-path guidance provided by conformal display of flightpath vector.



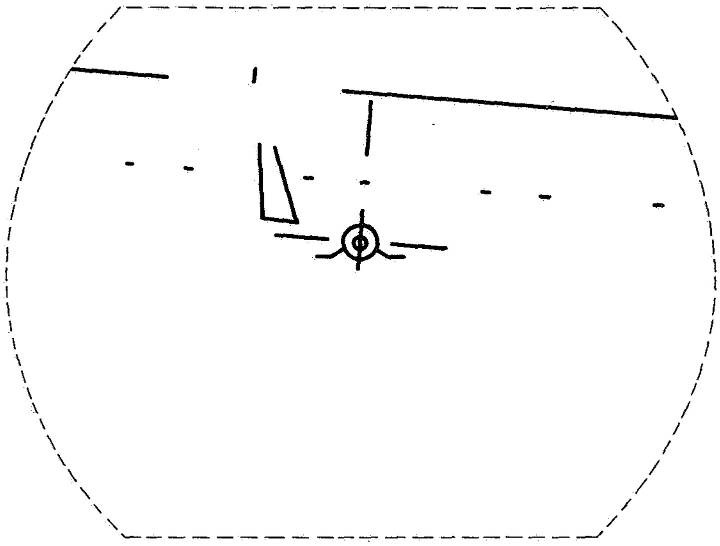
(c) On 3° approach flightpath.

Figure 3.- Concluded.

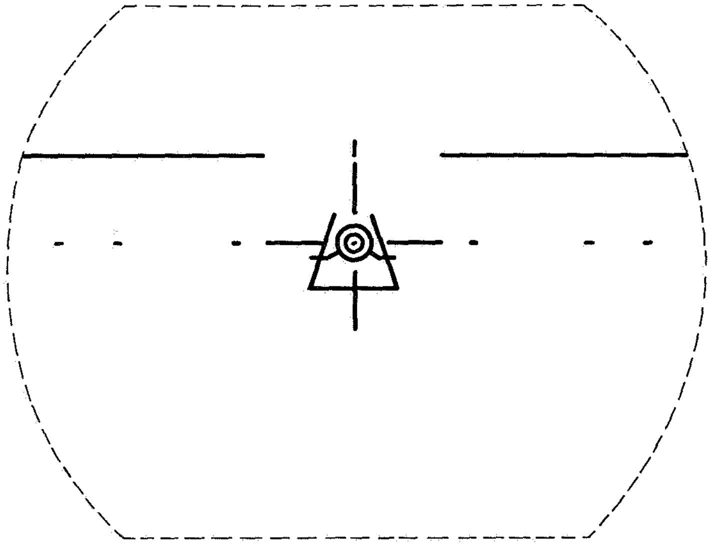


(a) Glide-slope and localizer-error indications.

Figure 4.- ILS guidance.



(b) Tracking combined error signals to effect convergence to ILS path.



(c) On ILS approach path.

Figure 4.- Concluded.

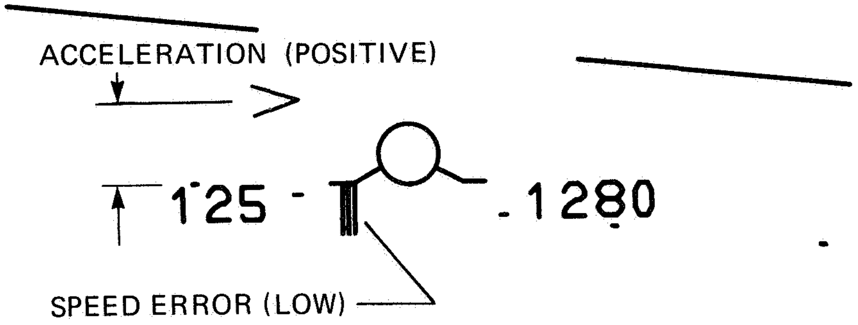


Figure 5.- Fligthpath symbol and associated array of speed and altitude indications.

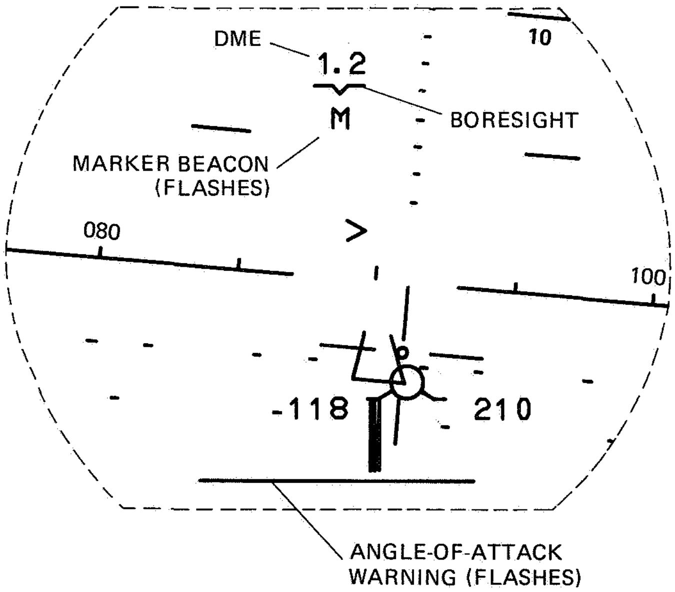


Figure 6.- Additional display references.

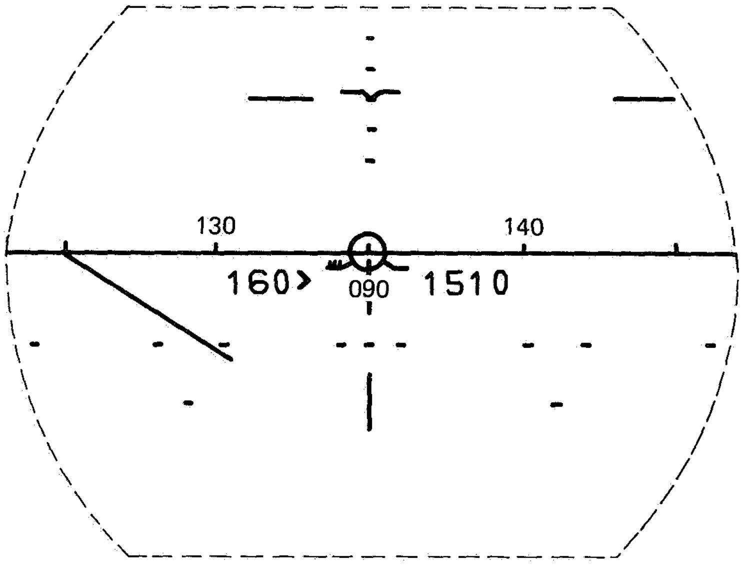
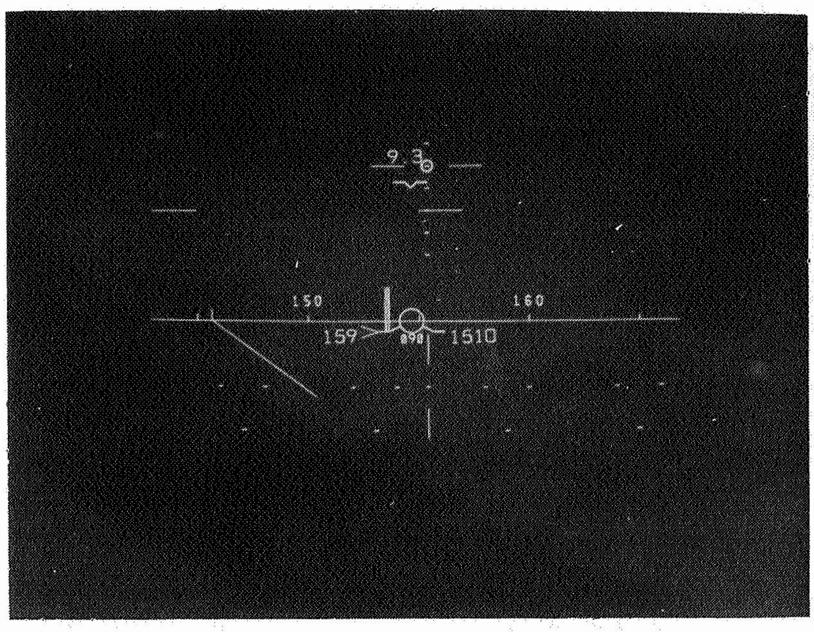
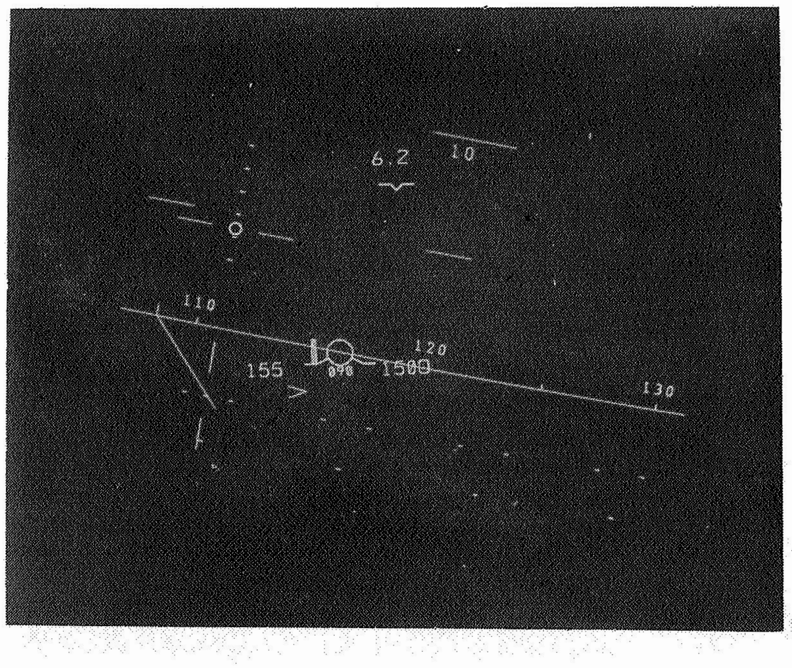


Figure 7.- Lateral guidance prior to localizer capture.

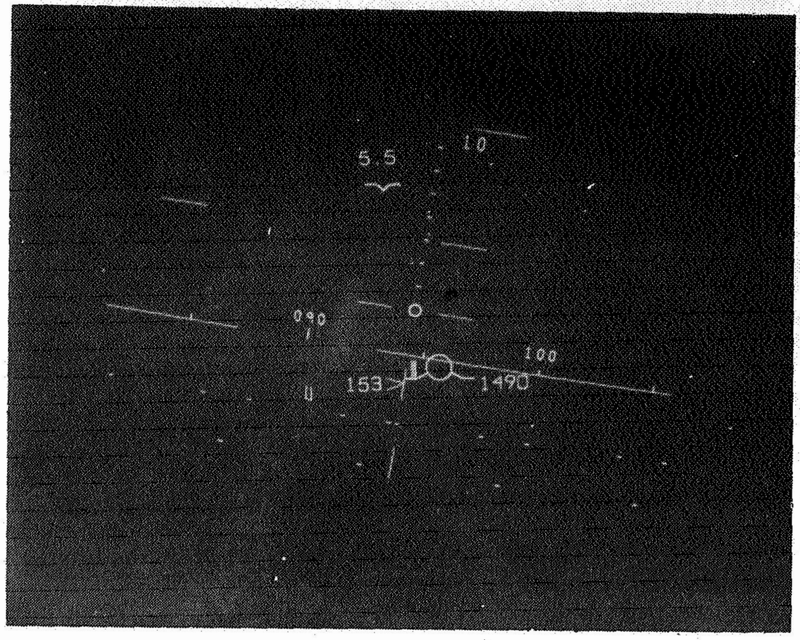


(a) Level flight on intercept heading.

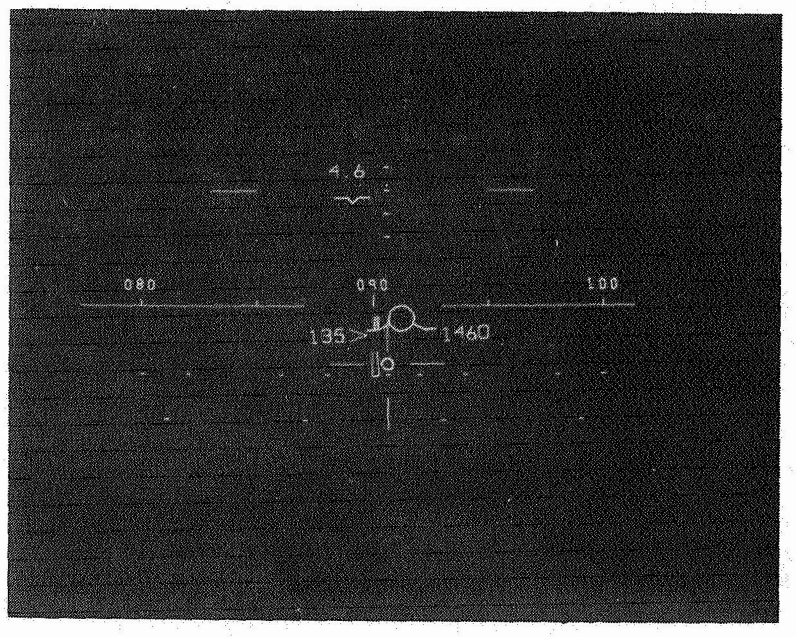


(b) Turning to localizer course.

Figure 8.- Photographs of HUD during simulated ILS approach.

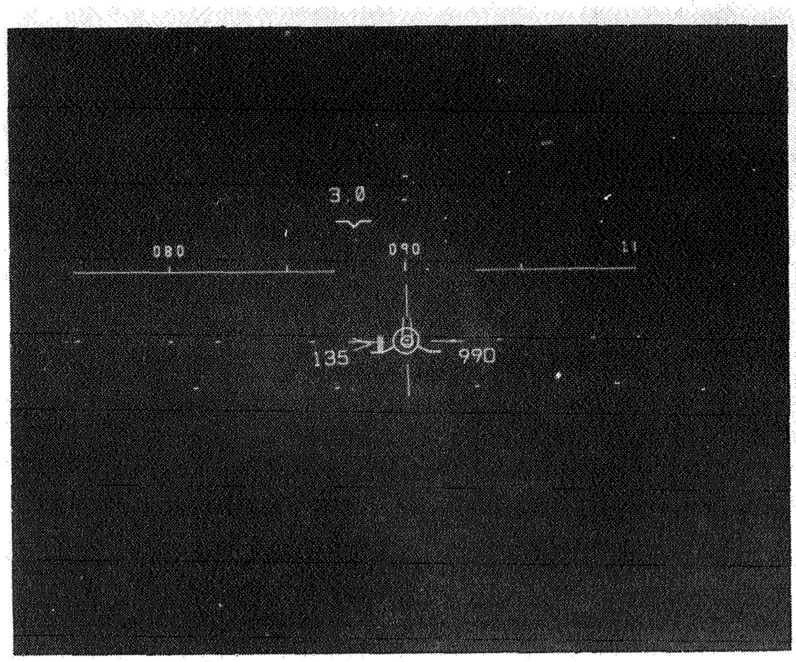


(c) Near completion of localizer capture.

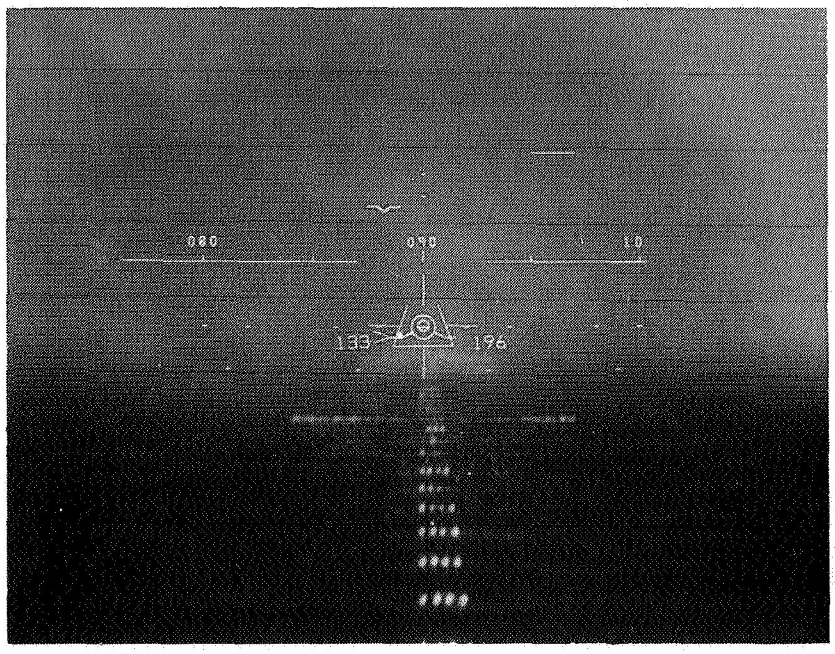


(d) Initiating pushover to ILS glidepath.

Figure 8.- Continued.

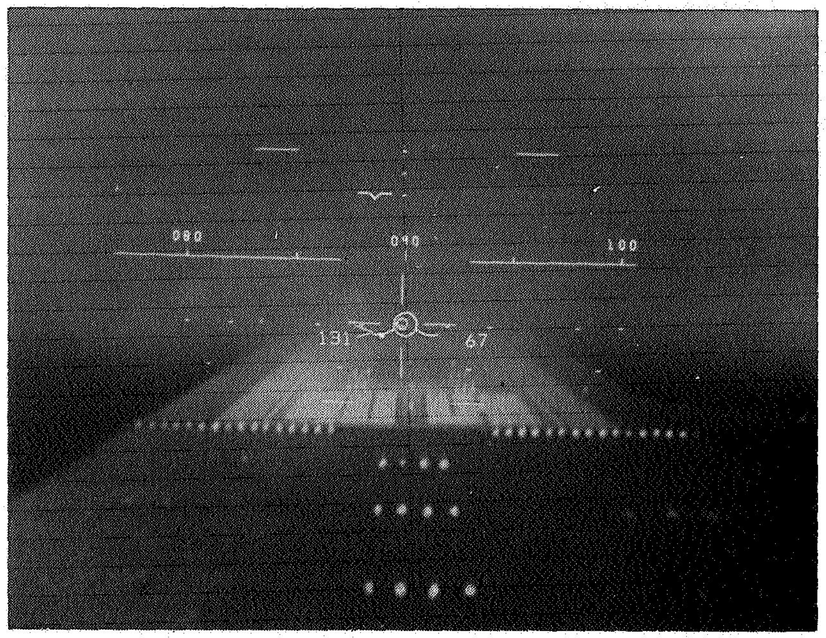


(e) On approach path.



(f) Runway in sight, 900-m (0.5-mi) visibility.

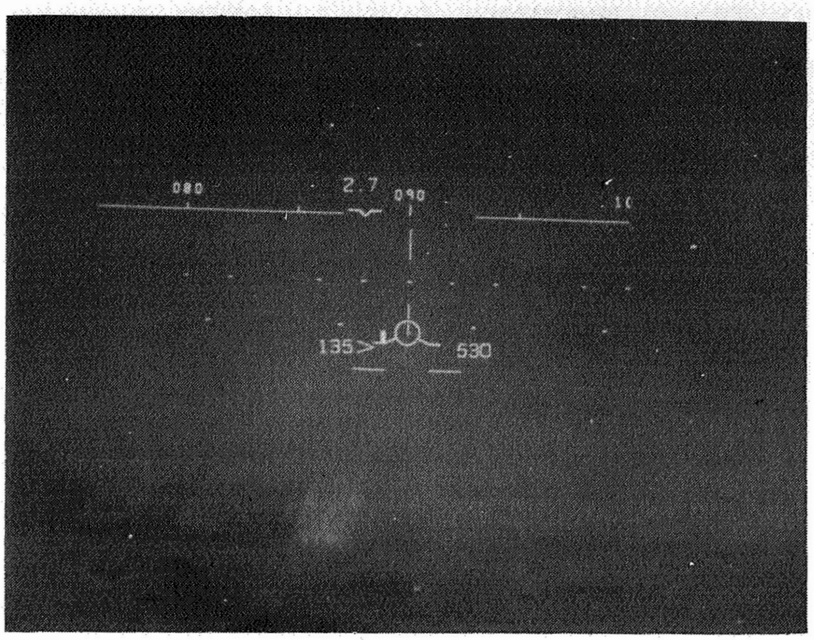
Figure 8.- Continued.



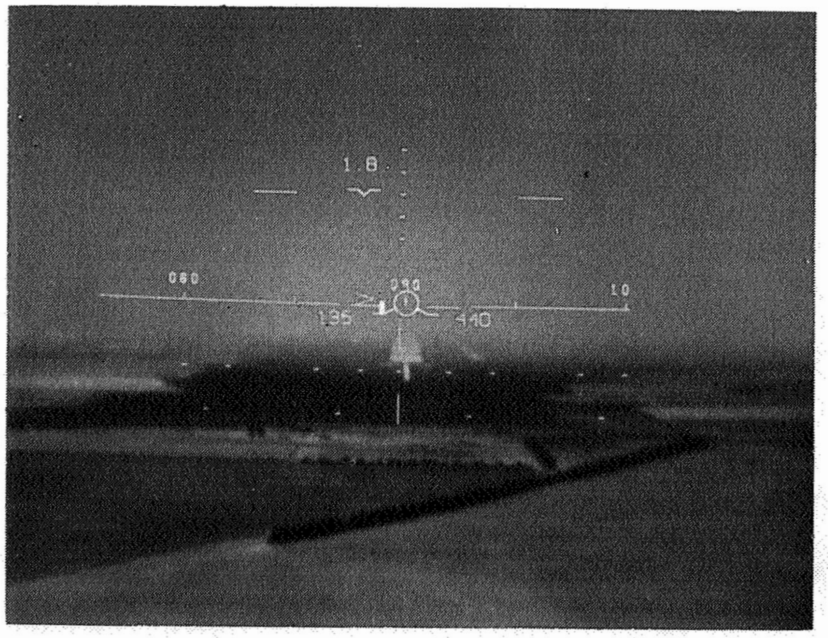
(g) Ground-proximity symbol rising.

(h) Tracking ground-proximity symbol in flare.

Figure 8.- Concluded.

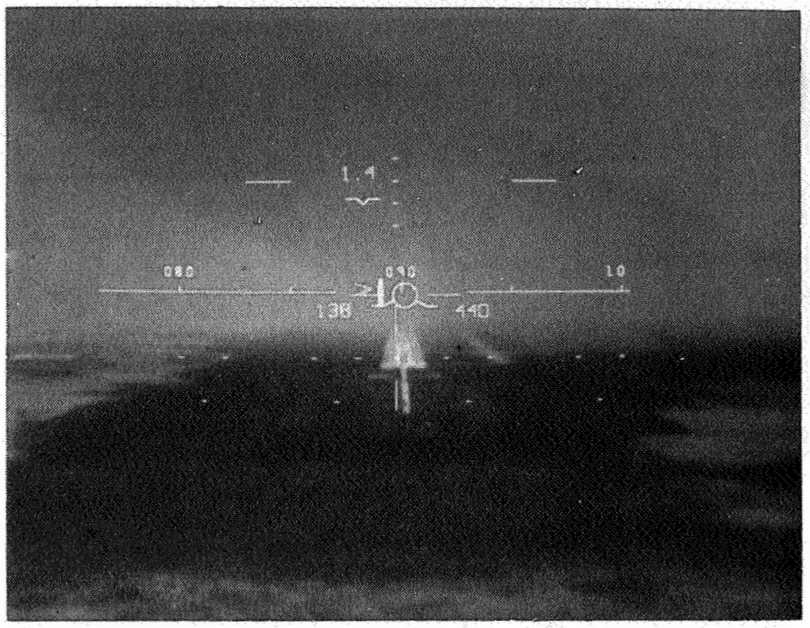


(a) Descending to MDA, target-altitude symbol rising.

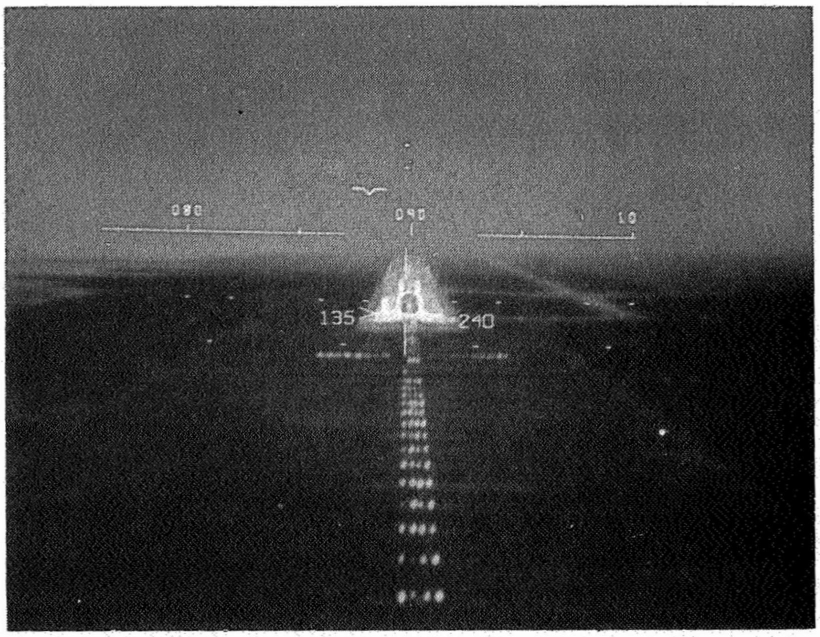


(b) Holding MDA by tracking altitude symbol.

Figure 9.- HUD in localizer-only nonprecision approach (NPA).

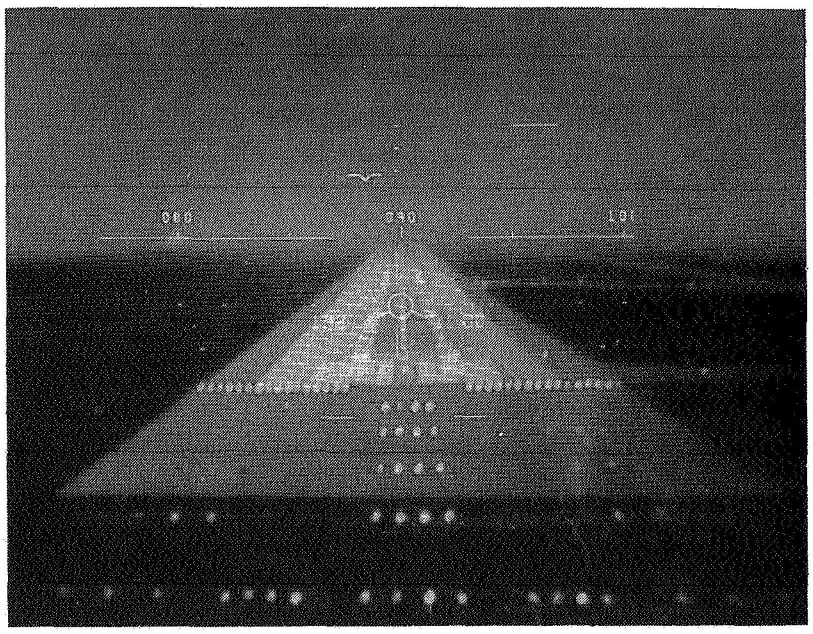


(c) Nearing 3° path to runway.



(d) Tracking intended touchdown area.

Figure 9.- Continued.



(e) Completing approach.

Figure 9.- Concluded.

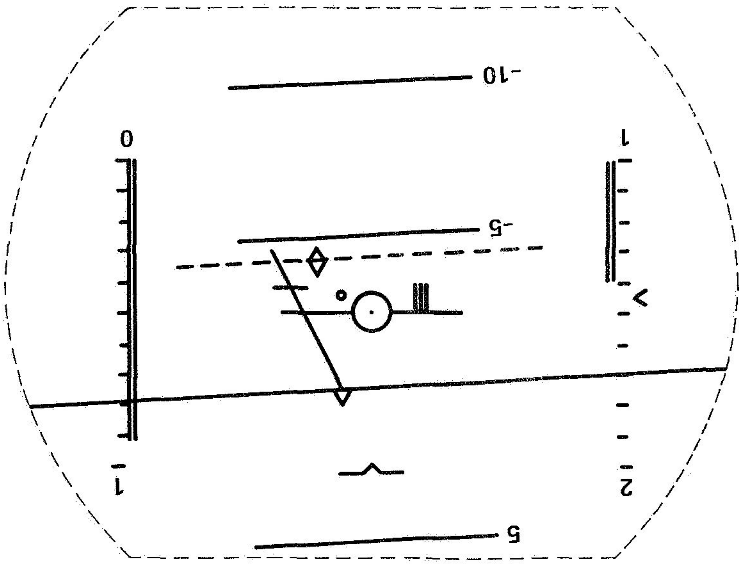


Figure 10.- Initial flightpath format of NASA-Ames HUD studies.

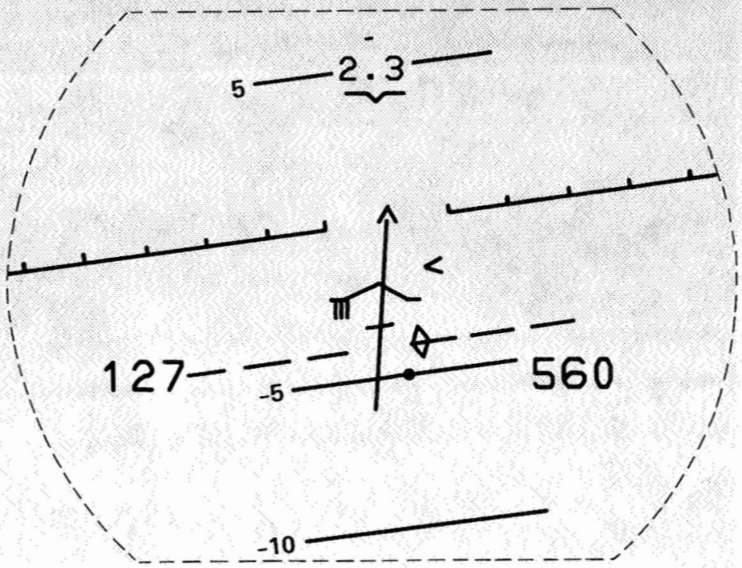


Figure 11.- First major variation of HUD format.

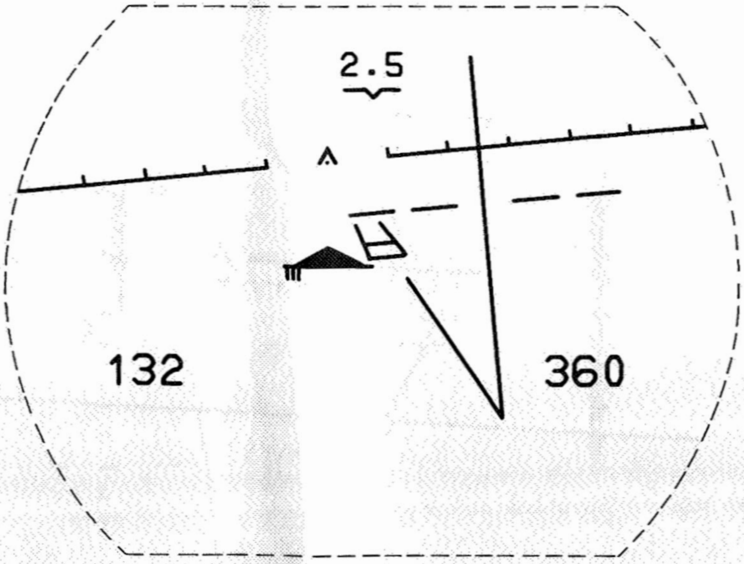


Figure 12.- Second variation of HUD format; assumes definition of ground track.

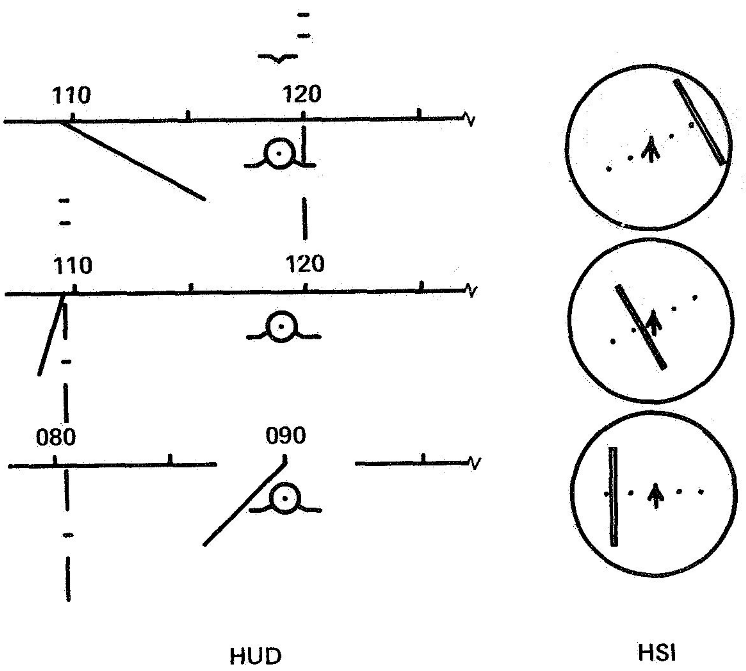


Figure 13.- Comparison of HUD and HSI indications of aircraft position and heading relative to ILS localizer course.

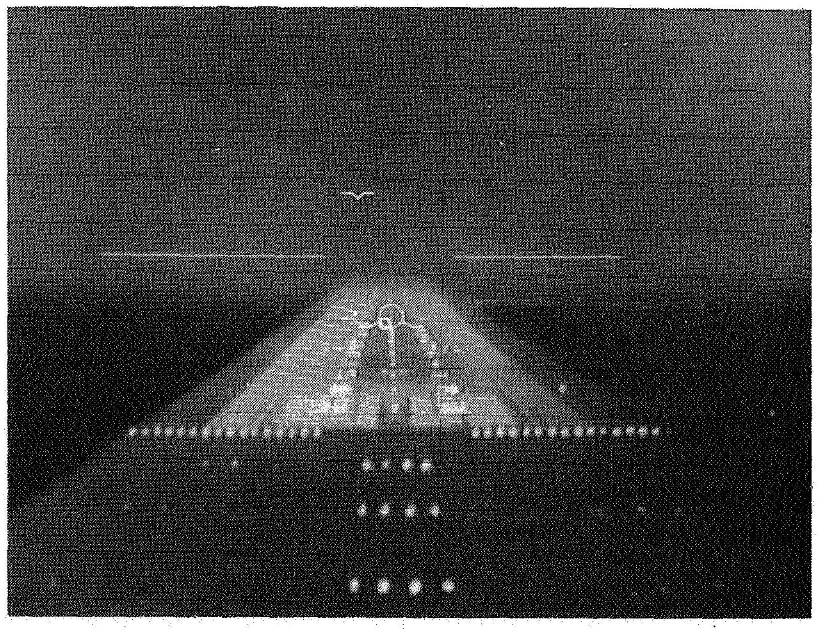


Figure 14.- "Decluttered" display.