# TUNNEL-IN-THE-SKY COCKPIT DISPLAY FOR COMPLEX REMOTE SENSING FLIGHT TRAJECTORIES*

Andrew K. Barrows and J. David Powell
Stanford University
Stanford, California, USA

## ABSTRACT

Three-dimensional flight displays can increase the efficiency of remote sensing flight operations by providing enhanced guidance and situational awareness on straight and curved flight paths. Such a display depicts an “out-the-window” perspective view of the world along with a tunnel through which the pilot flies the aircraft. Using differential GPS, inexpensive graphics hardware, and a flat-panel display, a prototype system was built and flight tested to demonstrate significant advantages over conventional instruments. Flight testing on a Beechcraft Queen Air demonstrated the ability to guide the pilot on complex paths, while testing onboard a Beechcraft King Air confirmed accurate positioning of a hyperspectral imager over ground targets. With minimal training time, pilots were able to maintain good accuracy and navigational situational awareness using the display. These benefits could translate to savings in flight time and flightline overlap.

## 1.0 MOTIVATION

Aircraft operating cost is a significant factor for remote sensing missions. Platforms employed are typically multi-engine aircraft often equipped with expensive turbine powerplants. Costs of flight crew, sensor equipment and skilled operators are equally important. Effective use of these resources is therefore critically important. Efficiency can be enhanced by minimizing row overlap and maximizing time spent recording data. This in turn requires accurate positioning and guidance as well as good spatial awareness for the pilot. After flying over a ground point or flightline, a minimum of maneuvering should be required to line up for the next data run.

Systems have been developed to aid the pilot in these tasks. Such systems are based on position deviation needles, lightbars, moving maps, and even raw numerical information. All of these systems require expensive pilot training in realtime interpretation of the displays. Since none of these display types present an immersive depiction of the world, it is easy to lose positional awareness, especially when maneuvering from one target or flightline to the next. Often the pilot makes a 180-deg turn and must correct for gross errors until standard needle or lightbar guidance becomes available.

## 2.0 TUNNEL DISPLAY

A prototype display has been developed at Stanford University that can address the unique needs of the remote sensing flight crew. The system uses the concept of a “tunnel in the sky” to present a three-

---

* Presented at the Fourth International Airborne Remote Sensing Conference and Exhibition/ 21st Canadian Symposium on Remote Sensing, Ottawa, Ontario, Canada, 21-24 June 1999.

dimensional view of the world and the desired flight path. Although the system was originally designed for general aviation instrument flying, developmental results suggest that it enables the precise path following and situational awareness demanded by remote sensing.

## 2.1 BACKGROUND

Instrument flight during bad weather is one of the more demanding tasks a pilot can perform, especially in light aircraft. The pilot must scan several instruments simultaneously to fuse together the "big picture" of what is happening. This assessment of the airplane's position relative to the desired flight path and terrain is referred to as position "situational awareness." Development of the tunnel-in-the-sky display concept was begun in the 1950s to improve situational awareness. Such a display depicts an "out-the-window" perspective view of the world along with a tunnel through which the pilot flies the aircraft. A large body of research has emerged over the last several decades (Grunwald, 1984; Wickens, 1989; Möller, 1994; Regal, 1995; Theunissen, 1997; Below, 1997), but the technology has not yet appeared in commercial form. The high cost of implementation has been driven by displays and expensive inertial navigation systems. Fortunately, the advent of the Global Positioning System (GPS), Active Matrix Liquid Crystal Displays (AMLCDs), and inexpensive computing power have combined to enable practical tunnel-in-the-sky displays in recent years.

To explore the operational benefits of such displays, Stanford University began a research program based on a *low-cost* and *operationally oriented* paradigm. The system described here was originally designed to enhance pilot situational awareness in light aircraft during approaches and missed approaches in instrument meteorological conditions. Developmental flight testing was performed onboard piston aircraft. During flight testing of the Tunnel Display, potential benefits for remote sensing missions were identified. With initial development complete, the display was flown during actual remote sensing work on a turbine aircraft carrying a hyperspectral imaging payload.

## 2.2 PILOT'S PERSPECTIVE

Display design was a compromise between including enough information for the pilot to perform the flying task and preventing excess clutter. The display shown in Figure 1 presented an artificial horizon along with numerical readouts of altitude, heading, and groundspeed. The field of view was 40 deg horizontal by 50 deg vertical. The approach and missed approach paths were depicted as a series of 100-m wide by 60-m tall "hoops" spaced at 200-m intervals. Trajectories were stored as sequences of segments with constant turn radius (straight segments were a degenerate case) and constant gradient (level, climbing, or descending). For the remote sensing tests described here these trajectories were all at constant altitude.

Predictor symbology similar to that used in (Grunwald, 1996) provided pilot guidance through the tunnel. A "predictor symbol" shaped like a circle with wings displayed the aircraft's predicted position (based on current position, velocity, and lateral acceleration estimated from bank angle) 3.5 sec in the future. Another symbol, the "nominal path symbol," was presented as four tick marks that represented the aircraft's desired position in 3.5 sec if it were flying perfectly down the center of the tunnel. The predictor time of 3.5 sec was chosen to suit aircraft dynamics – longer times are suitable for larger aircraft with slower dynamics (Grunwald, 1996). From the pilot's point of view, the guidance task was simply to fly the predictor symbol into the center of the four tick marks. This task is very similar to flying with a flight director since the higher derivatives used to drive the predictor symbol provide lead compensation.

Test pilots expressed a desire to see raw horizontal and vertical deviation information, so scales similar to the familiar localizer and glideslope needles were added.

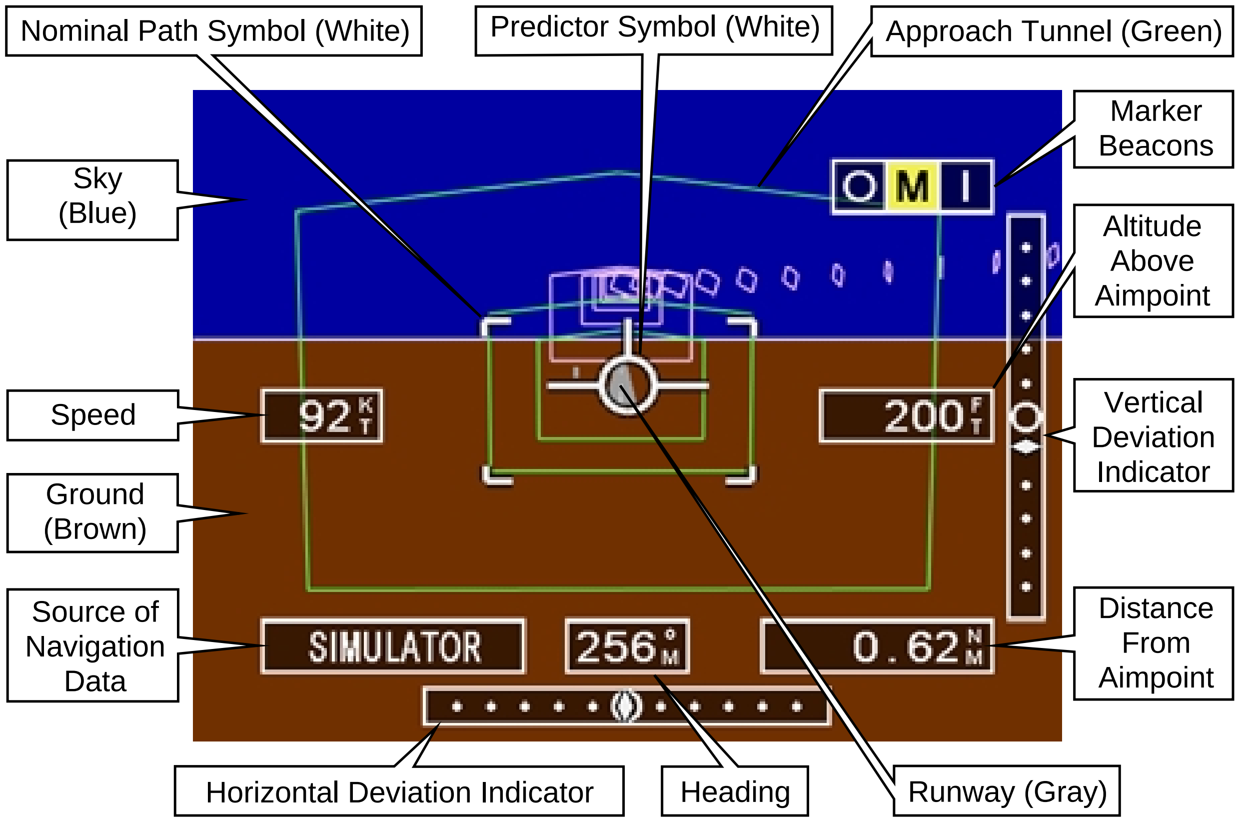


Figure 1. Tunnel Display Symbology

## 2.3 SYSTEM ENGINEERING

Differential GPS (DGPS) was chosen as the position sensor to avoid expensive navigation-grade inertial instrumentation. For flight testing on the Beechcraft Queen Air, DGPS data was supplied by the Stanford University Wide Area Augmentation System (WAAS) prototype using the FAA National Satellite Test Bed network of reference receivers. This provided the Tunnel Display with 2 m 95% of vertical accuracy (Enge, 1996). During King Air testing, position information was provided by a GPS receiver supplied with differential corrections from the commercial Omnistar service. Horizontal accuracy was specified as 3 m horizontal 95%, and vertical accuracy would typically be a factor of two or three larger. Actual values appeared to be much better.

Roll, pitch, and true heading data in the Queen Air was supplied by a system based on complementary filtering of GPS attitude with low-cost inertial sensors (Hayward, 1997). This system used a small triangular array of three GPS antennas on top of the fuselage to provide carrier phase differential attitude measurements. To eliminate noise and dropouts in the GPS attitude signal, inexpensive quartz tuning fork rate gyros were integrated using a Kalman filtering scheme. In the King

Air, attitude information was provided by an Applanix POS/AV position and orientation determination system having a stated accuracy of 0.05 deg in pitch and roll and 0.33 deg in heading. The POS/AV was an integral part of the hyperspectral imaging system.

The computer driving the Tunnel Display was a ruggedized Pentium PC running at 90 MHz with Windows NT as the operating system and OpenGL as the 3-D graphics library. A sunlight-readable 6.4-inch diagonal AMLCD was mounted in the Queen Air instrument panel to the left of the heading indicator – close enough to the center of the pilot's scan to serve as the primary flight display. In the King Air, a 10.4-inch diagonal AMLCD was mounted on the copilot's control yoke sleeve. This provided a large, sunlight-readable primary flight display directly in front of the copilot.

## 3.0 FLIGHT TESTING

### 3.0 INITIAL FLIGHT TESTING

Developmental testing focused on typical instrument flight operations such as straight-in approaches and missed approaches. These tests took place at general aviation airports in California in 1995 and 1996 using a single piston-engine Piper Dakota (Barrows, 1996). The level of path complexity was increased for tests at Moffett Federal Airfield, CA, chosen for its long parallel runways and lack of air traffic. The research aircraft was also changed to a twin piston-engine Beechcraft Queen Air.

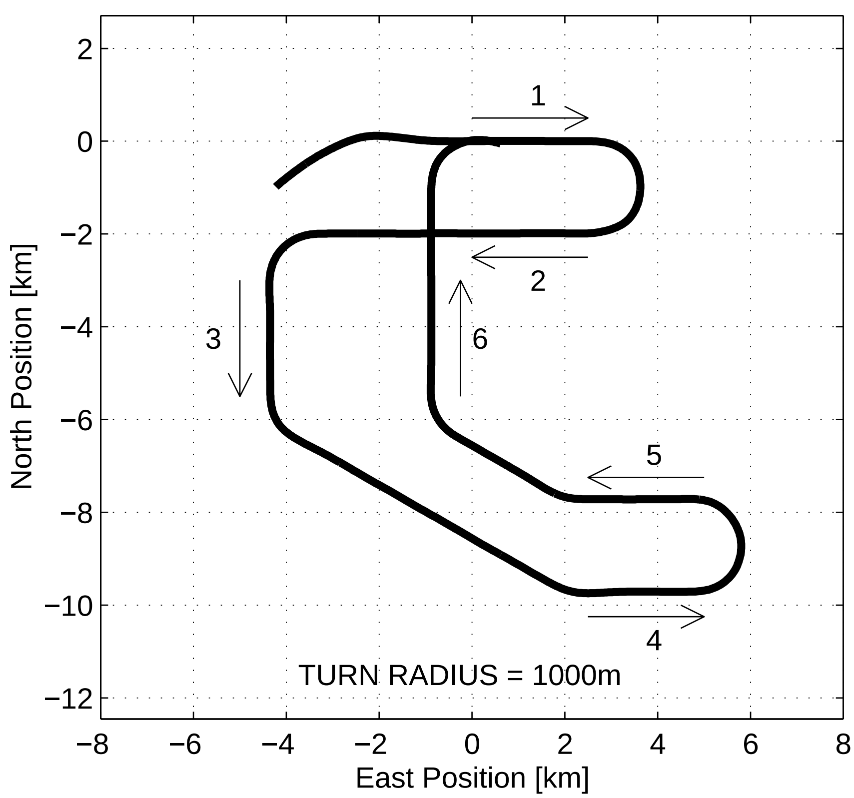


Figure 2. Complex Trajectory (Actual Flight Data)

Tests included segmented and curved approaches as well as flying traffic patterns on instruments. Flying of very complex paths (skywriting by instrument reference!) was also demonstrated (Barrows, 1997). During these tests, the project pilot did not look outside the cockpit, relying only on the Tunnel Display for flight path information. These experiments were performed in visual flight conditions with a safety pilot in the right seat monitoring the pilot.

## 3.1 COMPLEX TRAJECTORIES

To quantify the system's achievable accuracy in the Queen Air, a set of flight tracks was flown with controlled straight and curved segments. Turns of 30, 60, 90, and 180 deg were flown with radii ranging from 750 m to 3000 m. One example is shown in Figure 2. These patterns were flown with the pilot wearing view-limiting glasses (to simulate instrument flight conditions) and a safety pilot in the right seat. Preliminary analysis indicates that for over 75 min flying on straight-line level paths, root mean square flight technical errors (RMS FTE) were 6.6 m horizontally and 3.6 m vertically. (FTE is the path-following error – the difference between sensed position and desired position.) Patterns such as these would be extremely difficult to duplicate with conventional guidance systems.

## 3.2 POSITIONING A HYPERSPECTRAL IMAGER

The Tunnel Display was flown onboard a twin turbine-engine Beechcraft King Air 200 carrying a hyperspectral Compact Airborne Spectrographic Imager (casi) from ITRES Research Limited. The aircraft was operated from Mojave, CA, to demonstrate the imager's ability to detect exploded or unexploded ordinance on the ground. The display system provided guidance for the aircraft over various ground targets near Mojave Airport and at Edwards Air Force Base.

In one instance there were two ground targets at the Edwards Downfall range spaced approximately 1350 m apart. A tunnel trajectory was generated that overflew both targets. This display flexibility allowed the two targets to be imaged in a single pass thus saving on flight time. The runs were flown at an altitude of 370 m (1200 ft) above the ground. To obtain maximum sensitivity from the imaging system, the aircraft was flown as slowly as possible - sometimes at 80 knots indicated airspeed with landing gear and flaps down. This resulted in sluggish handling that would normally make it very difficult for the pilot to achieve high path following accuracy. After each run, a racetrack pattern was flown to rejoin the straight tunnel about 4 km from the first target. (On one run this was cut short to 2 km to save time.) The ground tracks flown during this test are shown in Figure 3.

An expanded plot of the ground tracks between the two targets is shown in Figure 4 with the crosstrack scale greatly expanded to +/-20 m full-scale. The six ground tracks were all very accurate, with the maximum crosstrack error observed being 17.3 m. The horizontal RMS FTE for these runs was only 6.3 m, allowing for complete capture of the target by the narrow 100-m image swath of the hyperspectral imager. Flying at a higher airspeed would likely have produced even better accuracy. The pilot commented that although the system's accuracy was very favorable, its most useful benefits were in improved position awareness and simplified training. During the remote sensing trials, it was easy to visualize the racetrack pattern and flightline intercept even in the dynamic flight environment. This ability would be especially valuable when a mission does not go exactly as designed and the plan needs to be changed rapidly. The pilot did suggest that an additional downward-looking map display would be very useful for additional orientation cues.

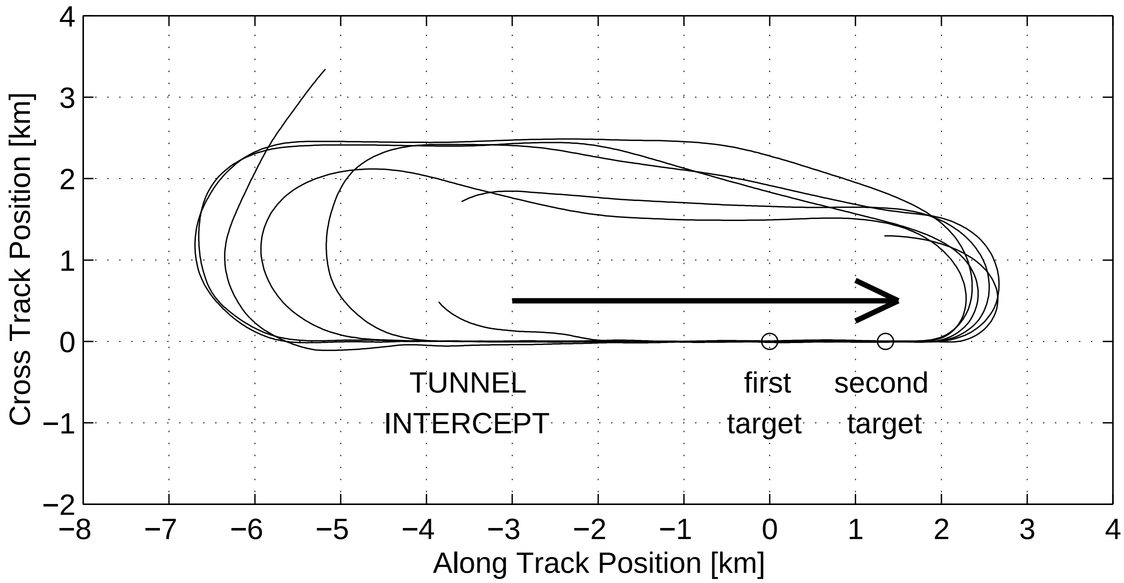


Figure 3. Flight Tracks Over Downfall Range at Edwards AFB

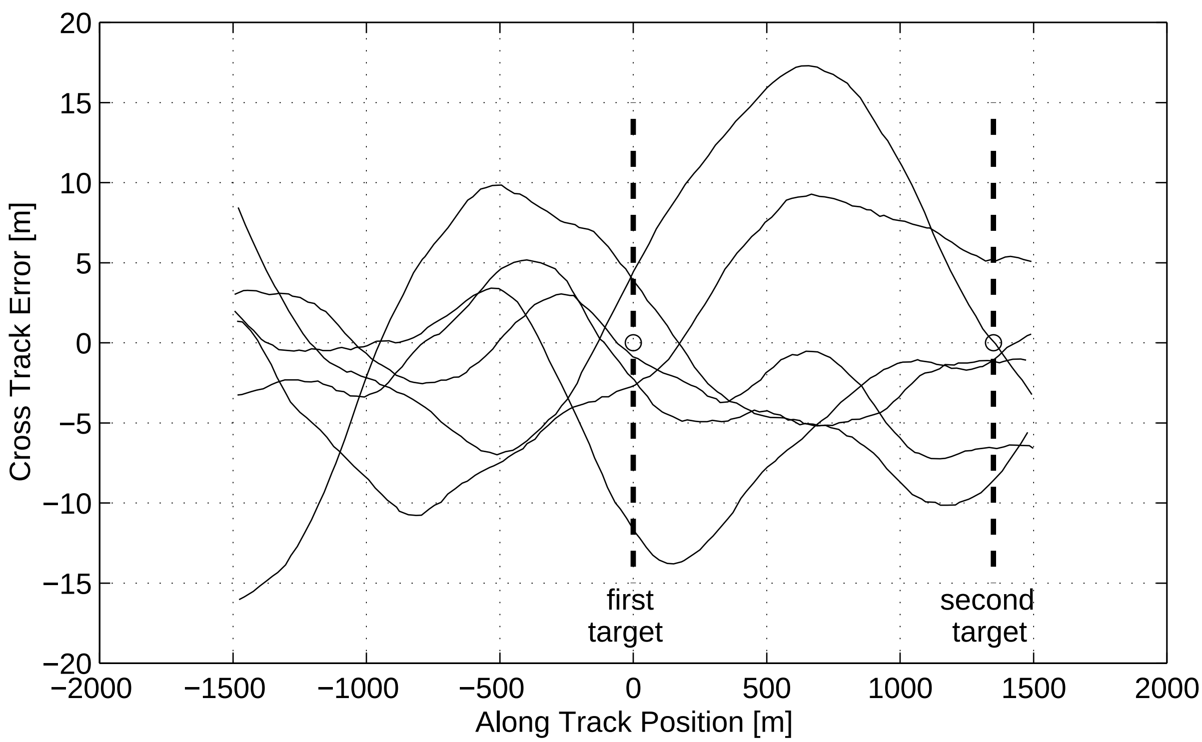


Figure 4. Crosstrack Errors Over Targets at Downfall Range

## 4.0 CONCLUSIONS

Flight testing demonstrated accuracy and situational awareness benefits of tunnel-in-the-sky displays for airborne remote sensing. The achieved accuracy indicated the potential to reduce overlap, missed spots, and time not spent taking data. The pilot was also able to maintain good position situational awareness relative to flightlines and targets, even in maneuvering flight. Because of the Tunnel Display's intuitive presentation, these benefits can be had with less expensive training than typical systems. Additionally, the ability to fly arbitrarily complex patterns suggests potential applications in search and rescue, forest fire fighting, aerial application, and flight inspection.

## ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support of the Federal Aviation Administration Satellite Program Office in developing the Tunnel Display and WAAS prototype systems. For the Queen Air flight tests, the members of the Stanford WAAS lab developed the positioning system, and Roger Hayward and Demoz Gebre-Egziabher created the GPS/inertial attitude determination system. Guy Byrne of the Australian Commonwealth Scientific Industrial Research Organisation and Ben Laurence-Rogers of Environmental Mapping Services provided valuable help setting up and running the positioning and attitude system in the King Air. Finally, the efforts of Sky and Roger Vickers of Environmental Mapping Services in encouraging this work, sharing wisdom on remote sensing flight operations, and enabling the cooperative King Air flight tests are deeply appreciated.

## REFERENCES

A. K. Barrows, P. Enge, B. W. Parkinson, J. D. Powell, "Evaluation of a Perspective-View Cockpit Display for General Aviation Using GPS," *NAVIGATION: Journal of the Institute of Navigation*, Vol. 43, No. 1, pp. 55 - 69, Spring 1996.

A. K. Barrows, K. W. Alter, P. Enge, B. W. Parkinson, and J. D. Powell, "Operational Experience with and Improvements to a Tunnel-in-the-Sky Display for Light Aircraft," *Proceedings of ION GPS-97*, pp. 791 – 799, Sept. 1997.

C. Below, H. von Viebahn, M. Purpus, "Flight Tests of The 4D Flight Guidance Display," *Proceedings of SPIE Enhanced and Synthetic Vision*, pp. 74 – 80, April 1997.

P. Enge, T. Walter, S. Pullen, et. al., "Wide Area Augmentation of the Global Positioning System," *Proceedings of the IEEE*, Vol. 84, No. 8, pp. 1036 – 1088, Aug. 1996.

A. J., Grunwald, "Tunnel Display for Four-Dimensional Fixed-Wing Approaches," *AIAA Journal of Guidance, Control, and Dynamics*, Vol. 7, No. 3, pp. 369-377, May-June 1984.

A. J. Grunwald, "Improved Tunnel Display for Curved Trajectory Following: Control Considerations," *AIAA Journal of Guidance, Control, and Dynamics*, Vol. 19, No. 2, pp. 370-377, March-April 1996.

R. C. Hayward, D. Gebre-Egziabher, M. Schwall, J. D. Powell, and J. Wilson, "Inertially Aided GPS Based Attitude Heading Reference System (AHRS) for General Aviation Aircraft," *Proceedings of ION GPS-97*, pp. 289 - 298, Sept. 1997.

H. Möller and G. Sachs, “Synthetic Vision for Enhancing Poor Visibility Flight Operations,” *IEEE Aerospace and Electronic Systems*, Vol. 9, No. 3, pp. 27-33, March 1994.

D. M. Regal and D. Whittington, “Guidance Symbology for Curved Flight Paths,” *Proceedings of the Eighth International Symposium on Aviation Psychology*, April 1995.

E. Theunissen, *Integrated Design of a Man-Machine Interface for 4-D Navigation*, Delft University Press, Delft, The Netherlands, 1997.

C. D. Wickens, I. Haskell, and K. Harte, “Ergonomic Design for Perspective Flight Path Displays,” *IEEE Controls Journal*, June 1989.