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Evaluation of Two Cockpit Display Concepts for Civil Tiltrotor Instrument Operations on Steep Approaches

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ABSTRACT

A piloted simulation experiment was conducted using the NASA Ames Research Center Vertical Motion Simulator to evaluate two cockpit display formats designed for manual control on steep instrument approaches for a civil transport tiltrotor aircraft. The first display included a four-cue (pitch, roll, power lever position, and nacelle angle movement prompt) flight director. The second display format provided instantaneous flight path angle information together with other symbols for terminal area guidance. Pilots evaluated these display formats for an instrument approach task which required a level flight conversion from airplane-mode flight to helicopter-mode flight while decelerating to the nominal approach airspeed. Pilots tracked glide slopes of 6, 9, 15 and 25 degrees, terminating in a hover for a vertical landing on a 150 feet square vertipad. Approaches were conducted with low visibility and ceilings and with crosswinds and turbulence, with all aircraft systems functioning normally and were carried through to a landing. Desired approach and tracking performance was achieved with generally satisfactory handling qualities using either display format on glide slopes up through 15 degrees. Evaluations with both display formats for a 25 degree glide slope revealed serious problems with glide slope tracking at low airspeeds in crosswinds and the loss of the intended landing spot from the cockpit field of view.

FLIGHT DIRECTOR SYMBOLS

ABAR	Roll command bar displacement
CTAB	Power lever command tab displacement
EBAR	Pitch command bar displacement
K_A	Roll command bar gain
$K_{C\dot{z}}$	Height rate error gain for power lever
K_{Cz}	Altitude error gain for power lever
K_C	Power lever command tab gain
$K_{C\dot{x}}$	Velocity error gain for power lever
K_{DC}	Power lever position washout gain
K_E	Pitch attitude command bar gain
$K_{E\dot{x}}$	Velocity error gain for pitch attitude
$K_{E\dot{z}}$	Height rate error gain for pitch attitude
K_{Ez}	Altitude error gain for pitch attitude
$K_{\dot{y}}$	Lateral velocity error gain for roll attitude
$K_{\dot{\theta}}$	Pitch rate gain for pitch attitude
K_{θ}	Pitch gain for pitch attitude
$K_{\dot{\phi}}$	Roll rate gain for roll attitude
K_{ϕ}	Roll attitude gain for roll attitude
K_y	Yaw attitude gain for roll attitude
s	Laplace operator
ϕ	Roll attitude
λ_{Awo}	Lateral command bar washout frequency
λ_{Cwo}	Power lever command tab washout frequency
λ_{Ewo}	Pitch command bar washout frequency
θ	Pitch attitude
τ_A	Lateral stick position washout filter time constant
τ_C	Power lever position washout filter time constant
τ_{CL}	Power lever position lead filter time constant
τ_E	Longitudinal stick position washout filter time constant
ψ_{ac}	Aircraft yaw attitude

INTRODUCTION

Increased air travel using hub-and-spoke airline systems has increased airport air traffic congestion and delays. A feeder airline system based on vertical flight aircraft, principally tiltrotor aircraft, has been proposed as a means of alleviating the conventional, long-haul aircraft runway operations problems (Ref. 1). Such a system would employ vertiports, conveniently located to population and industry centers. Vertiport design must

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consider both the land requirements for obstruction clearance (Ref. 2) and community noise impact (Refs. 3-4). Steep terminal operations have been proposed as a possible means of reducing vertiport land requirements and noise impact (Ref. 1).

Government and industry studies seek to define operational and aircraft design requirements for a civil tiltrotor transport and the ground and airway infrastructure required to support it. As part of this effort, a series of piloted simulation experiments was conducted at NASA Ames Research Center to identify handling qualities and flight mechanics influences on terminal operations and cockpit design issues for civil tiltrotor transports (Refs. 5 & 6). Reference 6 describes two experiments. The first experiment utilized "raw data" glide slope and localizer approach guidance and demonstrated the need for improved flight path cuing. The second experiment evaluated two display concepts: a four-cue (pitch, roll, power and nacelle angle) flight director and a flight path vector display. The flight path vector display presented instantaneous aircraft state information and a suggested flight path in the terminal area. It represents an alternate display and guidance technology which should provide the pilot with better situational awareness by graphically presenting information as it might be viewed from the cockpit windshield. This second civil tiltrotor terminal operations simulation experiment provided the initial evaluations of this display concept applied to tiltrotor aircraft. Pilot handling qualities ratings and comments and objective task performance measures for the flight director were reported in Reference 6. This paper expands upon that report and documents similar results using the alternate flight path vector display, thereby providing a comparative assessment of the two display concepts.

This paper presents the design, conduct, and results of the piloted simulator investigation of the two display concepts for the instrument approach task flown to civil transport standards. Recommendations for further development and evaluation are provided.

EXPERIMENT DESIGN

Facility

The experiment was conducted using the NASA Ames Research Center Vertical Motion Simulator (VMS). The VMS features a reconfigurable, interchangeable, cockpit cab mounted on a large motion platform as shown in Figure 1. Maximum vertical acceleration capability is limited to ±0.67g. Since longitudinal cues are particularly important during tiltrotor conversion operations, the cab was oriented for the longitudinal axis motion along the main beam of the VMS, turning it 90 degrees to that shown in Figure 1. With this cab orientation, the maximum longitudinal acceleration limit is ± 0.5g. The lateral acceleration capability of the VMS was not used for this experiment. The motion washout logic used in the VMS is described in detail in Reference 7. Table 1 lists the motion gain and filter frequencies used for the low speed operations of the simulation experiment.

The simulator cockpit was configured to provide a basic instrument panel with sufficient instrumentation for tiltrotor instrument approaches (Figure 2). The center panel CRT display presented computer-generated images of either conventional instruments (Figure 3) or a flight path vector display (Figure 4). The conventional instrument display provided a "standard T" layout (the attitude-direction indicator, ADI, above the horizontal situation indicator, HSI, and flanked by airspeed, torque and rotor speed on the left and altitude, climb rate and radar altitude on the right). The flight path vector display provided an abstract representation of cues available in visual flight plus aircraft state data. The functions of the flight path vector display symbology are described later in this paper. For both displays, the nacelle angle was displayed on an analog instrument to the left of the center panel CRT and on a digital display immediately above the CRT. A digital distance measuring equipment (DME) display was located above the altitude indicator and provided the horizontal distance to go to the landing spot.

The experiment used a three-window cockpit view with the external scene provided by an Evans and Sutherland CT-5A Computer Image Generation system. The three windows were arranged horizontally, covering a field of view approximately 140 degrees wide by 34 degrees high as shown in Figure 2. This provided a 17 degree look-down capability. An alternate window arrangement having a right lower "chin" window instead of the left side view was available, but pilots preferred the three-across arrangement. Reasons cited included the desire for mostly level pitch attitude operations of a commercial transport, a preference for the velocity and position cues provided by the left side window, and the small size and generally poor visual cuing provided in the chin window.

Control inceptors included a center stick, pedals and a power lever with the nacelle beep switch located on its grip (see Fig. 2). The throttle-like power lever geometry was similar to that used in the V-22. As shown in Figure 5, the grip reference point rotated from a position just aft of vertical for minimum power through 24 degrees forward for maximum power, with a total linear motion of four inches. A laterally-oriented thumbwheel on the power lever grip was used to control a lateral translation control mode, described below. The flaps were automated based on schedules of nacelle angle and airspeed. The landing gear was extended throughout the approach evaluation task.

A system of preprogrammed nacelle angle stops was developed to assist the conversion from airplane mode to helicopter mode. The stops were typically provided at 60, 80 and 90 degree nacelle angles. In addition to the tiltrotor continuous movement "beep" controller, pilots could activate a semiautomatic nacelle movement system. Depressing a button on the power lever started the nacelles moving aft at a fixed rate to the next stop. Forward movement of the nacelles, toward airplane mode, was not inhibited by these stops.

Aircraft Model

The aircraft math model was based on the generic tiltrotor simulation model (Ref. 8) and configured as a large transport of 40,000 pounds gross weight. An attitude command-attitude stabilization control system was used for pitch and roll. Yaw axis augmentation featured heading hold at low speeds (below 40 knots) and turn coordination at high speeds (above 80 knots) with linear blending between these modes. The control system was derived from an early design intended for the V-22 (Ref. 9). Table 2 lists approximate aircraft dynamic response characteristics identified using the "CIFER" system identification software described in Reference 10. A torque command and limiting system (TCLS) was employed for the power lever controller (Ref. 11). A lateral translation control mode, LTM (Ref. 9), was implemented to provide nearly pure, wings level, side force in helicopter mode by applying lateral cyclic pitch to both rotors.

The aircraft mathematical model was implemented on a digital simulation computer which cycled at 26 msec. The computational pipeline for the CT-5A produced a new external view image 100 msec after a new aircraft position was supplied by the mathematical model. The cockpit panel center display received update information from the main simulation every other cycle, i.e. every 52 msec. The panel display image had an asynchronous delay of up to 33 msec.

Evaluation Task

The experiment investigated an instrument approach task with evaluation subtasks of: (1) a level flight conversion to approach configuration and airspeed, (2) glide slope tracking, and (3) completion of the landing following breakout. Evaluation atmospheric conditions are listed in table 3. The winds and turbulence were modeled using the "BWIND" routine described in Reference 12. Crosswinds (speed and direction) remained constant to touchdown with no wind shear modeled near the ground. Approach angles of 6, 9, 15 and 25 degrees were investigated. Based on previous flight research experience at NASA Ames (Ref. 13), the nominal glide slope tracking airspeed was adjusted for each approach angle to keep the rate of descent below 1000 feet per minute. Table 4 lists the approach speed and nacelle angle specified for each glide slope.

The nominal approach profile shown in Figure 6 guided flight director command law development. It was briefed to pilots using the flight path vector display as the recommended procedure. Evaluation runs were begun in airplane mode in level flight at 180 knots, 1300 feet altitude above ground level (AGL), 6.5 nm out from the landing spot, and offset from the localizer by 1000 feet. The pilot's first task was to capture and track the localizer as closely as possible. Deceleration and conversion toward helicopter mode began approximately 4 nm out. A pause in the configuration change was recommended at the intermediate configuration of 120 knots and 60 degrees nacelle angle. This allowed the aircraft to stabilize on a trim condition prior to commencing the final nacelle angle change before glide slope intercept. The conversion was continued to 80 knots and 80 degrees nacelle angle. This condition placed the aircraft at the airspeed for minimum level flight power required in helicopter-mode. It also served as the nominal approach configuration for a 6 degree glide slope. The 6 degree glide slope was intercepted and captured at 2 nm out. For steeper glide slopes, a further level flight deceleration and movement of the nacelles toward the helicopter position took place prior to glide slope intercept and capture. Table 4 lists these nominal approach configurations.

Pilots were required to decelerate to a hover above a minimum-sized, 150 feet square, vertipad (Ref. 2). The flight director command laws were adjusted to terminate the approach in a hover at 10 feet altitude above the landing pad, on glide slope. Pilots completed a vertical landing using visual cues. Following the flight path vector display, a pilot would achieve a hover at 30 feet altitude over the center of the vertipad. The pilot could then complete the vertical landing visually or by using the vertical landing guidance provided by the display.

Flight Director

A flight director which drove command needles on the ADI (Figure 3) was adapted from earlier flight evaluations on the X-22 (Ref. 14) and simulation evaluations of the XV-15 (Refs. 5 and 15). Pitch and roll command bars were displayed on the ADI with "fly to" logic, i.e. a pitch up command would be displayed as an upward deflection of the flight director pitch command bar movement. Similarly, a command to fly to the right would be displayed as a roll command bar displacement to the right. A supplemental scale with an indicator tab for power lever position was placed to the left of the ADI, as shown in Figure 7. During the experiment set-up phase, this tab was selected to drive in a "fly from" fashion, i.e. a command to reduce power was displayed when the moving (rectangular) tab was above the fixed (diamond) center reference. This sensing seemed to better match pilot responses with the power lever motion. An airspeed schedule prompted nacelle angle movements via a "beep nacelle" ("ITVIC" of Ref. 14) command light on the cockpit panel and by an upward pointing triangle above the power command indicator as seen in Figure 7.

Drive laws for the flight director command symbols were adapted from a design for the XV-15 (Ref. 5). They were tailored to the transport tiltrotor model with airspeed-based gain changes. The flight director response was tuned to the aircraft response to provide "K/s" controlled-element (flight director needle) response to pilot input for pitch and roll. Power director tab dynamics approximated "K" response for the height rate control task on the steep approaches. Incremental configuration changes were commanded through the "beep nacelle" symbol and based on a desired airspeed versus nacelle angle schedule. The command law in pitch was:

$$\mathrm{EBAR} = K_{\mathrm{E}}\begin{bmatrix} K_{\mathrm{E}\dot{x}}\varepsilon_{\dot{x}} + K_{\theta}\dfrac{s\theta}{s+\lambda_{\mathrm{Ewo}}} + K_{\dot{\theta}}\dot{\theta} \\ +K_{\mathrm{E}\dot{z}}\varepsilon_{\dot{z}} + K_{\mathrm{E}z}\varepsilon_{z} \end{bmatrix}\frac{1}{\tau_{\mathrm{E}}s+1}$$

where $\varepsilon_{()}$ represents the difference between the commanded flight profile and the actual path. Similarly, the roll command bar (ABAR) and power lever command tab (CTAB) were driven by:

$$\mathrm{ABAR} = K_{\mathrm{A}}\begin{bmatrix} K_{\dot{y}}\varepsilon_{\dot{y}} + K_{\phi}\dfrac{s\phi}{s+\lambda_{\mathrm{Awo}}} \\ +K_{\dot{\phi}}\dot{\phi} + K_{\psi}\psi_{\mathrm{ac}} \end{bmatrix}\frac{1}{\tau_{\mathrm{A}}s+1}$$

$$\mathrm{CTAB} = K_{\mathrm{C}}\begin{bmatrix} K_{\mathrm{C}\dot{z}}\varepsilon_{\dot{z}} + K_{\mathrm{C}z}\varepsilon_{z} + K_{\mathrm{C}\dot{x}}\varepsilon_{\dot{x}} \\ +K_{\mathrm{Dc}}\delta_{\mathrm{C}}\dfrac{s}{s+\lambda_{\mathrm{Cwo}}} \end{bmatrix}\frac{\tau_{\mathrm{CL}}s+1}{\tau_{\mathrm{c}}s+1}$$

Values for the gains, washout frequencies, and time constants of these equations are listed in table 5 for airspeeds of 180 and 80 knots and hover. Note the shift in gains for the height ($K_{\mathrm{E}z}$) and height rate ($K_{\mathrm{E}\dot{z}}$) errors for the pitch (EBAR) and power lever (CTAB) commands as the airspeed moves from airplane mode at 180 knots to helicopter mode in hover. Opposite trend shifts in gains occur for the velocity ($\dot{x}$) gains. This technique is used to command a shift of flight control strategy such that pitch attitude is used to control altitude at high speeds while, in hover and at low airspeeds, altitude is controlled by power lever movements. Referring to the power-required-versus-airspeed curve, the pitch-attitude-for-altitude control technique is known as "front-side" while the latter technique for low speed flight is known as the "back-side" control technique.

Flight director command laws were designed to accomplish the approach task under instrument meteorological conditions (IMC) based on an approach profile using DME range to the landing spot. This profile required a level flight deceleration and conversion from airplane-mode flight to helicopter-mode flight at the desired approach speed. Conversion and deceleration were accomplished in two segments starting at 3.5 nm out to achieve a condition of 80 degrees nacelle angle at 80 knots by 2 nm from the intended landing spot. This condition represents the level flight minimum power required airspeed and signals a shift of control strategy to use power to control altitude (or glide slope angle) for the approach. The control strategy shift below 80 knots was commanded in the flight director drive laws by changing the gains on altitude and airspeed errors to feed those errors to the appropriate control command bar (pitch command for airspeed and power command for altitude or glide slope). For glide slope angles steeper than 6 degrees, an additional level-flight deceleration (at 0.1 g) was commanded for the pilot to slow the aircraft to the appropriate approach speed (see table 4). Glide slope intercept was commanded at a half degree of flight path angle change per second. Once on glide slope, a gentle deceleration was commanded, based on distance to go, to achieve a hover on glide slope at 10 feet altitude. The deceleration initiation point was adjusted based on the required time to decelerate from the approach speed to achieve the desired hover location. To keep the pitch attitude below 5 degrees nose-up, the deceleration was kept to a very low value, 0.025 g. This allowed the pilot to concentrate on the glide slope tracking task with power adjustments. Upon achieving a stable hover ten feet above the pad, pilots were instructed to complete the landing visually.

Flight Path Vector Display

As an alternative to the compensatory tracking form of the flight director, a flight path vector display format was evaluated. Based on display designs investigated at Ames Research Center for conventional transport (Ref. 16), short takeoff and landing (Ref. 17) and vertical takeoff and landing aircraft (Ref. 18), this flight path vector display sought to apply to tiltrotor aircraft a "situation" display philosophy featuring a flight path vector symbol representing the instantaneous flight path of the aircraft. The movements of earth-frame-related references, which include the guidance elements, reflect the pitch, roll and yaw motions of the aircraft in an "out-the-window" format. The guidance elements are presented as "follow the leader" advisors or "suggesters", which, if closely tracked by the pilot with the flight path symbol, provide precise control of the approach flight path. Abstract "command" indications as seen in a typical flight director display are avoided. Control of the aircraft during reconversion and approach is conducted essentially as in the visual flight mode. Without explicit prompting or command, as with a flight director, the pilot adjusts his control strategy from "front-side" to "back-side" as the reconversion toward helicopter mode progresses.

Aircraft status and guidance selection data are displayed in the upper right and left corners of the display as seen in Figure 4. The flap angle, as driven by the automatic flap system, and average engine torque, commanded and limited by the TCLS are displayed in the upper left corner. The selected altitude and heading and the status of the approach and landing guidance system appear in the upper right corner of the display. Some of these information blocks are deleted from the display function diagrams (Figs. 8-14).

Initial Approach Display — Figure 8 shows the symbols used for initial approach to a terminal area. The panel-mounted display used for this investigation provided a selection of colors to help separate symbols by function e.g. flight path, aircraft status, and guidance or command information. Significant features include a winged flight path symbol with aircraft status information arrayed about it, a horizon line and pitch ladder (omitted from Figure 8), and the aircraft attitude reference provided by a pair of large, subdued, diamonds. As illustrated in Figure 9, airspeed, altitude, longitudinal acceleration (referenced to the airspeed numerals), and either DME distance to a terminal (in airplane mode) or nacelle angle (in tiltrotor mode) are arrayed about the flight path symbol and move with it. Moving the nacelles off the airplane stops changes the flight path array by replacing the DME distance below the flight path symbol with nacelle angle. A bracket about the airspeed numerals is added which moves to represent the relative position (airspeed versus nacelle angle) in the conversion corridor. A longitudinal deceleration command may be displayed relative to the flight path symbol "wing tips" to convey a deceleration profile based on DME distance to the landing spot.

Several guidance command symbols are

available for the initial approach flight phase including a selected heading, specified or target altitude, and the selected approach angle (microwave landing system or equivalent capability assumed). Using these command symbols, the pilot flies the aircraft in such a fashion as to overlay the flight path symbol on the command heading line and the altitude reference as seen in Figure 10. This strategy will bring the aircraft onto the desired flight path.

Glide Slope Capture — When the aircraft enters the localizer capture cone as it approaches the terminal area, the pitch ladder field below the horizon line is replaced by perspective lines representing the ground plane (Fig. 11). The central line of this ground plane represents the extended runway or approach course. In addition, as the aircraft comes within the glide slope capture cone (defined as one third of the selected glide slope angle, e.g., within 2 degrees for a 6 degree glide slope), a "leader" symbol appears which represents an aircraft on the desired track, three seconds ahead of the own aircraft. Figure 11 shows the display view seen as the aircraft approaches the glide slope (from below it). As the aircraft approaches the glide slope from below, the leader symbol will descend until it overlays the glide slope reference line (the dashed horizontal line in Figure 11) at the point of glide slope intercept. A pilot may achieve a smooth glide slope capture by beginning the descent prior to the leader symbol overlaying the selected approach angle. Note that the runway centerline now terminates in a small "goal post" symbol at its lower end, which becomes larger in the display as distance to the landing spot decreases.

Also seen in Figure 11 are the acceleration command symbols which display error from the approach deceleration profile by their position with respect to the flight path symbol. A position above the flight path symbol indicates airspeed too high for the approach profile. The pilot obtains the nominal approach deceleration schedule by nulling the displayed error with respect to the flight path symbol, using power at high speed or pitch attitude at low speed.

Glide Slope Tracking — Pilot strategy on approach is to overlay the own-aircraft flight path vector symbol on the leader symbol to achieve the desired track. Figure 12 shows the display for a condition where the aircraft is above and to the left of the desired course track. The dashed line in this figure, extending from the landing spot "goal posts" through the leader symbol is not displayed but is drawn here to help the reader visualize the desired course track.

Hover and Vertical Landing — A unique hover symbology set is provided near the landing pad. It attempts to provide additional longitudinal position cuing for the landing without resorting to the planform view common to many hover displays. With the addition of a longitudinal "hover position" bracket, the display provides X-Y hover guidance while maintaining its consistent Y-Z plane perspective, similar to that seen outside the cockpit windshield.

Figure 13 shows the aircraft approaching hover over the landing spot. In this figure, the aircraft is on course, at 45 feet and 15 knots, with the nacelles in the pure helicopter position of 90 degrees. Following the leader symbol and nulling the acceleration command symbols will bring the aircraft to a hover at 30 feet altitude over the intended landing spot. At low speeds in the vicinity of the landing spot, the conversion corridor bracket is doubled in size and changed to a white color (as with other terminal guidance symbols such as the goal posts) and now represents the longitudinal position with respect to the intended landing spot.

With the aircraft in a hover within the desired landing zone, a display function switch, located on the center stick grip, may be cycled to provide vertical landing guidance. When activated, the leader symbol drops below the flight path symbol. Reducing power to overlay the flight path symbol on the leader symbol, as seen in Figure 14, will achieve a gentle landing.

Data Collection

Data collection included objective performance measures, such as tracking accuracy, and subjective measures, including Cooper-Harper Handling Qualities Ratings (Ref. 19) and pilot commentary. Figure 15 shows the dichotomous decision tree of the Cooper-Harper Handling Qualities Rating system. Task performance standards were established based on airline transport pilot (ATP) check flight criteria (Ref. 20). Adequate task performance was defined equal to the ATP standards. Desired task performance was defined as half the ATP standards. For the mostly decelerating approach task (little constant speed flight), desired performance standards included altitude (within fifty feet of the designated altitude in level flight) and guidance error (consistently less than a half "dot" error with no one "dot" exceedances). One "dot" error on the raw data indicators was 1.25 degrees in elevation and 2.5 degrees in azimuth.

Eight evaluation pilots, representing NASA, FAA, the British Civil Aeronautics Authority, Bell Helicopter Textron International, and Boeing Defense and Space Group, Helicopter Division participated in the experiment. Each pilot had both rotary-wing and fixed-wing flight experience. Four also had tiltrotor flight experience. All received familiarization training and task training in the simulator prior to beginning evaluations. Table 6 lists the number of pilots and evaluation runs contributing to handling qualities and performance statistics for each glide slope angle and display format combination.

RESULTS

The experimental results for each of the two display formats (flight director and flight path vector display) are described below for each of the evaluation subtasks of the instrument approach.

Initial Approach and Reconversion Using a Flight Director

During the initial approach phase, the aircraft was reconfigured from airplane mode to helicopter mode and decelerated to the final approach airspeed. The baseline transport tiltrotor configuration of this investigation produced a strong "ballooning" tendency during the initial phase of the reconversion due to early deployment of 40 degree flaps and the increment of rotor thrust aligned with the vertical axis. An alternate flap movement schedule based on both nacelle angle and airspeed and the development of a pilot-initiated, semiautomatic, nacelle movement control provided some workload relief. A large nose-down pitch input was still required, though, to maintain the desired altitude. The flight director helped prompt this movement. It also proved helpful in commanding a steady deceleration and prompting required nacelle movements.

Figure 16 shows handling qualities ratings for level flight reconversions flown in calm or turbulent conditions and ending at the nominal approach speeds for the four glide slopes investigated. Borderline satisfactory handling qualities were achieved for reconversions to airspeeds appropriate to approaches up to 15 degrees. A slight degradation in handling qualities was associated with reconversion and deceleration to the 20 knot airspeed required for the steepest (25 degree) glideslope. Pilot commentary identified workload (particularly in crosswinds and turbulence) during the final deceleration segment, from 80 knots to the approach speed, as the principal reason for degraded ratings.

The flight director commanded a deceleration at 0.1 g for the final deceleration below 80 knots required for approaches at 9, 15 and 25 degrees. This contrasts with the 0.025 g deceleration commanded on the glide slope. For the 6 degree glide slope, the on glide slope deceleration began at 80 knots, overlapping the airspeed range of the final level-flight deceleration used for the steeper glide slopes. Since the 0.025 g deceleration from 80 knots was successful on the 6 degree glideslope, one may infer that a smaller deceleration command might have helped the final level-flight deceleration required for the steeper glide slopes. Based on pilot commentary noting an abrupt nose-up pitch input to accomplish this final level-flight deceleration at 0.1 g, a slower deceleration should be investigated.

Task standards required maintaining less than 50 feet altitude variation during the level flight segment of the approach. The average maximum altitude gain during reconversions using the flight director was 51.6 feet for borderline satisfactory performance as reflected in the pilot ratings. Three of the 164 evaluation runs contributing to this statistic yielded altitude gains in excess of 100 feet, exceeding the tolerance for adequate performance.

Turbulence contributed to altitude control degradation as reflected in the handling qualities ratings for deceleration to the approach speeds for 6, 9 and 15 degree glide slopes. The average altitude gain in calm conditions was 45.2 feet, while the addition of crosswinds and turbulence resulted in a 55.4 feet average altitude gain. In contrast to level-flight decelerations for the other glide slopes where the peak altitude gain occurred early in the conversion, the peak altitude gain for deceleration to 20 knots often occurred in the final level-flight deceleration segment. This altitude peak during the final level-flight deceleration occurred in both calm and turbulent conditions, reflecting more on the commanded deceleration than the atmospheric conditions.

Glide Slope Tracking Using a Flight Director

Execution of the final approach using only raw angular tracking error instrumentation proved difficult on steep glide slopes in previous investigations (Ref. 6). The flight director was designed to provide additional instrument cuing important for control and tracking at the low airspeeds required for steep approaches. The flight director response and command laws provided cuing appropriate to the "backside-of-the-power-curve" control technique required for the approaches evaluated. It also commanded a deceleration on glide slope to achieve a hover just above the intended landing spot.

Figure 17 shows the handling qualities ratings for the glide slope tracking subtask with the flight director compared to previous results using raw guidance data only. Satisfactory glide slope tracking was achieved with the flight director on approaches up to 15 degrees. Ratings for the 15 degree glide slope were degraded somewhat by the loss of the intended landing spot from the cockpit field of view through much of the approach in clear conditions or after breakout in low visibility conditions. While particular cockpit windshield fields of view vary among aircraft models, this points to an important criteria for developing an approach procedure. The pilot must assure himself of a clear landing spot on final approach whenever atmospheric visibility conditions permit and certainly prior to moving over the landing spot. The 25 degree glide slope ratings reflect both the complete loss of visual contact with the landing spot and the increased workload required to correct for crosswinds and turbulence at the slow (20 knots) approach speed. Ratings for the 25 degree glide slope degrade to include some inadequate (very high workload) ratings in moderate turbulence. The spread of handling qualities ratings was much less with the flight director than with only "raw data guidance," reflecting the consistent performance and implicit workload reduction achieved with a flight director.

Objective task performance measures are consistent with the pilot ratings. Glide slope and localizer tracking errors are typically distributed equally on both sides of the desired path, averaging to a small, meaningless error statistic. Root mean square (rms) of the tracking error is a time-weighted average of the absolute value of the error; hence it is a better measure of tracking accuracy. The rms tracking errors were averaged for all pilots and atmospheric conditions for the four approaches. Figures 18 and 19 show the average rms tracking error for the glide slope and localizer, respectively. Also shown are the ranges of rms tracking error for the evaluation runs. Average tracking errors were less than 0.25 degree for glide slopes up through 15 degrees, with none worse than the "half dot" specified for desired performance. Tracking performance on the 25 degree glide slope averaged about a half degree, within the desired "half dot" criteria. Note that some runs on this glide slope, however, produced elevation tracking errors as large as 2.16 degrees, much worse than the "one dot" error specified for adequate performance. High workload coupled with large tracking errors caused the evaluation pilots to state that the 25 degree approach procedure with manual control using the flight director did not meet certification standards.

Initial Approach and Reconversion Using the Flight Path Vector Display

The flight path vector display provides cuing analogous to visual flight. While guidance for a nominal approach deceleration profile is provided, the pilot may fly a different airspeed profile. This display provides considerably better situational awareness of position during minor deviations when compared to the information provided by the flight director with its structured command approach profile. In contrast to the flight director, the flight path vector display, as evaluated, provides no discrete prompts for configuration changes, relying on the pilot to maintain flight within the nacelle angle-airspeed conversion corridor. In contrast to the flight director, which was largely conventional in presentation, the flight path vector display required considerable training for proper pilot interpretation and response to its symbology and graphical presentation.

Figure 20 shows handling qualities ratings for the reconversion and deceleration to approach airspeed subtask. Four pilots were trained sufficiently with the flight path vector display to contribute to these ratings. The 25 degree approach was rated by only two of the four evaluation pilots, somewhat reducing the statistical validity of the results presented. Satisfactory ratings were achieved with the flight path vector display for the conversion task. Pilots commented that displacements of the flight path vector symbol with respect to the horizon and the selected altitude symbol were sufficiently compelling to achieve tight altitude tracking performance. Altitude ballooning during configuration change was reduced to half that experienced with the flight director with an average maximum altitude gain of 24.3 feet. Reconversions in calm air produced an average maximum altitude gain of 20 feet while reconversions in turbulence produced an average maximum gain of 26.9 feet. Both altitude statistics were well within the desired tolerance of fifty feet.

Conversion cuing in the form of a sliding bracket around the airspeed numerals on the display was not compelling enough to prompt configuration changes. During a deceleration, as airspeed approached the lower conversion corridor bound at a fixed nacelle angle, the bracket bottom would move close to the bottom of the display's airspeed numerals. This situation should have prompted pilot action--typically a further aft movement of nacelle angle. Instead, pilots flew the approach task by initiating discrete steps in nacelle position at prebriefed DME distances. The semiautomatic nacelle movements, coupled with the modeled tiltrotor's drag characteristics, tended to keep the aircraft in the center of the broad conversion corridor. Thus the potential configuration change cuing provided by the corridor bracket was not used by the pilot, being replaced by the approach profile briefing which suggested configuration changes at specified DME distances. In the final analysis, pilots expressed a preference for discrete cuing (such as that provided by the "beep nacelle" light of the flight director) to prompt the required configuration changes at appropriate positions during the approach.

Glide Slope Tracking with the Flight Path Vector Display

Handling qualities ratings for glide slope tracking using the flight path vector display are shown in Figure 21. The glide slope tracking handling qualities were assessed as satisfactory up through a 15 degree approach in calm air. Handling qualities in crosswinds and turbulence degraded into the adequate range based on reported higher pilot workload at the slower approach speeds. Pilots reported a higher workload associated with all control axes to maintain the desired track. Most pilots commented on the lack of sufficient guidance for power lever positioning, reflecting more on the actual power lever geometry (to be discussed below) than the difficulty of height / flight path control during the approach. As with the flight director, degraded handling qualities ratings on glide slopes of 15 degrees and steeper, reflect the loss of the intended landing spot from the cockpit field of view.

Desired tracking performance was clearly achieved for glide slopes up through 15 degrees as shown by the flight path vector display tracking statistics in Figures 18 and 19. Glide slope and localizer tracking performance similar to that obtained with the flight director was achieved. With one third as many evaluation runs contributing to these tracking statistics, one should not draw too many comparisons between the two displays for the maximum rms error achieved. What is significant about the worst rms tracking errors are that they never exceeded the "half dot" error specified for desired performance. Thus, although the pilot workload increased on steeper glide slopes as reflected in the handling qualities ratings, the tracking performance remained consistently good up through a 15 degree glide slope.

With only two pilots rating the 25 degree approach, the numerical handling qualities rating and tracking error averages are included only for completeness. Pilot commentary associated with the use of the flight path vector display on the 25 degree glide slope amplified similar comments made for shallower glide slopes. Marginally adequate glide slope tracking performance (Fig. 18) and only adequate handling qualities (Fig. 21) were recorded for this glide slope angle. Detailed examination of the tracking performance data show adequate performance, on average, with an extended range from very good in calm conditions to worse than "one dot" tracking in moderate turbulence and crosswinds.

Both pilots reported extensive activity required in all controls axes with cuing insufficient for the large, precise, control inputs desired. In particular, they reported difficulty maintaining airspeed control, citing difficulty attaining precise pitch control as the issue. In contrast to the flight director which provided attitude command for airspeed control at low airspeed, the flight path vector display concentrated the pilot's attention on the control of flight path. On the 25 degree glide slope, the flight path symbol was displaced well below the display horizon which drew attention away from the pitch attitude references which were expected to remain near the horizon for level attitude. To obtain the desired attitude status, pilots had to scan a larger area of the display while maintaining precise flight path tracking. Within the scope of this evaluation, it was not clear whether this pilot concern for pitch attitude reference was a training, display design, or other flight dynamics and control issue.

Further development and evaluation are warranted for the use of the flight path vector display on steep glide slopes.

Flight Path Vector Display Issues

The flight path vector display was originally developed as a head-up-display (Refs. 16-18) where its angular presentation was conformal with outside visual cues. The pitch axis, in particular, was designed to displace on the display through the same angle as the real world when the display was viewed from the design eye point. This experiment employed the flight path vector format in a panel-mounted display which was expected to represent the display capability of a typical civil transport. As a panel-mounted display, the flight path vector display was no longer constrained to a conformal pitch scale, although conformal scaling was used for the shallower glide slope angles. Flight path status and guidance for the steepest glide slopes was accommodated on the panel mounted display with reduced pitch scaling (typically half of conformal scaling). This had a desensitizing effect on the display for these approaches, perhaps loosening tracking performance. Conversely, reduced scaling may be the technique needed to desensitize the flight path vector display for the shallower glide slopes which most pilots reported as too sensitive in response leading to higher workload. Further tuning of this display's sensitivity is warranted.

Displacement of the flight path vector symbol below the horizon was another aspect of the display affecting handling qualities ratings and comments on all approaches. Figure 12 provides an illustration of the display in use for glide slope tracking. Attention was focused primarily on the flight path vector symbol and the attempt to overlay it on the "leader" symbol. Steeper glide slope angles displaced the flight path symbol further below the horizon and pitch reference. Pilots had to develop new scan patterns to pick up the pitch reference which was normally close to zero (the horizon line) for the approach task.

Reduced awareness of the heading situation was an issue when the flight path vector symbol was displaced well below the horizon on steep glide slopes. With the heading tape overlaying the horizon and pilot attention focused on the flight path symbol, well below, pilots lost awareness of the heading situation. Pilots who reacted to the effect of crosswinds at low airspeed with a large crab angle required a large heading change upon breakout to locate the landing spot. Likewise, pilots who used sideslip to compensate for crosswinds required constant attention to both desired heading and flight path control. Both control strategies required awareness of heading which was well separated in the display from the flight path symbol. The desired heading was displayed with a large tick mark on the heading tape, but it was not easily identified.

All pilots noted the relatively long training time required to achieve a satisfactory skill level with the flight path vector display, especially relative to the more conventional presentation format of the flight director. Even after ten to fifteen hours of experience with the display flying a familiar task (approach and landing), pilots were discovering additional ways to use the display. This experience parallels that for previous uses of the flight path vector display philosophy on head-up displays (Ref. 16). Although some structured training with the display was conducted, a more structured training and familiarization program should be developed.

A strong feature of this display format was its consistent *Y-Z* plane presentation, to include the low airspeed portion of the envelope. The landing pad longitudinal position bracket alongside the airspeed numerals was easily interpreted for longitudinal position. The goal posts in the immediate area of the landing zone provided lateral position cuing. Most pilots commented favorably on the display's cuing for final hover position and let-down. Pilots noted, however, that use of the display for hover position was often driven by difficulties in transitioning between the display and outside visual cues. In addition, pilots noted for the final let-down using the display that the flight path vector symbol gave them instant feedback on power lever movements as they controlled height. The flight path vector symbol drive laws did not provide this height response cuing at speeds above those associated with hover.

Power Lever Geometry

Concern for wrong-way movement of the power lever during critical flight phases was frequently expressed by most pilots throughout this experiment. Its combination of shaft rotation and grip orientation (shown in Figure 5) provided the sense of a helicopter collective control at high power settings. Neither its throw length (4 inches) nor the fact that it rotated, much as an airplane throttle quadrant, were questioned; rather, it was the sensation of collective-like movement (up-down) but with opposite sense that provoked the concern expressed in pilot comments. The flight director provided a direct indication of power lever movement relative to a desired setting thus helping compensate for the power lever geometry and sensing. The flight path vector display had no such direct indication of power lever position, similar to flight with visual references. The lack of power lever position indication and consequent concern for improper power lever movement were frequently cited as increasing pilot workload with the flight path vector display. Development and evaluation of alternative power control inceptors is warranted for the approach and landing task.

CONCLUSIONS

A piloted simulation experiment conducted on the NASA Ames Research Center Vertical Motion Simulator investigated the use of two types of cockpit displays to help guide and control instrument approaches on steep glide slopes for a civil transport tiltrotor. The experiment was conducted with all aircraft systems functioning normally, full engine power available (no one engine inoperative evaluations), and with an attitude command control mode (pitch and roll, plus heading hold at low speeds). All approaches were carried through breakout to a vertical landing (no missed approaches). Environmental conditions included either clear or restricted visibility and either calm air or crosswinds with turbulence. Based on the results of 550 simulated approaches flown by eight evaluation pilots, the following conclusions may be drawn:

1. Pilots attained desired performance with both display formats on approaches up through 15 degrees. Generally satisfactory handling qualities were reported in calm conditions for these approaches. Crosswinds and turbulence degraded the handling qualities such that only adequate handling qualities were reported on a 15 degree glide slope.

2. Approaches on a 25 degree glide slope resulted in degraded performance and handling qualities with either display format. Pilot workload was strongly affected by crosswinds and turbulence, the large variations in power lever position required for height control at low airspeed to maintain glide slope tracking, and the loss of the landing spot from the cockpit field of view during visual flight segments of the approach.

3. The four-cue (pitch, roll, power and nacelle angle) flight director was quickly learned and easily interpreted. Pilots commented favorably on its configuration change (nacelle angle movement) prompts and the power lever cuing. The power lever cuing helped overcome a power lever geometry which was not well suited to the task and often was referred to during the final landing phase, even when hover longitudinal and lateral positioning was done with outside visual references.

4. The flight path vector display provided a *Y-Z* plane format, similar to an out-the-window view, for presentation of aircraft state, status (including torque and configuration settings) and guidance information for a variety of glide slope angles. Pilots achieved more precise altitude control during level flight conversions using this display. Pilots achieved precise glide slope tracking at the expense of higher workload than that experienced with the flight director. The flight path vector display provided flight status information in a format useful to operation in a variety of situations and warrants further development and evaluation.

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TABLE 1. Vertical Motion Simulator Motion Drive Characteristics

Motion Axis	Gain	Filter Break Frequency (rad/sec)
Roll	0.5	0.25
Pitch	0.5	0.7
Yaw	0.5	0.5
Longitudinal	0.6	0.7
Lateral	0.0	1.0
Vertical	0.8	0.25
Pitch-tilt	0.7	6.0
Roll-tilt	0.7	3.0

TABLE 2. Reduced-order Aircraft Response Dynamic Model Characteristics.

a. Pitch response to longitudinal stick:

$$\frac{\theta}{\delta_{\mathrm{LNG}}}=\frac{Ke^{-\tau s}}{\left[s^2+2\zeta\omega s+\omega^2\right]}$$

	Airspeed (knots) / Nacelle Angle (degrees)		
Parameters	Hover / 90	80 / 80	180 / 0
K, deg/in	22.4	20.0	23.0
τ, sec	0.0096	0.0	0.0043
ζ, ND	1.0	1.16	1.58
ω, rad/sec	1.27	1.36	1.30

b. Heave (height rate) response to power lever:

$$\frac{\dot{h}}{\delta_{\mathrm{THT}}}=\frac{Ke^{-\tau s}}{(s+a)}$$

	Airspeed (knots) / Nacelle Angle (degrees)		
Parameter	Hover / 90	80 / 80	180 / 0
K, ft/sec/in	9.23	16.3	N/A
τ, sec	0.041	0.052	
a, rad/sec	0.33	0.35	

TABLE 3: Evaluation Task Atmospheric Conditions

a. Winds

Wind Condition	Crosswind (knots)	Turbulence (feet per second, root mean square)
Calm	—	—
Light	5	1.5
Moderate	10	4.5

b. Visibility

Ceiling (feet)	Visual Range (feet)
Clear	unlimited
200	2000
100	1000

TABLE 4: Nominal Approach Conditions.

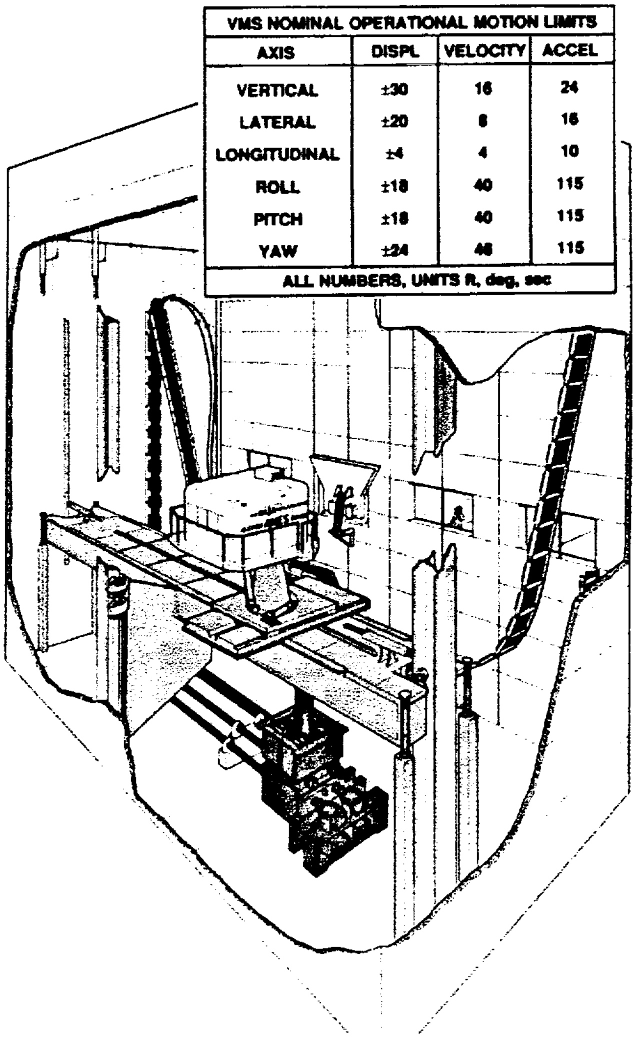
Glide Slope (degrees)	Airspeed (knots)	Nacelle Angle (degrees)
6	80	80
9	55	85
15	35	90
25	20	90

TABLE 5. Flight director gains.

	Hover	80 knots	180 knots
EBAR			
K_E, in/in	1.0	1.0	0.5
$K_{E\dot{x}}$, in/ft/sec	-0.0140	-0.0093	0
K_θ, in/rad	-3.50	-3.50	-3.50
λ_{Ewo}, 1/sec	0.1	0.1	0.1
$K_{\dot{\theta}}$, in/rad/sec	-1.40	-0.70	-0.70
$K_{E\dot{z}}$, in/ft/sec	0	0	-0.0150
K_{Ez}, in/ft	0	0	-0.0070
τ_E, sec	0.1	0.1	0.1
ABAR			
K_A, in/in	1.00	1.00	0.25
$K_{\dot{y}}$,in/ft/sec	0.055	0.055	0.055
K_ϕ, in/rad	-2.00	-2.00	-2.00
λ_{Awo}, 1/sec	0	0	0
$K_{\dot{\phi}}$, in/rad/sec	-0.60	-0.60	-0.60
K_ψ, in/rad	0	0	0
τ_A, sec	0.1	0.1	0.1
CTAB			
K_C, in/in	3.0	1.0	1.0
$K_{C\dot{z}}$, in/ft/sec	-0.010	-0.0250	0
K_{Cz}, in/ft	-0.015	-0.0070	0
$K_{C\dot{x}}$, in/ft/sec	0	0	0
K_{DC}, in/in	-0.30	-0.14	0
λ_{Cwo}, 1/sec	0.2	0.4	0.4
τ_{CL}, sec	0	0	0
τ_C, sec	0.1	0.1	0.1

TABLE 6. Evaluation runs and pilots.

	Glide Slope Angle (degrees)			
	6	9	15	25
Flight Director				
pilots	8	8	8	6
evaluation runs	46	44	42	31
Flight Path Vector Display				
pilots	4	3	4	2
evaluation runs	23	16	15	11



VMS NOMINAL OPERATIONAL MOTION LIMITS			
AXIS	DISPL	VELOCITY	ACCEL
VERTICAL	±30	16	24
LATERAL	±20	8	16
LONGITUDINAL	±4	4	10
ROLL	±18	40	115
PITCH	±18	40	115
YAW	±24	46	115
ALL NUMBERS, UNITS ft, deg, sec			

Figure 1. Vertical Motion Simulator. Cab was oriented along the beam for large longitudinal acceleration for tiltrotor simulation.

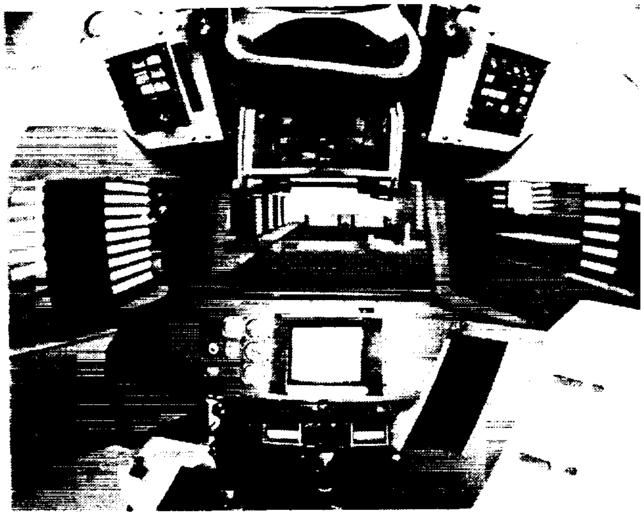


Figure 2. Cockpit interior. Visual scene portrays approach to urban vertiport.

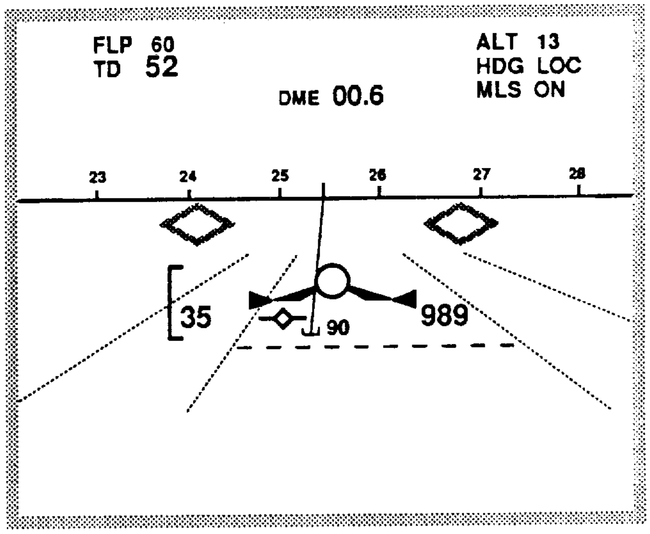


Figure 4. Diagram of flight path vector display for cockpit center panel CRT.

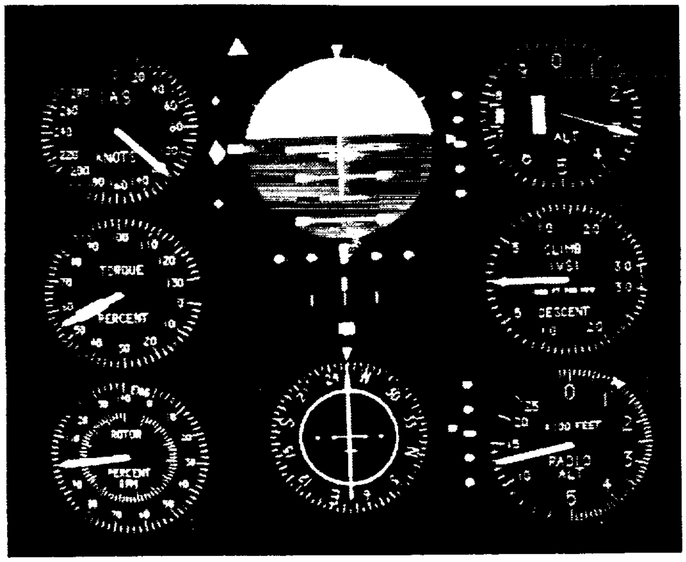


Figure 3. Central cockpit panel display with conventional instrument format.

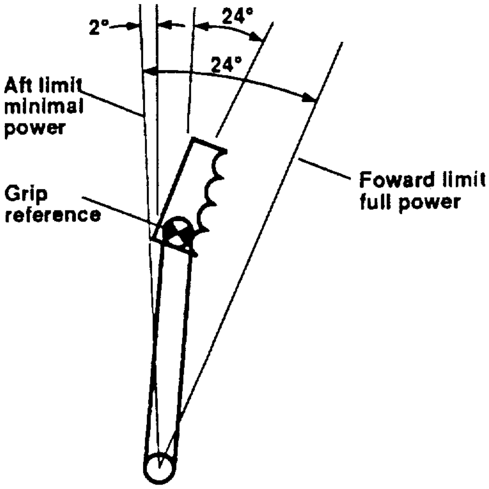


Figure 5. Power lever geometry.

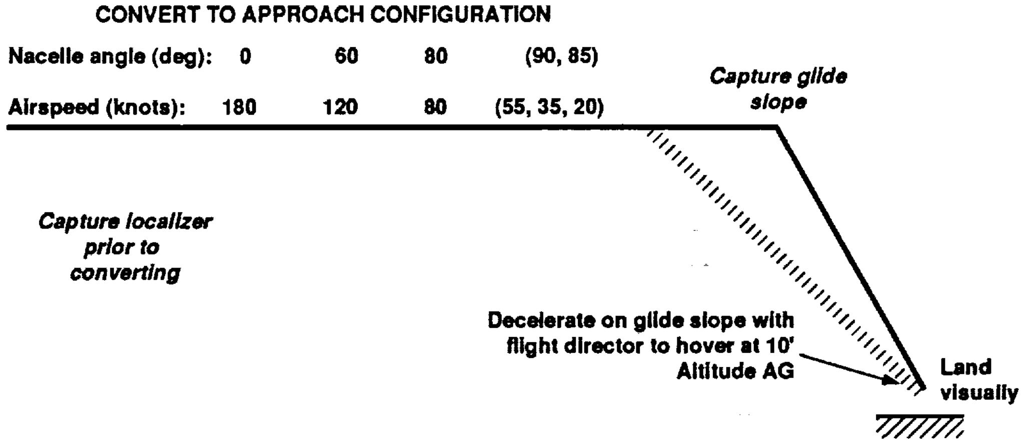


Figure 6. Approach profile.

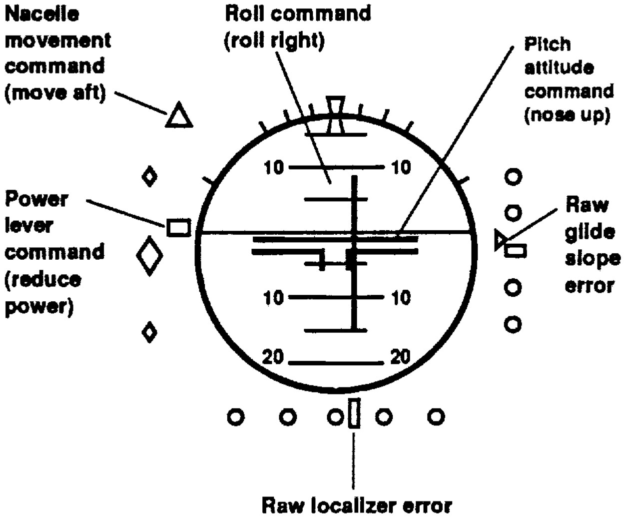


Figure 7. Flight director command symbols arrayed about the attitude direction indicator (ADI).

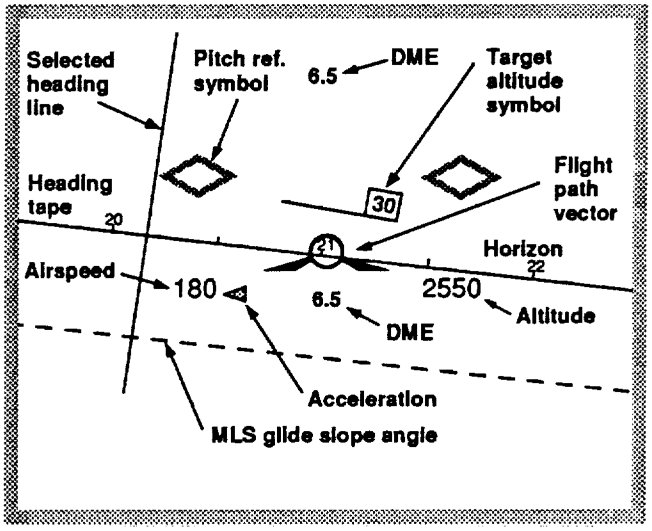


Figure 8. Flight path vector display for the initial approach.

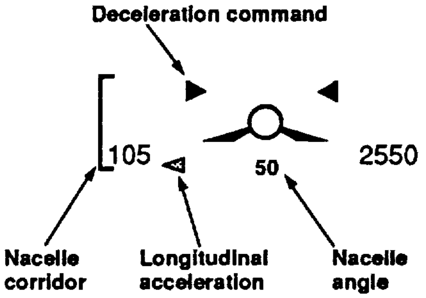


Figure 9. Flight path array elements

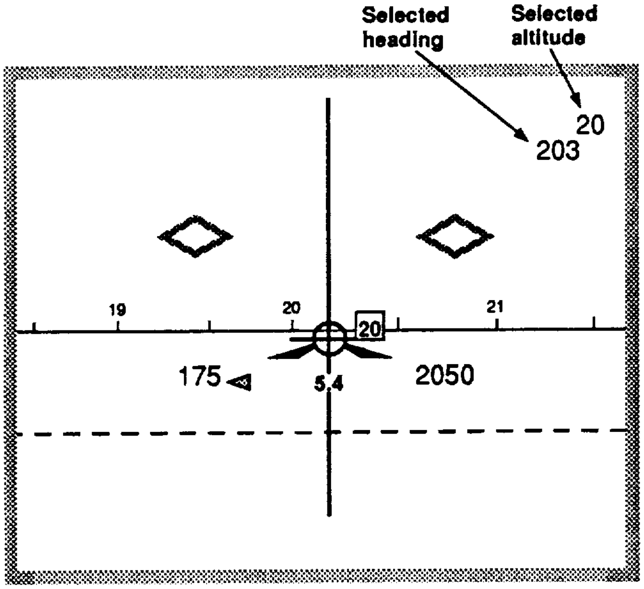


Figure 10. Flight path vector display showing flight on selected heading and approaching selected altitude. At the selected altitude (2000 feet), the selected altitude command bar will overlay the horizon. The aircraft is decelerating through 175 knots and is 5.4 nm from the DME reference point.

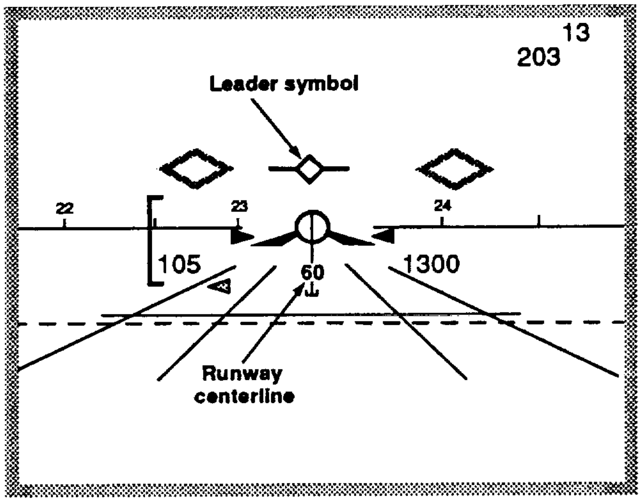


Figure 11. Flight path vector display approaching glide slope intercept (from below).

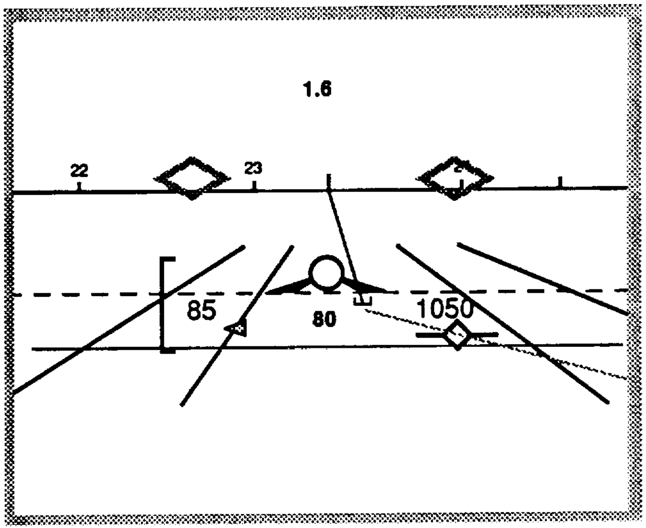


Figure 12. Flight path vector display on approach. Own aircraft is above and to the left of the desired glide slope.

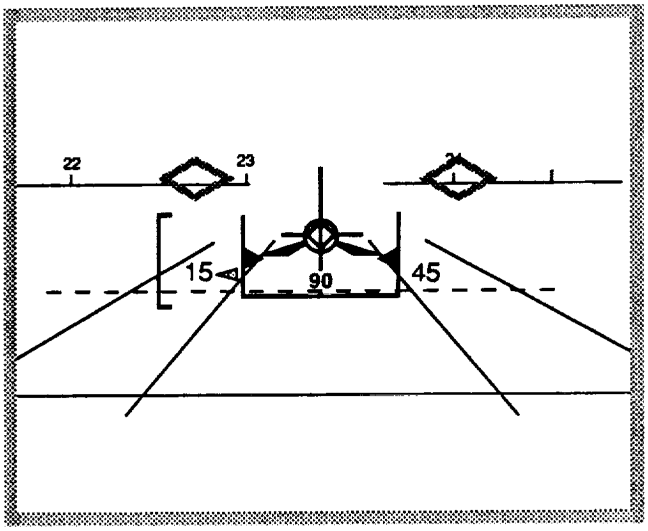


Figure 13. Flight path vector display on final approach to a vertipad.

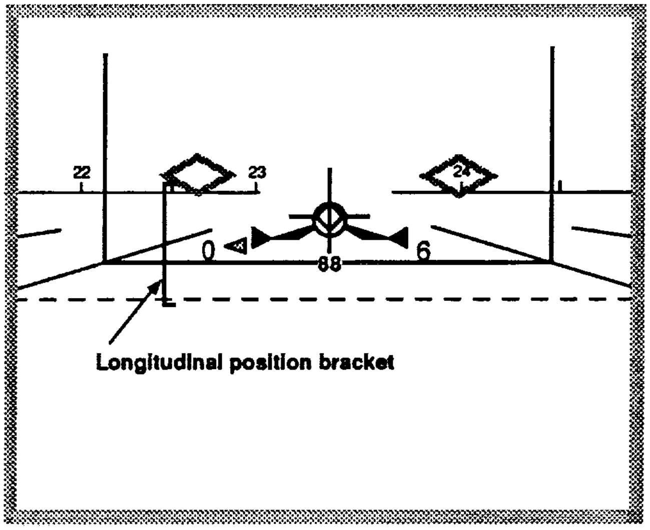


Figure 14. Flight path vector display showing vertical landing guidance.

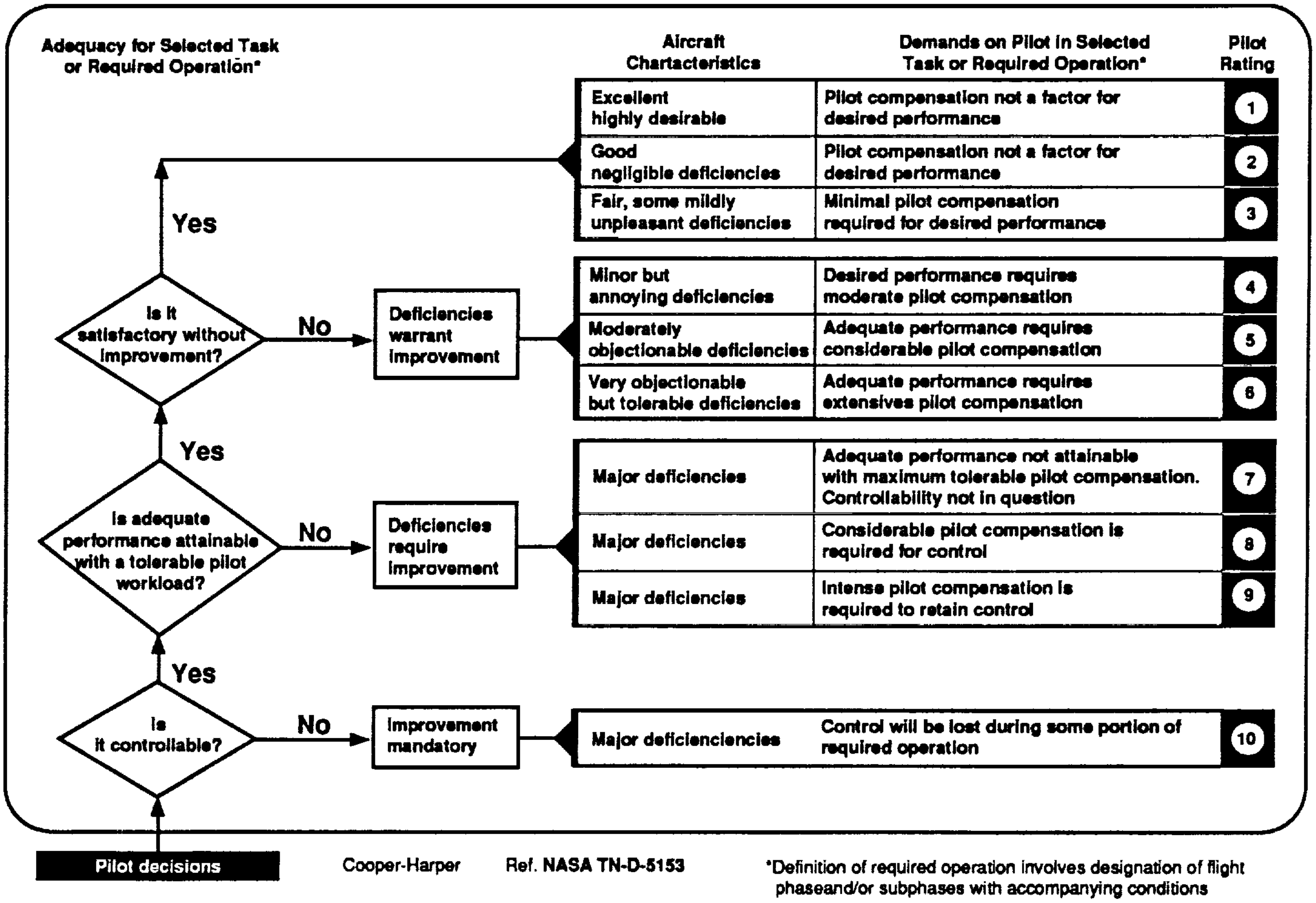


Figure 15. Dichotomous decision tree for Cooper-Harper Handling Qualities Ratings from NASA TND-5153 (ref. 18).

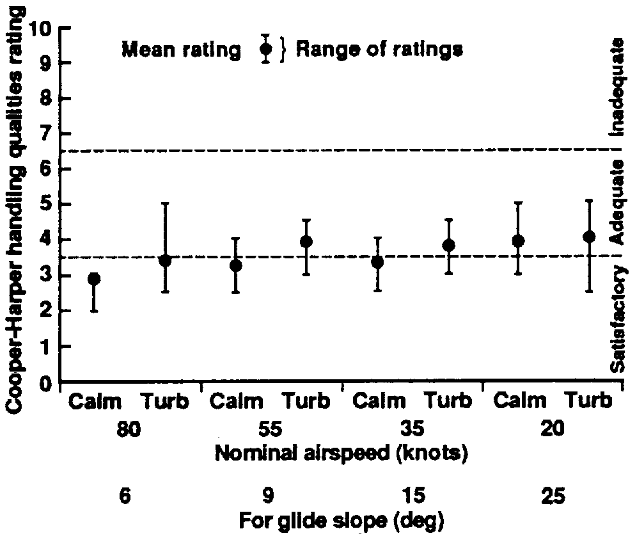


Figure 16. Level flight conversion handling qualities ratings using the flight director.

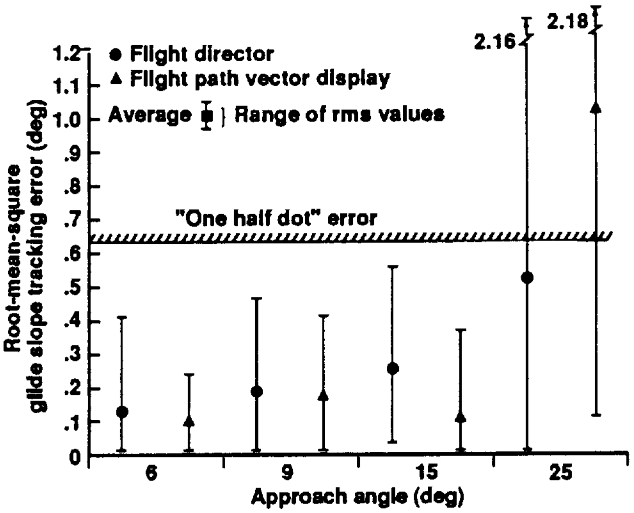


Figure 18. Glide slope elevation tracking root mean square error.

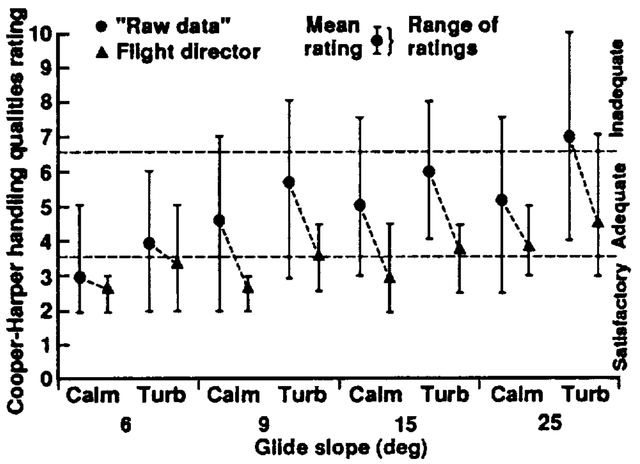


Figure 17. Handling qualities ratings for glide slope tracking using the flight director.

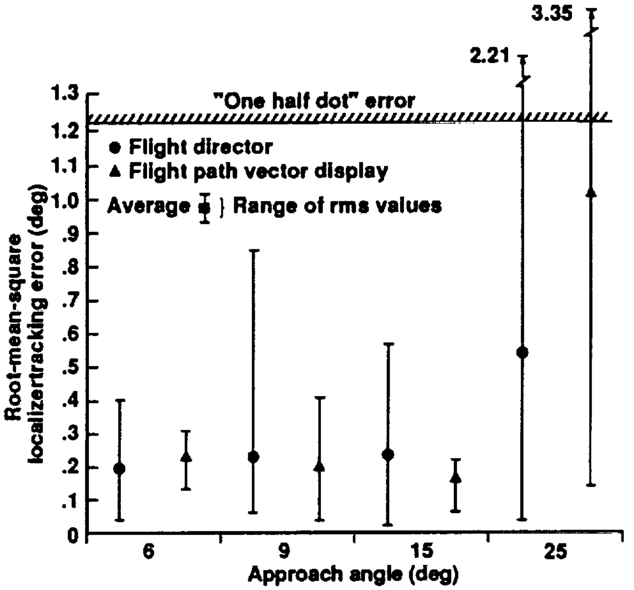


Figure 19. Localizer tracking root mean square error.

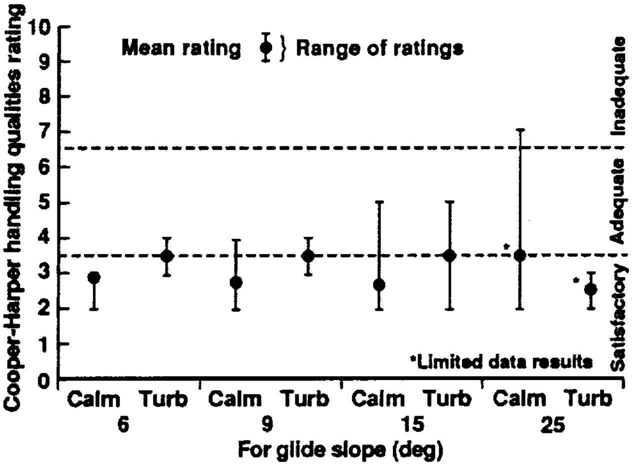


Figure 20. Level flight conversion handling qualities ratings using the flight path vector display.

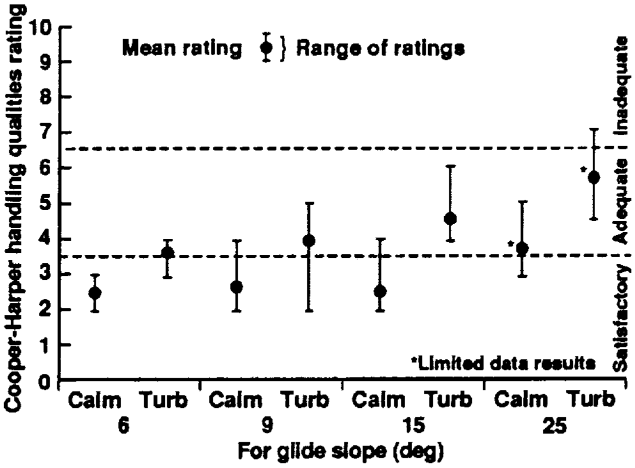


Figure 21. Glide slope tracking task handling qualities ratings using the flight path vector display.