# Feasibility Demonstration of the Earth-Referenced Maneuvering Flight-Path Display

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**A feasibility demonstration of integrated cockpit guidance and control display concept, the maneuvering flight-path display, is reported. The display provides attitude, altitude, direction, and speed director information to the pilot in the form of an electronically generated, graphical representation of the real-world flight path that should be flown. There are two types of moving elements constituting the display: the flight-path and the speed-index elements. The flight-path elements are analogous to "tar strips" on a highway. The speed-index element, immediately to the left of the flight-path elements, moves perspectively to denote deviation from proper speed by either moving away from or toward the aircraft to signal "too slow" or "too fast," respectively. The feasibility demonstration was carried out on a fixed-base simulator. The practicability of using an Earth-referenced flight-path display as the principal source of pilot guidance and control information during representative flight modes was investigated. The flights demonstrated the feasibility and desirability of the concept, and its development is continuing.**

## I. Introduction

THE maneuvering flight-path display (MFPD) has been under development for about two and a half years. In January 1977, the Northrop Corporation Aircraft Division was awarded a contract by the Naval Air Development Center to demonstrate the feasibility of the flight-path display concept. This paper reports on that feasibility demonstration.

The principal objective of the MFPD is to assure the precise and effective guidance and control of piloted aircraft at all times. The display system achieves this goal by computing the desired or "command" flight path and the deviations of the aircraft from that path, and then presenting a graphical representation of this combined "director" and "orientation" information to the pilot. Complete information on the attitude, altitude, speed, and direction of the aircraft is presented continuously by the MFPD, whether the aircraft is under manual or automatic flight control. Therefore, the pilot is able to control all of the vehicle's six degrees of freedom by reference to the single, integrated display.

The flight-path display concept may be applicable to all phases of flight eventually, but the present developmental effort is confined to Earth-referenced applications. Accordingly, the feasibility demonstration was limited to three such applications: takeoff, landing, and fixed-target air-to-ground attack. The sections that follow describe the flight-path display concept, the feasibility demonstration of the concept, and the results of the demonstration.

## II. Maneuvering Flight-Path Display Concept

The concept of the flight-path display was formulated under Navy sponsorship in the 1952-1963 period in response to three chronic, basic needs: greater aircraft weapon system performance, increased flight safety, and decreased pilot training. The then-prevailing state-of-the-art limitations in computer technology frustrated development of the concept, and interest waned. A suitable means of satisfying the three basic needs still had not been found when, in early 1975, Northrop initiated action to extend the earlier work on the flight path. Promising results in this effort led to renewed Navy interest, and the previously described contract in January 1977.

The maneuvering flight-path display provides both command and actual guidance and control information to the pilot. The information is presented in the form of an electronically generated, visual representation of the real-world flight path that the pilot should be flying. When the aircraft is "on flight path," the presentation on the pilot's head-up display (or his head-down vertical situation display) would appear as a highway in the sky which extends out in front of, from a position immediately below, the aircraft. The flight-path elements are analogous to "tar strips" on a highway and move under the aircraft at a rate that is proportional to the vehicle's speed. These flight-path elements also denote the proper vehicle attitude, altitude, and direction. Speed information is given by a velocity marker that is located to the left of the flight path. The velocity marker moves toward the pilot to denote "too fast," away from the pilot to denote "too slow," and does not move at all to denote "on speed."

The flight path, being Earth-stabilized, always appears to the pilot in its geometrically correct aspect and with the proper perspective, regardless of the airplane's attitude. In other words, when the real-world flight path is within the pilot's field of view, the electronically generated facsimile of that flight path appears on the display exactly as the real flight path would appear if it were visible to the pilot through the windscreen. This geometric fidelity also insures that the flight-path presentation exhibits the proper dynamic behavior. That is, the motion of the aircraft in all axes (i.e., the aircraft $x$, $y$, and $z$ axes) on and about the flight path is always depicted correctly by the display. Figures 1-9 show how the flight path would appear to the pilot under a variety of conditions. It should be noted that an earlier configuration of five rectangular velocity markers, instead of the present configuration of a single circle, is shown in Figs. 1-9. The reason for this change is discussed subsequently.

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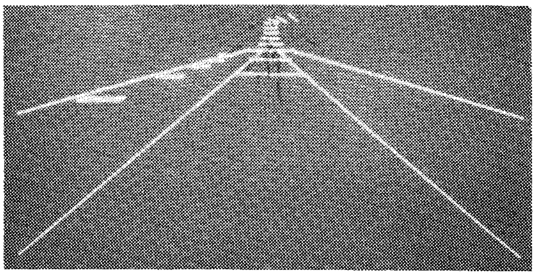


Fig. 1 The flight-path display as it would appear to the pilot during takeoff.

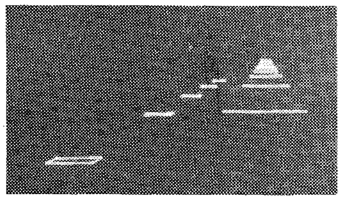


Fig. 2 The flight-path display as it would appear to the pilot when the airplane is "on the flight path."

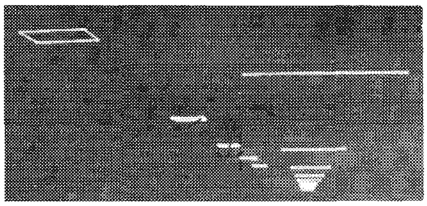


Fig. 3 The flight-path display as it would appear to the pilot when the airplane is "too low."

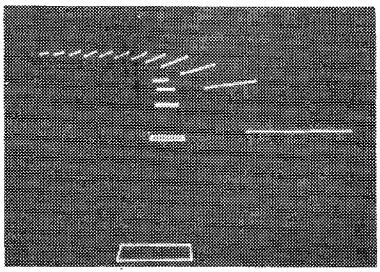


Fig. 4 The flight-path display as it would appear to the pilot when the airplane is "slightly to the left" and a left turn is coming up.

The maneuvering flight-path display concept can be understood readily if it is considered in contrast to flying by reference to conventional instruments. In the case of conventional instruments, the pilot controls the aircraft to achieve the desired trajectory through the air by constantly referring to a number of parametric displays. Each of these displays presents flight information such as attitude, heading, altitude, and speed. Simply stated, the pilot must visualize the desired trajectory, or flight path he wishes to make good, as a continuum of discrete values of the flight parameters of interest. He then attempts to fly the visualized flight path by controlling the aircraft to the corresponding set of specific flight parameter values. These flight parameter values are displayed conventionally as instantaneous numbers, letters, or symbols; hence, little or no anticipatory information is available. The visualized or "command" flight path exists only in the pilot's mind, and, in order to fly such a projected path, the pilot is required to correlate continuously the "actual" values of the flight parameters being displayed to that mental image. Although the "command" flight path is invisible, it is altogether real and therefore subject to

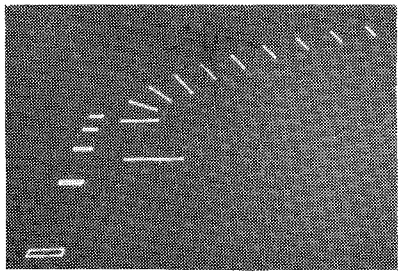


Fig. 5 The flight-path display as it would appear to the pilot when the airplane is "too high" and a climbing right turn is coming up.

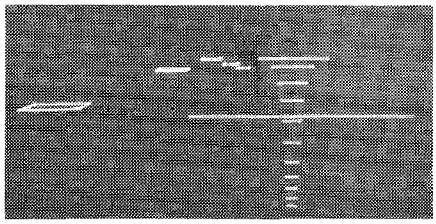


Fig. 6 The flight-path display as it would appear to the pilot when the airplane is "slightly low" and a pushover is imminent.

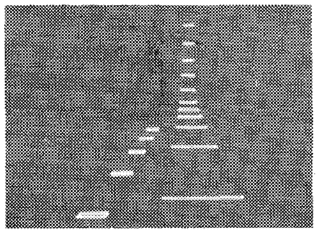


Fig. 7 The flight-path display as it would appear to the pilot when the airplane is "slightly high" and a pullup is coming up.

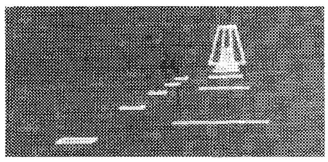


Fig. 8 The flight-path display as it would appear to the pilot when the airplane is "on path" and approaching for landing.

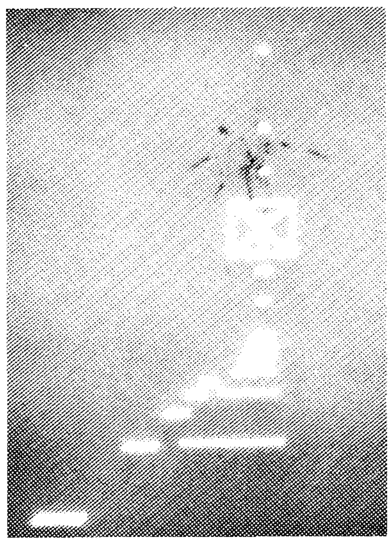


Fig. 9 The flight-path display as it would appear to the pilot when the airplane is "slightly high and to the right" during a fixed-target air-to-ground attack.

mathematical description and graphical representation. The maneuvering flight-path display is simply the graphical representation of the "command" flight path.

The aircraft "command" guidance and control data are used in combination with the "actual" aircraft dynamic state variables to generate the flight-path display. First, the desired "command" flight path is defined throughout its extent in terms of its attitude, altitude, speed, and direction. Then, the actual values of the flight parameters of the airplane are introduced into the flight-path perspective transformation equations to establish the location and orientation of the flight path in the pilot's field of view. Finally, the perspectively transformed, two-dimensional representation of the flight path is generated on a cathode ray tube and projected on the pilot's display medium. Since the presentation appears to the pilot as an explicit, geometrically correct highway in the sky, which he observes through his windscreen, he can readily perceive his deviation from the flight path and respond accordingly. "Actual" and "deviation" information are thus implicit in the display. This combination of explicit and implicit information obviates the need for the traditional pilot visualization of his flight path. Any available system inputs such as localizer and glideslope beams, during instrument lading approaches, and vhf omnidirectional range or inertial navigation system data, during the enroute phase, could be used as inputs to the flight-path display.

Since the flight-path display provides a continuous presentation of "command" guidance and control information, it inherently affords an opportunity always to "command" an optimal or near-optimal flight path for the aircraft to fly. Assume for a moment that the airplane's performance characteristics are as shown in Fig. 10. It is clear that, for each mode or phase of flight, there exists a regime in the flight envelope in which operation of the aircraft is preferred. These considerations can be reflected in the various segments of the flight path with relative ease. For example, consider the case in which the aircraft is free to cruise any altitude, and at any speed, and the flight-path display is augmented by a computer capable of performing energy management computations. The resultant flight-path display will always command a trajectory that achieves the desired goal of "maximum range." Similarly, provisions can be made to achieve "maximum-endurance" or "minimum-time" goals, all within the safety of the airplane's flight envelope.

The maneuvering flight-path display involves two application modes, which, in turn, necessitate two mathematical formulations. The more complex and, from the standpoint of pilot acceptance, the more controversial of the two is the moving reference version. This version would be used in those dynamic applications in which both ends of the flight path are referenced to moving points in inertial space. The best example of a situation involving such a flight path is air-to-air combat. The other flight-path application mode is the Earth-referenced version. In this case, the aircraft is maneuvering relative to specific geographic points; hence both ends of the flight path are referenced to specific points on the Earth's surface. Examples of situations in which such a flight path would be used are landing, takeoff, air-to-ground fixed-target strikes, enroute navigation/cruise, and traffic control. Fortunately, the Earth-referenced flight path is not only the simpler to compute and display, but also will have the more beneficial impact on system performance, flight safety, and crew training. In terms of exposure alone, all aircraft are continually involved in the Earth-referenced phases of flight, whereas only a relative few are engaged extensively in the moving reference phases. As a result, the system performance, flight safety, and crew training needs that the Earth-referenced flight-path display can satisfy are significantly more numerous and critical. For example, in the area of flight safety alone, many Navy aircraft accidents still occur during carrier takeoffs and landings. The ability to include precise command and actual information on the airplane's navigational status, attitude, altitude, and speed in a single, easy-to-understnad presentation such as the Earth-referenced flight path display should materially reduce pilot workload and error during such takeoffs and landings. The pure Earth-referenced version of the flight-path display could be extended readily to accommodate the moving reference requirements associated with carrier operations.

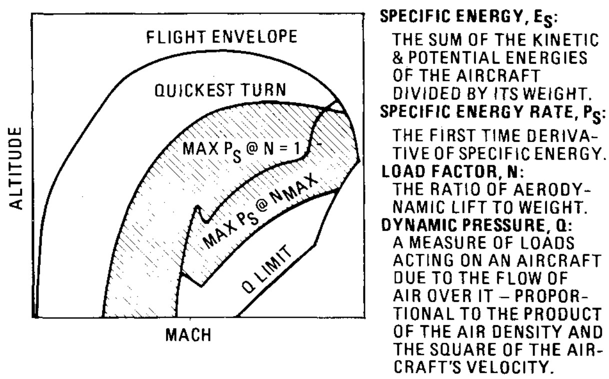



**Fig. 10 Aircraft performance considerations.**

## III. Development of Flight-Path Display

The flight-path display development work was undertaken as a consequence of earlier requirement analyses aimed at improving the overall guidance and control of fighter aircraft through improvements in the man-machine interface. It has been concluded that pilots could not obtain all of the available performance from their aircraft consistently, confidently, and safely using conventional cockpit instrumentation. Accordingly, a study effort was initiated to define the various fighter aircraft pilot information and information display requirements, and the related hardware and software implications. The flight-path display was judged to be one of the most promising means of meeting the identified fighter aircraft head-up display needs.

The development of the flight-path display started with the formulation of the basic mathematical expressions for the perspective transformation of the Earth-referenced command flight path. Figures 11 and 12 show a command flight path as it exists in an Earth coordinate system and as it relates to an aircraft coordinate system and the airplane's head-up display (HUD) field of view. A determination is made as to what part of the flight path is within the HUD field of view, and the coordinates of that portion of the flight path are transformed to the HUD coordinate system ($y_d$, $z_d$) so as to be perspectively, as well as positionally, correct. In other words, the more distant flight-path elements appear smaller when displayed in the HUD coordinate system. The basic algorithms for these transformations were developed and checked out on a simple $x$-$y$ plotter before any attempt was made to execute them in real time. During this phase, a limited dynamic representation of the flight path was achieved by successively photographing a progression of the static $x$-$y$ plots, one at a time, on 16-mm movie film and then projecting the resultant film at the normal 24-frames per second projection speed. The work then moved to the Northrop Aerosciences Laboratory, where the programming proceeded on a larger computer augmented with more extensive facilities. There the flight-path display was generated in real time on a graphics terminal. The display could be "flown," by means of a simple side stick control, just as though it were attached to an airplane. It was thus possible to change the flight-path algorithms and immediately assess the dynamic effect of the changes.

The flight-path algorithms are programmed in FORTRAN IV language for compatibility with the simulation programs. At the present stage of development, the flight-path program

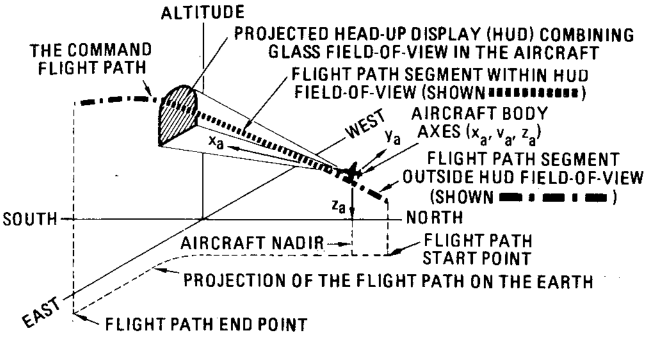



**Fig. 11 The Earth-referenced flight path and its relationship to the HUD field of view.**

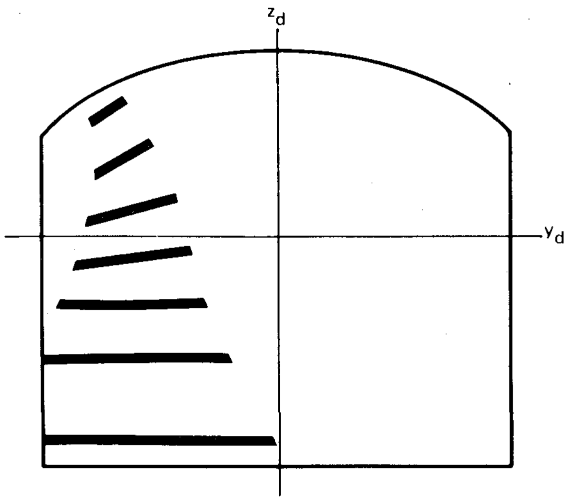



**Fig. 12 The Earth-referenced flight path as it would appear on the HUD after the transformation to the display coordinates ($y_d$, $z_d$).**

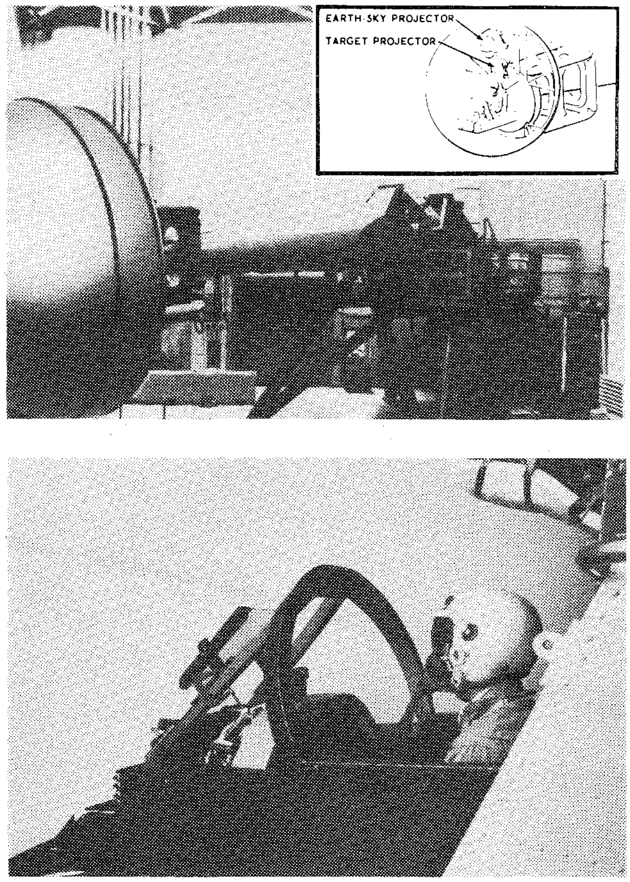



**Fig. 13 The Northrop large-amplitude simulator.**

requires 11,000, sixteen-bit words of memory. Program optimization efforts in the future are expected to reduce the memory requirements.

In order to demonstrate the feasibility of the flight-path display properly, the demonstration tests were carried out on the Northrop large-amplitude simulator (LAS), using a six-degree-of-freedom F-5E aircraft dynamics program. The LAS, which is a moving base simulator, was used in a fixed-base simulator mode for the demonstration; hence no motion cues were available during the test runs. Work on the flight-path display is continuing on the graphics terminal. The LAS will be used intermittently in the subsequent development program as the need is indicated. Eventually, the flight-path display will be evaluated in the simulator and in the Naval Air Test Center's display evaluation flight-test (DEFT) airplane.

## IV. Feasibility Demonstration

The purpose of the maneuvering flight-path display demonstration was to provide an opportunity to assess the practicability of the concept prior to embarking on the more expensive undertaking of development. Three appplications areas were identified for the demonstration: a landing, a takeoff, and a conventional fixed-target, dive-bombing strike. In the interest of economy and expediency, no attempt was made to go beyond simple, representative demonstration maneuvers. The demonstration maneuvers were to be flown with conventional flight controls and with respective jet fighter dynamic characteristics.

As previously noted, the large-amplitude simulator (LAS) was used as the test vehicle. The LAS, shown in Fig. 13, is a moving base simulator that incorporates both Earth-sky and terrain projection systems. The LAS cockpit also features a head-up display on which the flight path could be generated for pilot viewing. It was desired to use only visual stimuli during the demonstration runs; hence the LAS was used exclusively as a fixed-base simulator in the course of the tests. The terrain projection system was used in conjunction with the flight-path display during the takeoff and landing segments only; the Earth-sky projection system was used the rest of the time. This arrangement was used to avoid the necessity of restricting flight to the limited area convered by the terrain board. The LAS displays were driven in accordance with F-5E aircraft six-degree-of-freedom dynamics by a single Harris 6024/4 digital computer. The flight-path display was generated by a Varian 73 digital computer on the basis of aircraft state inputs provided by the Harris machine through a COMCOR 5000 analog computer. The graphics display presentation was mixed with the video of the Earth-sky and terrain projection systems to produce a picture on a monitor display of what the pilot was observing through the HUD combining glass. This mixed display was useful for observation outside the cockpit, as well as for video tape and motion picture documentation of the proceedings in the cockpit. An automated data measurement, recording, and display system completed the list of laboratory equipment involved in the tests. Measurements of the airplane's deviation from the flight path and of pilot control movements were recorded throughout the runs.

Two subjects were used in the demonstration runs. Both were instructor-pilots from an F-4 Replacement Air Group. Neither had flown in F-5E aircraft. The demonstration tasks consisted of flying a closed course, as shown in Fig. 14. The course consisted of a takeoff, a series of gentle turns, a 180 deg climbing turn, a straight segment with gentle pitch changes followed by a climb to an altitude of 10,000 ft, a 30 deg dive-bombing run on an electronically generated target, a 4-*g* pull-out at 2200 ft, another 180 deg turn, and, finally, an

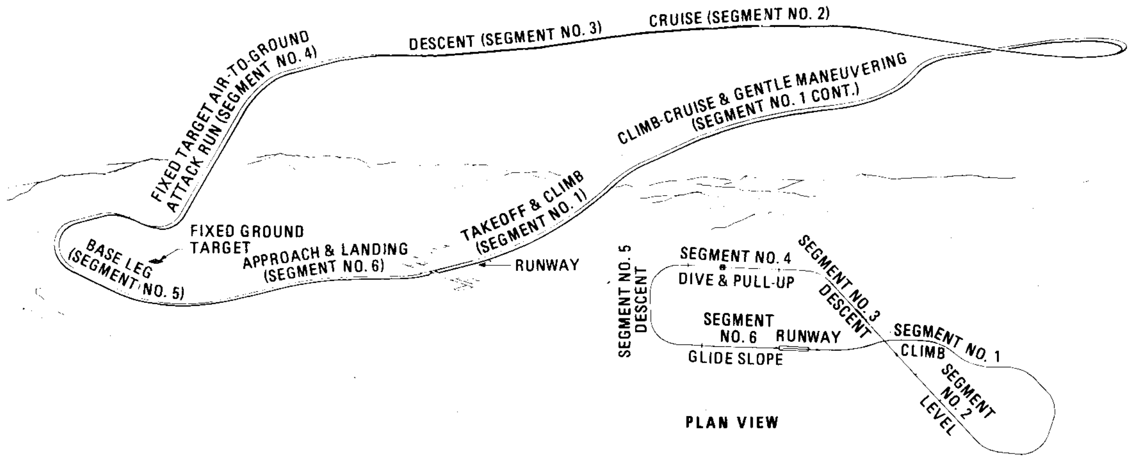



Fig. 14 Feasibility demonstration flight plan.

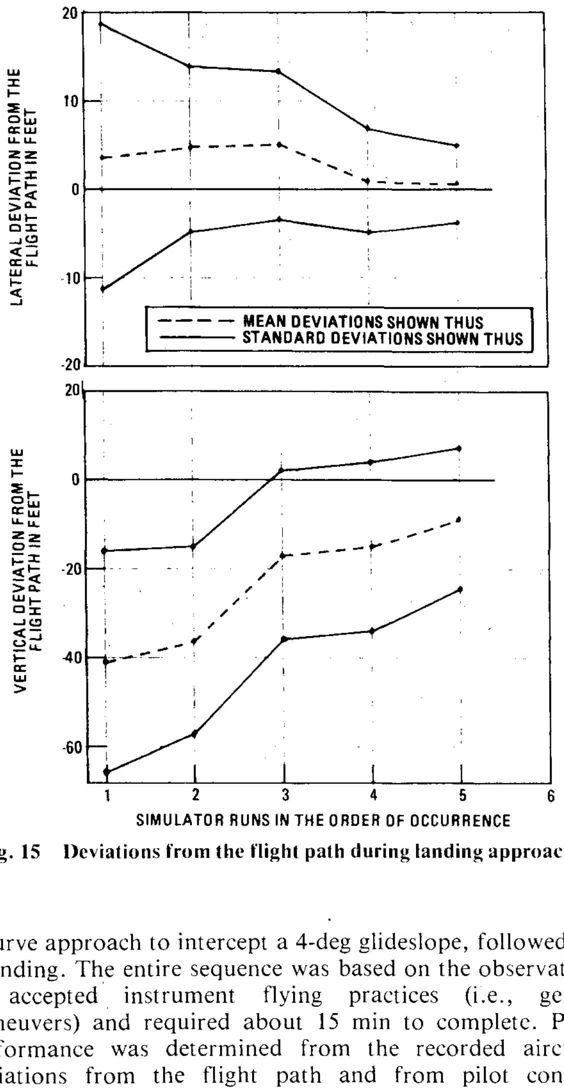



Fig. 15 Deviations from the flight path during landing approach.

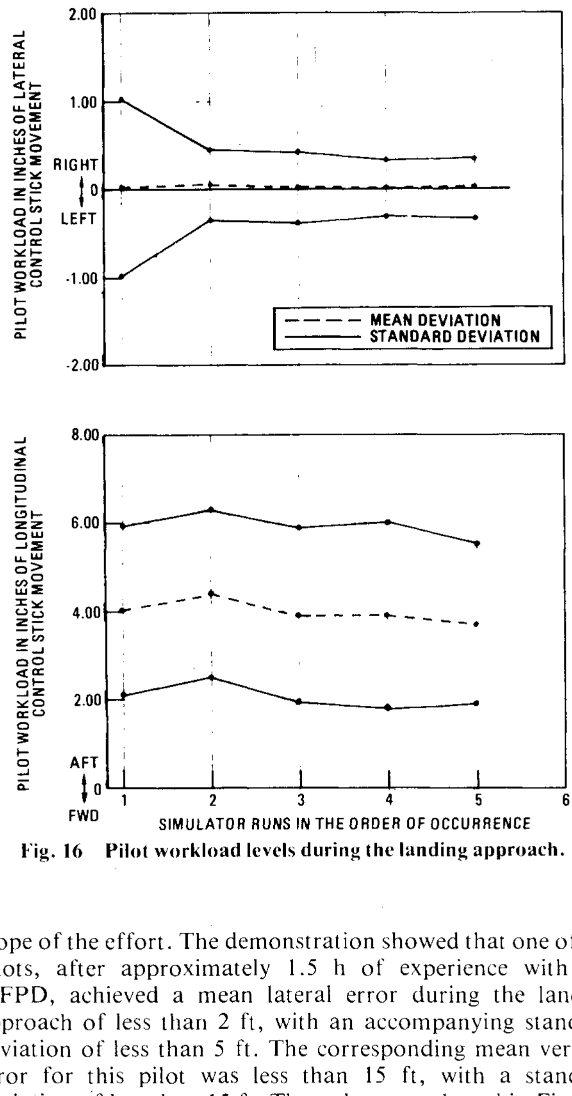
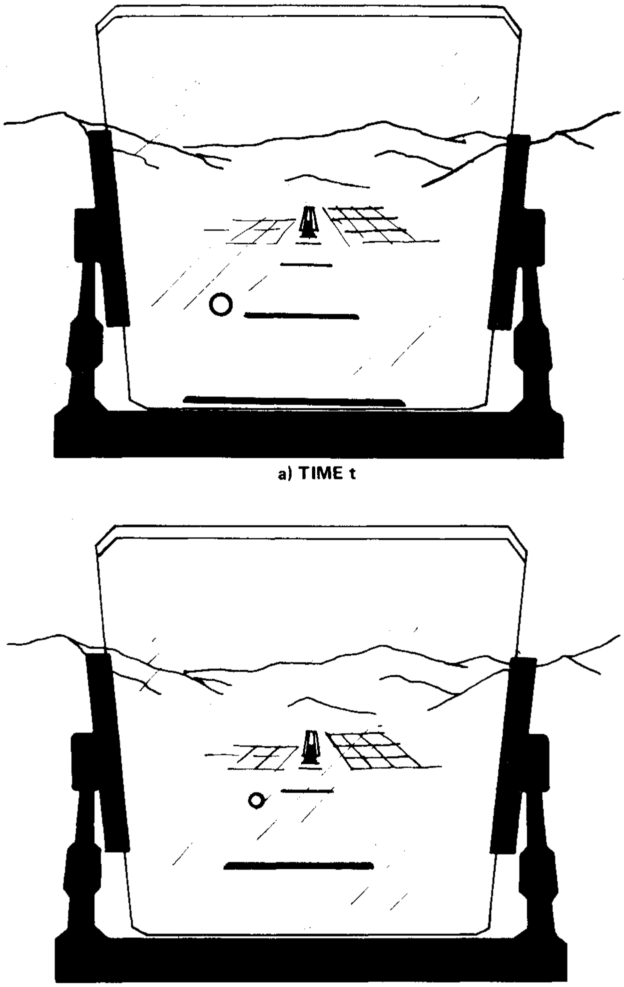



Fig. 16 Pilot workload levels during the landing approach.

S-curve approach to intercept a 4-deg glideslope, followed by a landing. The entire sequence was based on the observation of accepted instrument flying practices (i.e., gentle maneuvers) and required about 15 min to complete. Pilot performance was determined from the recorded aircraft deviations from the flight path and from pilot control movement measurements. Pilot comments on the effectiveness and desirability of the flight-path display were also recorded.

The simulation runs using the maneuvering flight-path display demonstrated that the concept is feasible and desirable for all of the contemplated Earth-referenced applications. Pilot comments were favorable on all conceptual aspects of the simulated flights, and performance measurements confirmed that precise trajectories were being flown with the display. Comparisons of the MFPD with conventional methods of performing instrument landings were beyond the scope of the effort. The demonstration showed that one of the pilots, after approximately 1.5 h of experience with the MFPD, achieved a mean lateral error during the landing approach of less than 2 ft, with an accompanying standard deviation of less than 5 ft. The corresponding mean vertical error for this pilot was less than 15 ft, with a standard deviation of less than 15 ft. These data are plotted in Fig. 15. Using the number of control movements as a coarse index of pilot workload, it was also observed that the pilot workload level in the roll channel (i.e., the lateral movement of the stick) diminished as more experience was gained with the flight-path display. The pilot workload in the pitch channel remained relatively constant throughout the tests. However, the level that was measured is not considered to be excessive. These data are shown in Fig. 16. The rapidity with which the two pilot subjects learned to "fly" the MFPD and the simulated F-5 dynamics clearly illustrates the potential ef-



a) TIME t

b) TIME t + Δt

Fig. 17 The flight-path display with the spherical velocity marker as it would appear on the pilot's head-up display at times $t$ and $t+\Delta t$ to denote "on path and too slow" while on final approach for landing.

fectiveness of the display. In comparison with the F-4, which the two pilots fly regularly, the F-5 is a more sensitive aircraft in both pitch and roll. Yet, despite the differences in dynamics, the pilots quickly adjusted to the simulator task and effectively flew the MFPD. This is considered to reflect favorably on both the skill of the two pilots involved and the effectiveness of the flight-path display. The results indicate that the Earth-referenced maneuvering flight-path display concept constitutes a promising means of meeting the objectives of increased system performance, increased flight safety, and decreased crew training, and its development should be continued.

## V. Concluding Remarks

In addition to the findings that demonstrate the feasibility of the flight-path display concept, a number of other significant conclusions were reached in the course of the demonstrations. Prior to the feasibility demonstration, it had been postulated that it would be necessary to generate a "transitional segment" in conjunction with the pure Earth-referenced flight-path display. The demonstration confirmed this belief. Essentially, the nearest 5000 ft or so of the displayed flight path would constitute the transitional segment. The transitional segment would always command maneuvers to keep the aircraft on, or direct the aircraft back onto, the pure Earth-referenced flight path. The near end of such a transitional segment would be referenced to the airplane so that the airplane would never deviate from it beyond a predetermined "window" of acceptable deviation. In other words, the aircraft could never get off the flight path beyond the limits defined by the "window." Thus the pilot would never lose essential velocity (V) and normal load factor (N) information when the aircraft excursions from the prescribed flight path became large. With a pure Earth-referenced flight-path display, the pilot could conceivably exceed the airplane's V-N limits (see again Fig. 12) when the airplane's deviation from the flight path became so large as to invalidate the V-N information being given by the display (i.e., the V-N information given by the flight-path display is valid only when the aircraft is on, or very nearly on, the flight path).

Another subject of interest was whether or not a hidden line algorithm would be necessary for the more complex flight-path trajectories. Speculation on this matter arose from the fact that, in the course of some air-to-ground strike maneuvers, the far segments of the flight path will appear behind the near segments and tend to clutter the display and confuse the presentation. In the instances where this overlaying occurred in the demonstrations, it served to increase the anticipatory information content of the display and actually proved to be beneficial. In view of the relative simplicity of the flight-path trajectories used in the demonstration, however, it would be inadvisable at this time to conclude that overlaying will always produce beneficial effects. Accordingly, this matter will be investigated in the near future.

It was believed prior to the demonstration that the flight-path field-of-view requirements would be compatible with even the very limited fields of view (i.e., approximately 15 deg) that characterize the early generation of operational HUD's. The demonstration showed that vital anticipatory information, which the flight path is capable of providing, is lost when the total field of view is less than 20 deg. An even larger field of view will be required if high-acceleration maneuvers are involved. A number of HUD's now entering production afford total fields of view that are equal to or greater than 20 deg; therefore, this limitation may not prove to be a serious problem. However, this matter, too, will be the subject of future study.

In the course of predemonstration trial runs, the velocity markers as shown in Figs. 1-9 were found to be distracting to the pilot. The concept of maintaining speed by "flying formation" with the velocity markers in itself did not appear to be invalid. Rather, the problem seemed to be simply one of visual noise resulting from the size, shape, brightness, and number of velocity markers involved. Although the final resolution of this problem is still pending, some improvement was realized by going to a single, spherical velocity marker. The spherical marker shown in Fig. 17 was flown in the subsequent demonstration runs.

The other mechanization problems encountered in the course of the effort were minor and pertained more to developmental than to conceptual issues. At this time, none of the problems appear to be cause for serious concern, either with respect to the feasibility of mechanization or the validity of concept. The Earth-referenced maneuvering flight-path display should be mechanized on the NADC simulator and in the NATC DEFT airplane within two years.