IN-FLIGHT ASSESSMENT OF A PURSUIT GUIDANCE DISPLAY FORMAT FOR MANUALLY FLOWN PRECISION INSTRUMENT APPROACHES

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ABSTRACT

In-flight evaluations of a pursuit guidance display system for manually flown precision instrument approaches were performed. The guidance system was integrated into the RASCAL JUH-60A Black Hawk helicopter. The applicability of the pursuit guidance displays to the operation of Runway Independent Aircraft (RIA) is made evident because the displays allow the pilot to fly a complex, multi-segment, descending, decelerating approach trajectory. The complex trajectory chosen for this in-flight assessment began from a downwind abeam position at 110 knots and was hand-flown to a 50 ft decision altitude at 40 knots using a rate-command/attitude-hold plus turn-coordination control system. The elements of the pursuit guidance format, displayed on a 10-inch liquid crystal display (LCD) flat panel, consisted of a flightpath vector and a "leader" aircraft as the pursuit guidance element. Approach guidance was based primarily on carrier-phase differential Global Positioning System (GPS) navigation, and secondarily on both medium accuracy inertial navigation unit states and air data computer states. Required Navigation Performance (RNP) concepts were applied to the construction of display elements such as lateral/vertical deviation indicators and a tunnel that indicated to the pilot, in real-time, the performance with respect to RNP error bounds. The results of the flight evaluations of the guidance display show that precise path control for operating within tight RNP boundaries (RNP 0.007NM/24ft for initial approach, RNP 0.008NM/19ft for intermediate approach, and RNP 0.002NM/9ft for final approach) is attainable with minimal to moderate pilot workload.

NOMENCLATURE

CTOL	conventional take off and landing
DGPS	differential GPS
EADI	electronic attitude direction indicator
EP	evaluation pilot
FBW	fly-by-wire
FCC	flight control computer
FTE	flight technical error
GPS	global positioning system
GPU	graphics processing unit
HSD	horizontal situation display
HUD	head-up display
IFR	instrument flight rules
INU	inertial navigation unit
LAC	lateral acceleration command
LDI	lateral deviation indicator
NDG	navigation display generator
NM	nautical mile
PDG	programmable display generator
PFD	primary flight display
RASCAL	rotorcraft aircrew systems concepts airborne laboratory
RCAH	rate command attitude hold
RCHH	rate command heading hold
RIA	runway independent aircraft
RFCCA	research flight control computer assembly
RFCS	research flight control system
RTCM	radio technical commission for maritime services
SA	selective availability
STOL	short take off and landing
TC	turn coordination
TFU	trim follow-up
VDI	vertical deviation indicator
V/STOL	vertical/short take off and landing
VTOL	vertical take off and landing

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INTRODUCTION

BACKGROUND

The Runway Independent Aircraft (RIA) Operations concept comprises a unique class of aircraft flying instrument approaches and departures, in instrument meteorological conditions, to or from locations on air traffic-saturated airports interspersed with large-body passenger transport aircraft landing, with minimum allowable spacing, to one or more primary runways. (Fig. 1.) The RIA concept is intended to alleviate some of the excess demand experienced at the busiest airports. It would allow these aircraft to free up landing slots on the primary runways by operating from some point on the airport surface that results in minimal interference with the flight and ground operation of the long-distance carrier aircraft.[1,2] The challenge of finding new, alternate landing areas on existing airports is one of the most difficult to overcome in implementing the RIA concept. Almost as difficult is the challenge of finding sufficient airspace, that is not already protected for operations to the primary runways, to serve the approach, missed approach and departure airspace needs of RIA.

A key navigation technology enabling RIA operations is the Global Positioning System (GPS). The GPS promises universal coverage and access to a wide range of navigational accuracies suitable for enroute, terminal area, and precision instrument approach operations. The unique capability of helicopters to operate from prepared or unprepared landing areas makes them ideal customers of this increasingly precise navigational information. The design and implementation of RIA procedures will most likely be within the context of a future satellite navigation environment employing a GPS Wide Area Augmentation System (WAAS) or a Local Area Augmentation System (LAAS).

The objective of the work discussed in this paper is to demonstrate the use of pursuit guidance displays to the operation of a manually-flown rotorcraft or STOL aircraft flying a complex, multi-segment, descending, decelerating, approach trajectory. The Federal Aviation Administration (FAA) has provided guidelines for the construction of procedures in a GPS[3] or Required Navigation Performance (RNP)[4] environment. However, they do not address the construction of close-in, aggressively-turning, and decelerating approaches, such as those made possible with these displays. This work can be used to augment the guidelines proposed by the Federal Aviation Administration for GPS and RNP rotorcraft operations in the short-term, and to fully exploit RIA operations in the long term.

Because the helicopter industry is particularly sensitive to the cost and weight of avionics currently required to support coupled approaches to low minima, any reduction in the level of automation and augmentation represents a potential increase in the number of approach-capable users. These displays have the potential to be a feasible and cost-effective alternative to autoland systems provided the necessary precision can be assured with moderate to minimal workload.

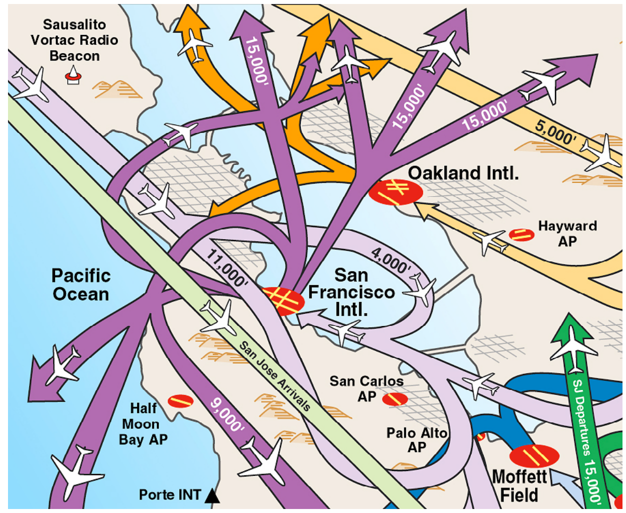

Fig. 1. San Francisco airspace environment.

The pursuit guidance displays developed at Ames Research Center over the last 30 years provide exceptional precision and enhanced situational awareness, while significantly reducing the workload of the pilot. The display concept has been applied to a wide variety of aircraft types and flight tasks, including manually flown blind landings.[5,6,7,8] The V/STOL Systems Research Aircraft (VSRA)[9,10] demonstrated the feasibility of using the pursuit display on a HUD for precision turning, descending, decelerating approach to hover. The displays from the VSRA program were also adapted to the joint Industry/NASA High Speed Research (HSR) program for the proposed High Speed Civil Transport (HSCT), and for the demonstration phase of the Joint Strike Fighter (JSF) Program. The work by Hardy[11] extended the pursuit display format with an "inverse" flight director to reduce pilot workload for the transition from frontside to backside configuration while still preserving the advantages of the basic pursuit display. While flight directors have been designed and flown to provide curved, decelerating guidance for STOL aircraft,[12] the work of others heretofore mentioned has shown the advantages of situational awareness provided by pursuit guidance displays.

The displays developed for this experiment refine the pursuit guidance concept for a RIA application with precision-GPS navigation in the RNP context to verify how accurately RIA approaches can be flown. The RNP values demonstrated by the in-flight evaluations can be used to help define terminal area separation requirements.

Pursuit Guidance Concept

The pursuit guidance concept, simplified, is shown in Fig. 2. A leader airplane symbol, drawn with perspective, provides a pursuit-following task for flightpath vector guidance, analogous to an in-trail formation flight task. The leader flies the desired trajectory perfectly, and is positioned on the display relative to the reference trajectory and with the viewing angles to the leader that would pertain from the ownship cockpit. The pilot's task is to place his flightpath vector on the leader symbol. This will cause the ownship to converge on the desired trajectory. The time or distance that the leader is flying ahead of the ownship determines 1) the location where the leader appears, 2) the pursuit tracking gains, 3) the resulting precision, and 4) the workload associated with the task. The pursuit display has often been complemented with the addition of a tunnel symbol element, researched by Grunwald[13] for application to helicopters, to present "preview" awareness of the guidance trajectory. The pursuit guidance display and tunnel are the embodiment of "contact analogue" displays first proposed by Hoover.[14,15]

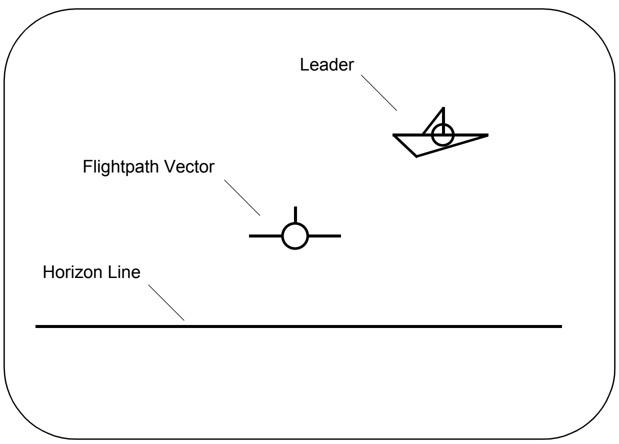

Fig. 2. Pursuit guidance concept – simplified.

A description of the research aircraft systems, along with a discussion of the "truthing" of the GPS position measurements will be given in the next section. Following this will be a more detailed description of the drive law algorithms for the pursuit guidance symbology. Lastly, a description of the experiment design and results from the in-flight evaluations will be given.

RASCAL SYSTEM DESCRIPTION

The Rotorcraft Aircrew Systems Concepts Airborne Laboratory (RASCAL) is a modified JUH-60A Black Hawk helicopter operated by the US Army Aeroflightdynamics Directorate and by NASA at the Ames Research Center. The RASCAL facility has been in operation, in various research and development phases, since 1989.[16,17,18] It is now in its fourth phase of development in which a full-authority fly-by-wire (FBW) flight control system, known as the Research Flight Control System (RFCS), and a flexible Linux/OpenGL® navigation and display system have been integrated into the helicopter. The aircraft provides an easily re-configurable, fully-programmable capability to investigate a wide range of flight control, cockpit display, and crew systems concepts, including integration of mission equipment. The RASCAL airborne laboratory environment is supported by several levels of flight simulation capabilities, resulting in an efficient desktop-to-flight capability for developing and flight-validating control or display concepts.[19]

Architecture

The overall RASCAL architecture shown in Fig. 3 consists of control, navigation, and display systems. As part of the GPS "truthing" for determining navigation system error post-flight, the onboard GPS receiver was augmented by a GPS data collection system.

Control System

The Research Flight Control System (RFCS) provides a full-authority fly-by-wire capability while retaining the unmodified JUH-60A mechanical flight controls as a backup. The evaluation pilot (EP) in the right seat flies the RFCS through a passive side arm controller in the right hand for cyclic control, and a displacement collective controller in the left hand for collective control. The RFCS controls the displacements of the JUH-60A primary servos by means of full-authority parallel-mounted electrohydraulic research servos commanded by algorithms programmed in the Research Flight Control Computer Assembly (RFCCA).

The system is characterized by the following features and capabilities:

1.) Fail-safe design — The RFCS disengages and control reverts to the JUH-60A mechanical system upon detection of critical RFCS faults, or disengagement by the safety pilot (SP).
2.) A high performance flight control computer (FCC) with extensive analog, discrete, and digital I/O to support the research mission of the RASCAL.
3.) Command and monitoring of the RFCS research servos with dual, physically partitioned servo control units (SCUs).
4.) JUH-60A main rotor primary actuators each driven by a separate research servo through existing linkages for swashplate control and a tail rotor primary actuator driven by a research servo mounted at the tail rotor gearbox.

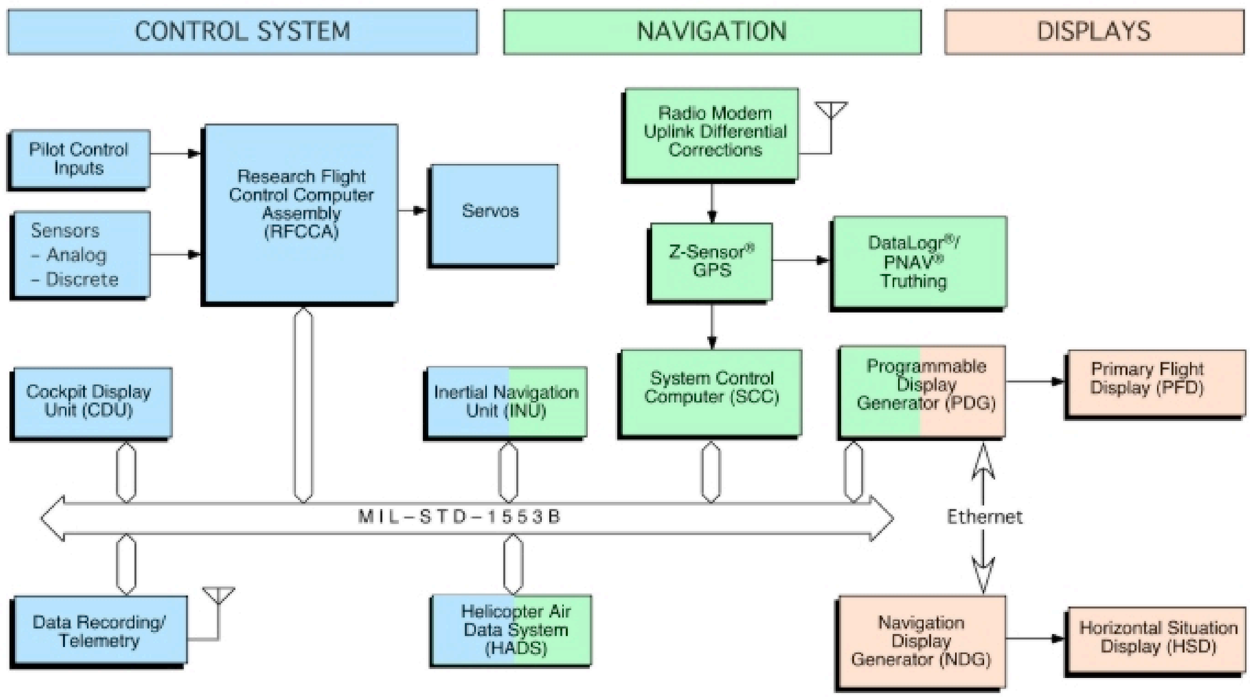

Fig. 3. RASCAL architecture.

5.) Mechanical flight control linkages of the JUH-60A backdriven by research servos.
6.) Transfer of control between the mechanical system and the research system using relays, hydraulic shutoff valves, and cockpit switches.
7.) Full-authority, electro-hydraulic research servoactuators with extensive health monitoring features.

Flight Control Laws

The structure and functionality of the flight control laws that were programmed in the flight control computer provided the aircraft response characteristics and the levels of stabilization appropriate and necessary for flying the complex trajectories that would be required of RIA aircraft in instrument conditions. The control law architecture was developed by Boeing Helicopters for the RASCAL RFCS Program.[20] The modes are summarized in Table 1 below. They have been modified from their original configuration described in Ref. 17 by replacing the velocity command and stabilization features with pitch rate-command, attitude-hold response characteristics which are better suited to the decelerating RIA trajectories. Mode changes affecting turn coordination, heading hold and attitude-command, attitude-hold were implemented automatically as a function of airspeed and roll attitude.

Table 1. RASCAL control modes

Control Axis	Airspeed, kn < 30	> 30
Longitudinal	ACAH + TFU	RCAH
Lateral	ACAH + TFU	RCAH
	Airspeed, kn < 50	> 50
Directional	RCHH	LAC +TC
Collective	Direct Drive	

NAVIGATION SYSTEM

The primary component of the RASCAL navigation system is the Ashtech Z-Sensor® GPS receiver operated in a carrier-phase differential mode with a base station Z-Sensor® receiver providing differential corrections via a radio modem link. The typical accuracies quoted by the manufacturer for this GPS sensor are given in Table 2. In the vertical axis, accuracy is degraded by about a factor of two from the values shown in the table. The airborne unit is configured for an update rate of 10 Hz.

Kalman filter integration

The position measurements of the differential GPS (DGPS) are combined with the velocity measurements of a medium-accuracy (0.8 NM/hr drift)

Litton LN-93 Inertial Navigation Unit (INU) in a 9-state Kalman filter that is updated at 33 Hz. The states consist of position, velocity, and velocity bias. This Kalman filter was tested in a MATLAB Simulink environment before integration into the current navigation system. This navigation system was put in place to alleviate the effect of GPS dropouts on the guidance algorithms that would otherwise directly affect the leader aircraft symbology element of the pilot's primary flight display.

Table 2. Ashtech Z-Sensor® performance

Mode	Horizontal Accuracy (typical)
Autonomous (SA off / on)	3.0 m / 100 m
RTCM code differential	1.0 m
Real-time carrier phase differential	0.020 m
Static (post-processed)	0.005 m

DGPS Performance & "Truthing"

Accuracy, or "truthing", of the DGPS used for this experiment was assessed with a post-processing forward-backward differential processing algorithm. The commercial software package used to implement this algorithm was Ashtech's *Precise Differential GPS Navigation and Surveying* (PNAV®). Figure 4 describes schematically the processes involved in the "truthing" of the DGPS data. Data shown in Fig. 5 and Table 3 are for the Navigation System Error (NSE) shown in Fig. 4. These data are for 19 runs of typical RIA precision approaches.

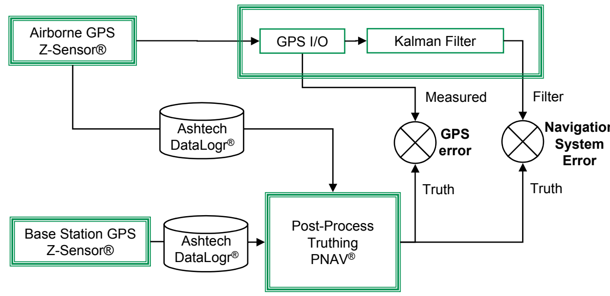

Fig. 4. DGPS "truthing".

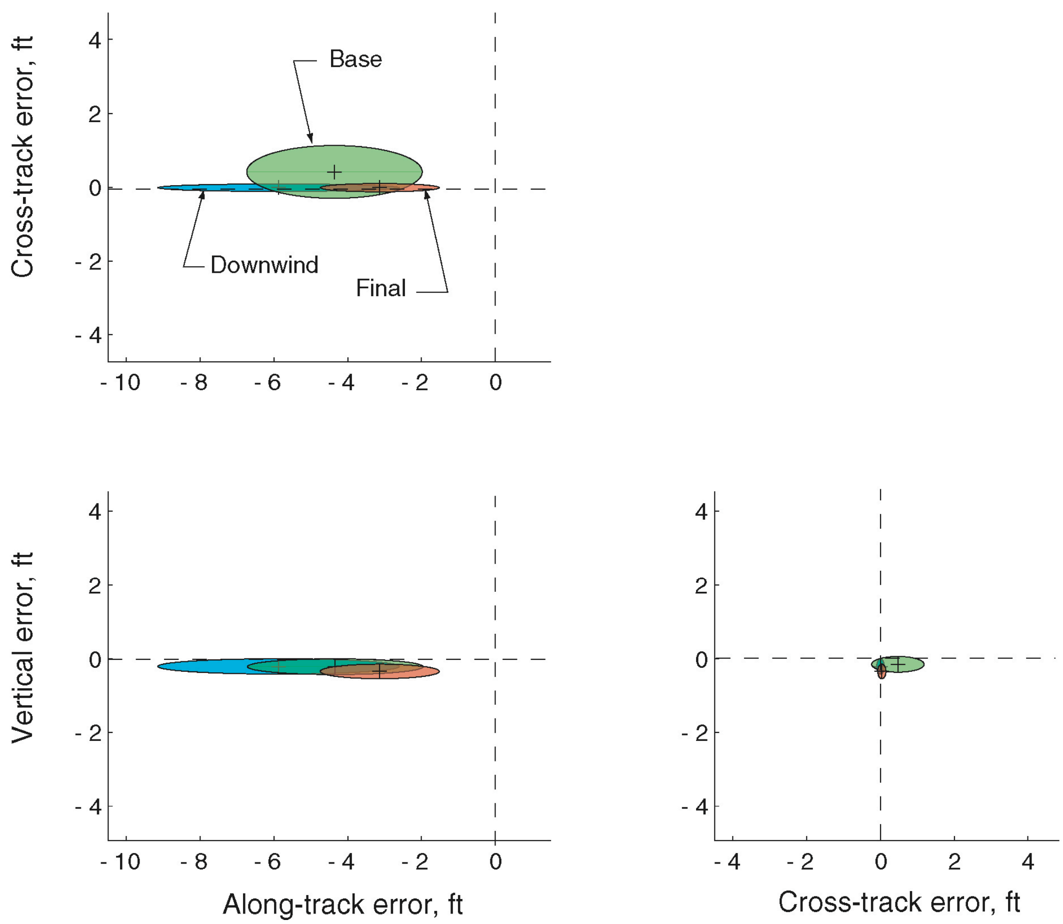

Fig. 5. Navigation system error ellipsoids.

Numerical values are given in a shorthand notation for normal (or Gaussian) distribution statistics of *N(mean:μ, standard deviation:σ)* in units of feet. Cross-track error for straight segments of the approach (i.e., downwind and final) is on the order of 0.4 inches (1 cm) with a standard deviation on the order of 1.3 inches (3.3 cm). Vertical axis error is on the order of -3.8 inches (9.8 cm) with a standard deviation of 2.4 inches (6.1 cm).

It can be seen that along-track error is about two orders of magnitude larger than the cross-track error, and the magnitude of the error is roughly proportional to the along-track speed at which the helicopter is moving. The formulation of the Kalman filter takes into account the GPS measurement latency and performs an approximate "time advance" of the position based on an averaged INU velocity and current GPS velocity to minimize measurement update residual. Additional work is needed to tune the filter to reduce these errors. For the manually-flown precision guidance task addressed by this flight experiment, these navigation system errors are small in comparison to the flight technical errors (FTE) that result from the pilot not tracking the guidance perfectly.

Table 3. Navigation system error values

	Downwind	Base	Final
Cross-track	*N*(-0.01, 0.10)	*N*(0.47, 0.71)	*N*(0.03, 0.11)
Along-track	*N*(-5.9, 3.2)	*N*(-4.3, 2.4)	*N*(-3.1, 1.6)
Vertical	*N*(-0.20, 0.21)	*N*(-0.17, 0.22)	*N*(-0.32, 0.20)

Note: Normal distribution statistics shorthand *N(μ, σ)* in feet.

These error data can be visualized simply by considering the placement of the "truth" position at the (0,0,0) location; this implies that the navigation Kalman filter estimate locates the aircraft forward (along-track), slightly to the right (cross-track), and slightly below (vertical) the (0,0,0) location.

DISPLAYS

The displays used by the Evaluation Pilot (EP) for this experiment consisted of 10- and 6-inch diagonal, sunlight-readable (1000 cd/m^2), 640x480 resolution, flat panel liquid crystal displays (LCD) for the Primary Flight Display (PFD) and Horizontal Situation Display (HSD), respectively. These displays are shown in the RASCAL helicopter cockpit in Fig. 6. Both displays were driven by a ruggedized PC employing an Intel® Pentium® III 850 MHz CPU with 512 MB RAM, and an *n*VIDIA® GeForce2GTX® Graphics Processing Unit (GPU) with 32 MB RAM. The GPU graphics card was configured with a composite video-out feature for capturing symbology to a digital video recorder. The GPU is capable of drawing more than 25 million triangles per sec and has an 800 million pixels per second fill rate.

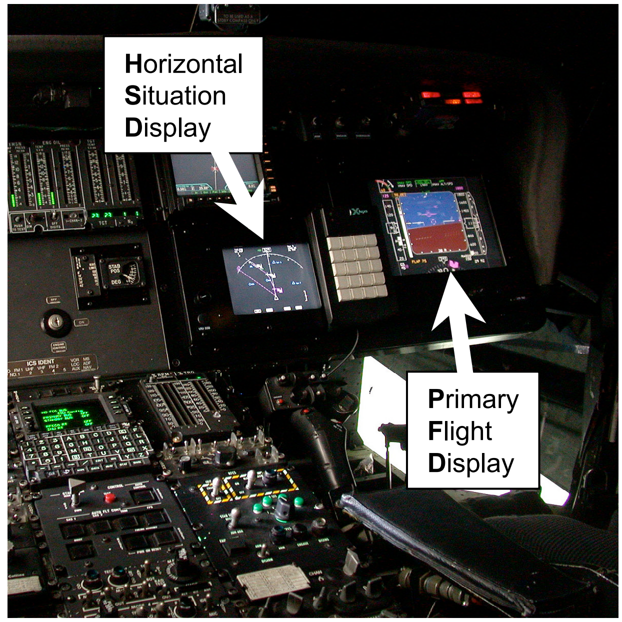

Fig. 6. RASCAL cockpit displays.

The PFD code was a mix of Fortran (for display, guidance and trajectory calculations) and C (for symbology drawing, Kalman filter, MIL-STD-1553B and Ethernet data I/O) with the drawing algorithms enabled by OpenGL® libraries. The combined Fortran/C executable was updated at a rate of 33 Hz. The Linux operating system (Red Hat® 7.1 distribution) was used for software development and in-flight operations with only minor modifications made to the graphics drivers to support the *n*VIDIA® GPU.

Primary Flight Display

The format of the Primary Flight Display (PFD), Fig. 7, is based on a typical transport-category Electronic Attitude Direction Indicator (EADI) modified to include flightpath-centered pursuit displays. A conformal perspective runway symbol is presented on the display during final approach to aid in situational awareness. Details of the flightpath and pursuit guidance symbology are discussed in following sections.

Horizontal Situation Display

A Horizontal Situation Display (HSD), shown in Fig. 8, provided situational awareness of progress along the approach profile. It showed the predefined track along with important points along the track such as the –3º and –6º glide slope intercepts, as well as the runway intercept point. This display allowed the pilot to quickly set up the initial approach and minimize the amount of time required to line up on the downwind segment, as well as provide anticipation of the upcoming base turn segment and changes in the glideslope angle.

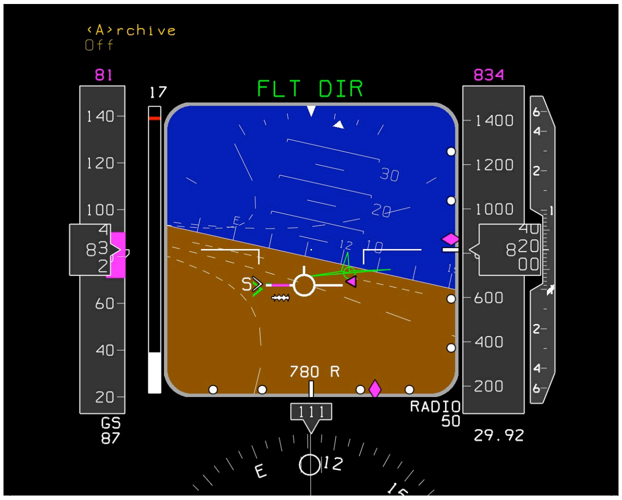

Fig. 7. Primary flight display (PFD).

Fig. 8. Horizontal situation display (HSD).

PURSUIT GUIDANCE SYMBOLOGY

As previously mentioned, the pursuit guidance concept employs a leader airplane symbol that provides a pursuit-following task for flightpath vector guidance, analogous to an in-trail formation flight task. The leader flies the desired trajectory perfectly and is positioned on the display relative to the reference trajectory and with the viewing angles to the leader that would pertain from the ownship cockpit.

Figure 9 shows the unique elements of the pursuit guidance displays. The flightpath vector symbol (circle with a tail view of wings and vertical fin) is shown near the center of the display and is similar to that used for several operational HUDs. The flightpath symbol represents the velocity vector and is driven laterally by track angle over the ground, χ, and vertically by the climb angle, γ. The subscript Q is shown on γ in Fig. 9 to indicate that pitch and collective quickening has been added to the basic climb angle to improve pilot control. Washed-out pitch and collective are added to the actual flightpath for the quickened signal.

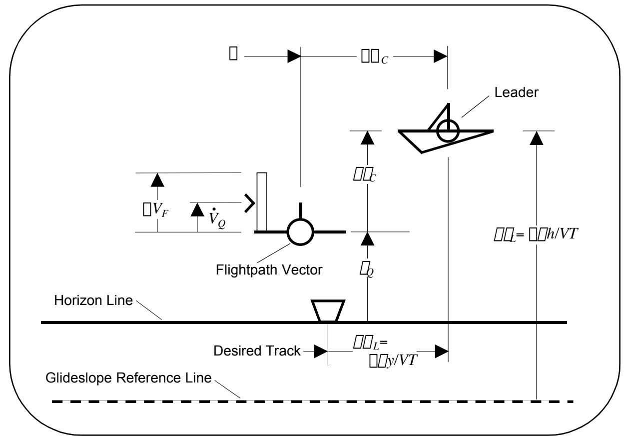

Fig. 9. Pursuit guidance symbology.

VERTICAL & LATERAL FLIGHTPATH CONTROL

The leader aircraft symbol is the delta wing vehicle with the "pusher propeller" at the upper right of Fig. 9 and drawn with perspective. It represents the ownship view of a leader aircraft flying a perfect trajectory T seconds ahead. Drawing the leader with its own perspective reinforces awareness of deviation from the desired path. Figure 10 shows a vertical plane view of the situation shown in Fig. 9.

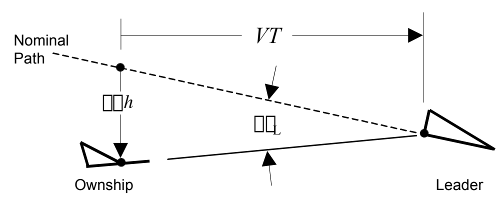

Fig. 10. Vertical plane view of guidance symbology.

In the situation depicted in Figs. 9 and 10, the ownship is Δh feet below the desired glideslope. The leader is positioned T seconds ahead, corresponding to a distance of VT feet (V is ownship groundspeed). The smaller the value of T, the closer the in-trail spacing, and the higher the pursuit tracking gains. Laterally, the ownship is Δy feet left of the desired track as shown in Fig. 9. The leader, which is on the desired trajectory, is seen from the ownship at small angle equivalents of $-\Delta y/VT$ degrees to the right of the desired course, and $-\Delta h/VT$ degrees above the desired glideslope. The pilot must turn right and climb in order to line up directly behind the leader on the desired trajectory, exactly as would be required in an in-trail formation task. Placing the ownship flightpath vector on the leader aircraft from an initial offset is a pursuit tracking control law characterized by exponential convergence to the desired path with a time constant of T sec. Values of T were varied from 10 to 4 seconds. The larger value is used where less precision is required and it is desired to maintain a low workload, such as the downwind leg of the approach profile; and the smaller value is used when approaching landing minimums. The value of T was varied as a function of altitude.

For lateral and vertical flightpath control, the pilot's task is to control the flightpath symbol onto the leader symbol using the controls appropriate for the aircraft configuration. Lateral control of the flightpath vector is done naturally through the lateral/directional control system; the ease of the task is dependent on the quality of the lateral/directional aircraft dynamics. Vertical control of the flightpath vector is made easier with the use of the pitch and collective quickening on the flightpath symbol described above.

AIRSPEED CONTROL

The vertical tape on the left wing of the flightpath symbol in Fig. 9 shows the error in true airspeed, $-\Delta V_F$, from the commanded value. The subscript F is used to show that it is filtered (τ = 1.0 s) to prevent excessive turbulence from making the display noisy. If the vehicle is faster than the commanded value, the tape moves above the wing. Additional information about speed error can be assessed through the use of the magenta commanded airspeed tab on the airspeed tape shown in Fig. 7.

The open green caret off the left wing of the flightpath symbol in Fig. 7, and $\dot{V}_Q$, in Fig. 9, indicates the total rate of change of filtered and quickened (with washed-out pitch and collective) true airspeed. The airspeed rate was filtered with a 2nd order filter with dynamics of ζ=0.8 and ω=0.2 rad/s. This caret is displaced relative to the left wing of the flightpath symbol. If airspeed is increasing, the caret moves above the wing.

The airspeed error tape and the airspeed rate caret can be used by the pilot to control to the commanded airspeed. He does this by using the controls appropriate for the aircraft configuration to place the caret on the opposite side of the wing from, and with the same magnitude of the airspeed error tape. This will cause the aircraft's actual airspeed to exponentially converge on the commanded airspeed with an appropriate time constant. For this work, a time constant of ten seconds has been used.

Tables of parameters that define the aircraft steady-state flightpath and airspeed rate response to pitch and collective inputs were the only parts of the display algorithms modified to account for a different aircraft type (UH-60 Black Hawk helicopter vice a civil tilt rotor from the work of Ref. 9). About an hour of flight test time was expended to gather this information in-flight for the RASCAL JUH-60A helicopter, and the results were incorporated into the symbology drive law tables.

"INVERSE" FLIGHT DIRECTOR ELEMENTS

Longitudinal flight director symbology is provided to aid the pilot in the pursuit-tracking task for configurations where flightpath and airspeed control are coupled. Details of the "inverse" flight director concept are given in the paper by Hardy[11] in which a civil tilt rotor model was used.

The collective director is the white handle (or "grip") shown deflected about 2º below the left wing of the flightpath symbol in Fig. 7. In the situation shown, it calls for an increase in collective (i.e., "pulling" the symbol up to the left wing of the flightpath symbol).

The pitch director is the magenta closed caret off the right wing of the flightpath symbol, shown here deflected about 0.5º above the right wing indicating the aircraft is a little fast. In the situation shown, it calls for the pilot to pitch the nose up in the amount which positions the caret adjacent to the right wingtip of the flightpath symbol. This action will produce a deceleration and bring the aircraft back on the desired speed schedule.

PERSPECTIVE TUNNEL

The tunnel shown as white "streamers" on the PFD in Fig. 7 aids in turn and flightpath change anticipation by providing a "preview" awareness of the guidance trajectory. It is scaled to represent allowable lateral and vertical deviations to be discussed in an upcoming section. The initial research that incorporated perspective tunnel displays for helicopters flying strongly curved trajectories was done by Grunwald,[13] and an implementation for this experiment was carried out by Wilkins.[21]

FLIGHT EVALUATIONS

APPROACH PROFILE

Identifying an airport that experiences some or all of the challenges of RIA operations adds realism to specifying a prototype RIA approach profile for evaluation. For the purposes of this development effort, San Francisco International Airport (SFO) was selected as the target operational environment (Fig. 1). The actual in-flight evaluations addressed by this paper were conducted at Moffett Federal Airfield based on an approach profile deemed potentially relevant to SFO. Factors that support selection of SFO as a design prototype include:

1.) Its status as a major air carrier hub in close proximity to Moffett Field.

2.) Frequent IFR operational capacity constraints induced by the low ceilings and visibility that characterize the San Francisco International Airport locale.
3.) An ongoing dispute between airport/city officials and the environmental community over proposals to fill in a portion of San Francisco Bay to support one or more new runways sufficiently separated from the existing runways to allow simultaneous IFR arrival and/or departure operations.
4.) The continuous displeasure voiced by surrounding local communities over noise pollution attributed to airport operations.
5.) The existence of sufficient airport surface to allow the addition of a hypothetical STOL runway parallel to the primary IFR arrival runways (Rwy 28L and R) with approaches over San Francisco Bay. (The RIA concept assumes a spectrum of possible passenger transport aircraft types ranging from rotorcraft, requiring no runway, through tilt rotors to STOL, requiring a relatively short runway surface.)

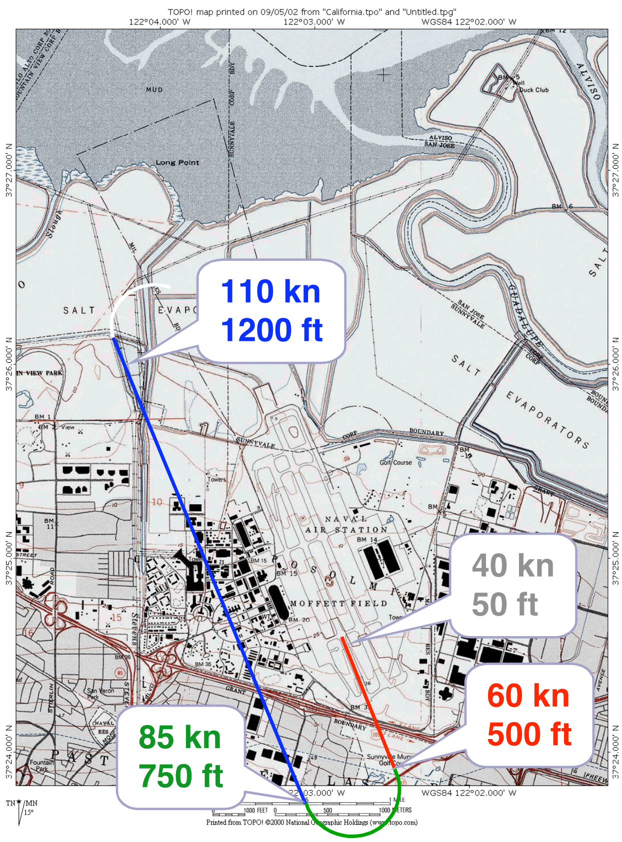

Fig. 11. Moffett Field approach profile.

The approach profile employed in this study is implemented as a fixed reference trajectory for the specific purpose of exploring the precision attainable on a very demanding profile. Once proven feasible, then other important factors such as monitoring of the navigation signal integrity and incorporation of alarm limits will need to be taken into account in arriving at the true capability of runway independent aircraft to operate within confined airspace.

The approach profile chosen for this experiment conducted at Moffett Federal Airfield in Mountain View, California is as shown in Fig. 11. It is a close-in, aggressively-turning, and decelerating approach. The nominal approach was a left downwind to Runway 32L. During conditions of inclement weather, the prevailing winds shifted to the south, and the profile was rotated 180º for a right downwind to Runway 14R. Details of the profile are shown in Fig. 12. Values for speeds, glideslope angles, and distances were chosen in such a way as to produce bank angles and decelerations that were deemed comfortable for RIA-type approaches.

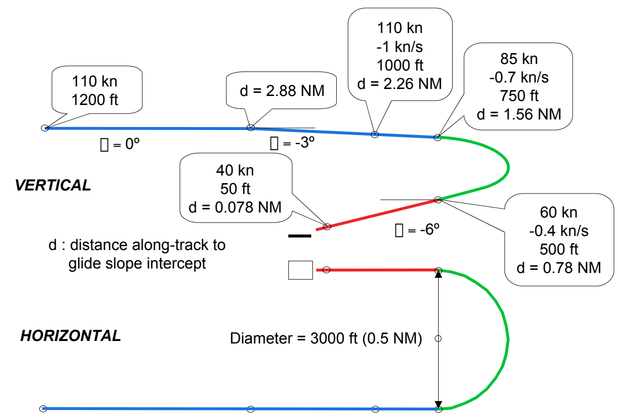

Fig. 12. Profile details.

EXPERIMENT DESIGN

Recommendations available in the FAA's Advisory Circular AC120-29A addressing Category I and II weather minima for approach[22] and Advisory Circular AC120-28D addressing Category III weather minima for takeoff, landing, and approach[23] were used to construct bounds on cross-track (lateral) and altitude (vertical) error. These documents specify RNP Levels for various phases of approach, viz., Initial, Intermediate, and Final.

The concept of RNP specifies the performance of the system to maintain the aircraft within a defined boundary 95% of the time. This 95% value is defined by the FAA to be 1xRNP. A value of 2xRNP is termed the containment limit.

The errors were displayed to the pilot as deflections of the lateral deviation indicator (LDI) and vertical deviation indicator (VDI). The LDI and VDI are shown on the PFD of Fig. 7 as the magenta diamonds on the bottom and right edges of the EADI. The PFD LDI/VDI scaling used was 1xRNP corresponding to one-dot, and 2xRNP "containment" corresponding to two-dots. Boundaries of the tunnel display in Fig. 7 were sized equal to the two-dot boundaries of the LDI/VDI.

The 1xRNP values are shown in Figs. 13 and 14. RNP values used at 100 ft and below were 0.003 NM (18 ft) laterally and 15 ft vertically. FAA Advisory Circular AC120-29A suggests that these values support Category I/II/III minima. Based on experience with this display format in the civil tilt rotor simulation reported by Hardy,[11] values for RNP for the initial approach segment of the profile were selected to be 0.02 NM (120 ft) laterally and 100 ft vertically. These values are tighter than the AC120-29A Initial/Baro-Vertical approach RNP Levels. These values were held constant above 667 ft. Between 100 ft and 667 ft the RNP values were proportional to altitude.

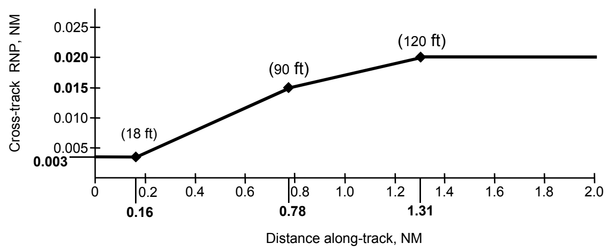

Fig. 13. One-dot (1xRNP) cross-track bounds.

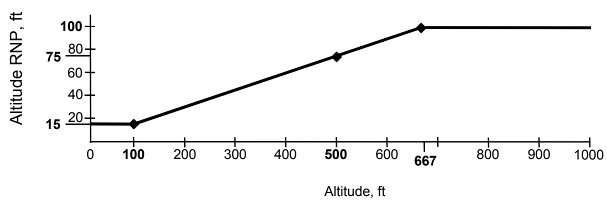

Fig. 14. One-dot (1xRNP) altitude bounds.

RESULTS & DISCUSSION

A series of in-flight evaluations was conducted at Moffett Federal Airfield using three NASA research pilots and one US Army experimental test pilot who flew a total of 56 approaches during 11 flights that were analyzed for cross-track/lateral, altitude/vertical, and airspeed performance in the context of the RNP Level boundaries discussed previously. Weather was generally good with winds calm to 9 knots and left and right crosswinds of about 5 knots, with the exception of one flight in which moderate turbulence as well as noticeable wind shear were present. An instrument hood was used by the evaluation pilots during all runs in which they provided handling qualities ratings and for which the FTE data are reported herein.

Path-tracking Performance Measures

Performance standards used by the research pilots to assess the handling qualities[24] of the system to perform the precision approach task are given in Table 4. The target performance was zero deviations from the nominal trajectory as indicated by null deflections of the LDI, VDI, and airspeed error tape (and corresponding magenta command airspeed tab on the PFD airspeed indicator). A half-dot deflection of the LDI/VDI and 5-knot deviation in airspeed were considered desired performance of the system, whereas a full dot deflection of the LDI/VDI and 10-knot airspeed deviation were considered adequate performance of the system.

Table 4. Performance standards for evaluation

Performance Standards	Target	Desired	Adequate
Altitude/Vertical, dots	0	± 0.5	± 1.0
Cross-track/Lateral, dots	0	± 0.5	± 1.0
Airspeed Deviation, knots	0	± 5	± 10

An ensemble of the path-tracking data is shown on the upper part of Fig. 15. The statistical summary of these data is shown on the lower part of the figure. Inscribed on the plots for cross-track and altitude errors are the aforementioned RNP one-dot boundaries as well as Instrument Landing System (ILS) one-dot boundaries. The airspeed performance plots show 5- and 10-knot error bounds. (There are no comparable ILS specifications for airspeed error in the context of a decelerating approach.)

The data are color-coded to indicate the different phases of the approach: downwind (initial) in blue; base turn to final (intermediate) in green; and final in red. The color-coding is the same as that used for the Navigation System Error ellipsoids discussed earlier, as well as for the Moffett Field approach profile of Figs. 11 and 12.

The concept of RNP specifies the performance of the system to maintain the aircraft within a defined boundary 95% of the time. Assuming the data are normally (Gaussian) distributed, a value of 1.96σ would contain 95% of the data. These 95% values are given in Table 5. These values are used to size the rectangles used in the statistical summary plots in Fig. 15. The performance values shown in the table exceed the FAA's recommended RNP values for all segments.

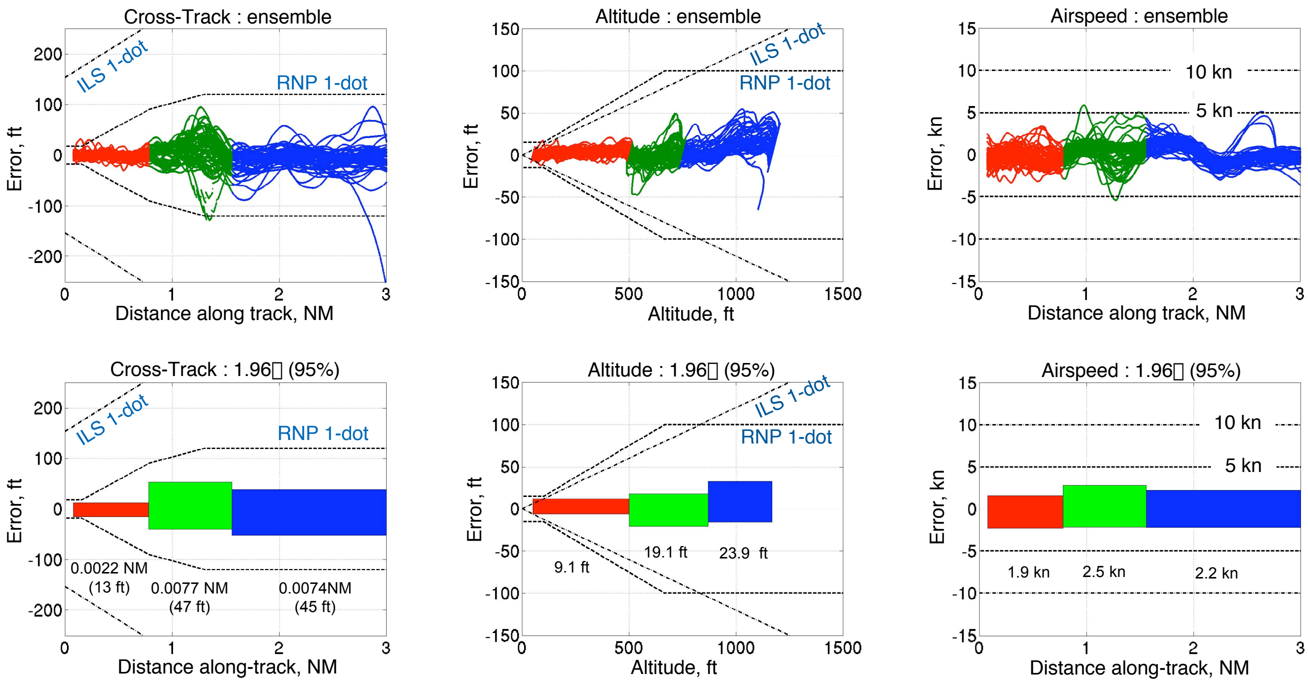

Fig. 15. Pursuit guidance display performance.

Table 5. RNP statistical summary

	Downwind	Base	Final
Cross-track	0.0074 NM (45 ft)	0.0077 NM (47 ft)	0.0022 NM (13 ft)
Altitude	24 ft	19 ft	9.1 ft
Airspeed	2.2 knots	2.5 knots	1.9 knots

Note: Normal Distribution, 1.96σ (95%)

The cross-track, altitude, and airspeed performance measures for the downwind, base turn, and final segments of the approach show that path deviations are generally within the bounds for desired performance as seen in Fig. 15. An exception is the flight in turbulent conditions where there are brief excursions of lateral, vertical, and airspeed errors towards the one-dot and 5-knot boundaries. Another exception is a very late entry onto the downwind leg. The pilot easily saved the approach using the pursuit guidance to place ownship on the desired trajectory.

Pilot Ratings and Comments

The pilots' handling qualities ratings (HQRs) shown in Fig. 16 are divided into flight segments: Downwind (or Initial), Base Turn (or Intermediate), and Final. They are further divided into longitudinal qualities (filled symbols) and lateral/directional qualities (open symbols). The ratings that were given for a flight evaluation in the presence of turbulence are identified with a small flag extending from the basic symbol. (In this experiment, only Pilot C was exposed to inclement weather conditions.) Pilot C commented that the atmospheric conditions substantially increased workload in all task segments in order to meet desired performance.

The satisfactory longitudinal and lateral HQRs for the downwind segment of the approach profile reflect the ease with which glideslope and airspeed are maintained relative to the desired trajectory. The leader aircraft time constant during this segment of the approach is ten seconds, resulting in low tracking gains and low pilot workload. Good situational awareness was provided by the HSD and the tunnel. Pilot comments for the downwind portion pointed out the good tracking performance, but noted that the –3° glideslope intercept and the initial 1 knot/sec deceleration take them a little bit by surprise. The constraints of the Moffett Field environment (due to general aviation traffic at the nearby Palo Alto airport) sometimes limited the amount of time that the pilot flew the level portion of the downwind segment before beginning the descent and deceleration.

The transition from low workload to higher workload begins during the transition from the downwind segment to the base turn segment. The workload increase is primarily in the lateral axis and is reflected in the borderline satisfactory/adequate lateral HQRs and pilot commentary. Much of the increase in workload results from the deficiencies with leader aircraft lateral cueing. There was a tendency to overshoot the desired bank angle at turn initiation, but recovery back to the nominal bank angle was made in time to allow good tracking, albeit with higher workload. Pilots sometimes felt the leader aircraft bank angle cueing was not quite what they would expect for the turn. It should be noted that the turn is not at constant speed. During this phase of the approach, the speed guidance calls for a 0.7 knot/sec deceleration from 85 knots at the start of the turn to 60 knots at the end of the turn on to final. A comment was made by one of the pilots about "wallowing" in the turn as evidenced by flying outside the turn and then inside the turn. Additionally there was a software bug that introduced a small, momentary, but noticeable, leader aircraft bank angle deflection that the pilots commented on as a "fake out".

Another factor influencing handling qualities in the turn was the cyclic controller ergonomic cross-coupling of roll inputs sometimes generating yaw inputs. The low control sensitivities would sometimes require large lateral deflections of the side arm controller and exacerbated the cross-coupling of roll into yaw. The roll axis precision and predictability was deemed poor by one of the pilots. One of the pilots commented on the need to adjust the control sensitivity gains to improve precision and predictability throughout the approach.

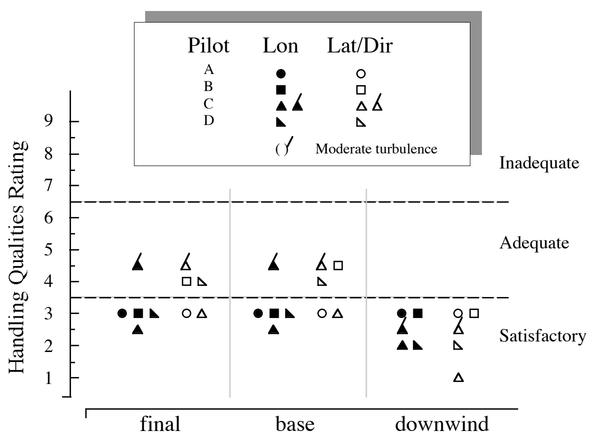

Fig. 16. Pursuit guidance display ratings.

The rollout onto final approach is accompanied by an increase in the glideslope from –3º to –6º and change to a deceleration of 0.4 knots/sec for the final segment. Additionally the leader aircraft lead time is continuing to decrease during the final approach, thus providing an increase in the tracking gain. Again pilots commented on the lateral/directional deficiencies with respect to tracking and predictability especially in the presence of crosswinds. Decrabbing the aircraft would sometimes introduce unwanted roll-yaw cross-coupling. The perspective runway symbol along with pitch and collective directors tended to receive favorable pilot comments. The growing perspective runway and necking-down of the tunnel added to the situational awareness during the final approach phase.

CONCLUSIONS

An in-flight evaluation of a pursuit guidance display system has been performed using the RASCAL JUH-60A Black Hawk helicopter. The following conclusions have been made:

1.) The pursuit guidance display format has shown that a manually-flown precision approach utilizing a precision GPS-based navigation and display system can be performed within very tight RNP constraints while descending, decelerating, and turning.
2.) The system demonstrated RNP 0.007NM/24ft for initial approach, RNP 0.008NM/19ft for intermediate approach, and RNP 0.002NM/9ft for final approach.
3.) Longitudinal handling qualities for this system were found to be satisfactory, but additional work is warranted to improve the lateral/directional handling qualities.
4.) The pursuit guidance system met the requirement for providing exceptional precision and excellent situational awareness along the complex approach trajectories.

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