# SYNTHETIC VISION DISPLAYS FOR INSTRUMENT LANDINGS AND TRAFFIC AWARENESS – DEVELOPMENT AND FLIGHT TESTING

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## Abstract

Over the past five years the GPS Laboratory at Stanford University has developed a 3-D "Out the Window" Tunnel-in-the-Sky Display. This display intuitively and accurately renders the attitude and location of the aircraft relative to the local terrain.

This paper summarizes the design, development, and implementation of the Stanford Tunnel-in-the-Sky Display from 1995 through Spring 2000. In particular, details of the display content and system hardware for each stage of development throughout the last five years will be discussed. Extensive flight-testing, culminating in 41 hours of Tunnel-in-the-Sky flight and 180 approaches, have proved invaluable in this research in that it led to solutions that did not appear in laboratory simulations. The research has shown that functional Tunnel-in-the-Sky Displays can be inexpensive, easy to fly, and provide exceptional guidance, terrain and traffic awareness.

## Introduction

Synthetic vision systems for aircraft have been the subject of discussion and research for 50 years. The concept of a Tunnel-in-the-Sky originated with George Hoover and the Army Navy Instrumentation Program in the 1950s. Early work dealt with researching the appropriate symbology to control an aircraft [9]. While answering fundamental design and implementation questions this research could not yield a system that was useable by all levels of aviation. The requisite sensor, computing, and display components of a Tunnel-in-the-Sky Display (Tunnel Display) were still prohibitively expensive for general aviation. The flight display research at Stanford University has been focused on the design, implementation and flight testing of displays for general aviation. Aspects of the research apply to commercial aviation and Civil Air Transport. This focus led us to address the practical and cost issues as well as to push the technical state-of-the-art.

Several years of research and development in this low-cost and operationally minded mode has yielded compelling results. Flight-testing has served as both validation and inspiration for the display research. Integrating the system and flying it in GA aircraft highlighted problems and led to solutions that were not visible in laboratory simulations.



**Figure 1 – Flight Test Aircraft**

**Beechcraft Queen Air**

## Motivation and Background

Flying and landing aircraft are complex tasks, especially in instrument conditions. Pilots must interpret data from a myriad of instruments that each provide only a piece of information. These pieces must be integrated into a mental model of the ownship state with respect to the destination, terrain, and other aircraft. Hundreds of accidents and incidents have

occurred because the pilots have not been able to maintain accurate situational awareness [18].

Started in 1995, the first goal of the research was to combine the Standard-T of instruments (attitude, heading, altitude, airspeed) with pathway guidance. The resulting display should convey better situational awareness, be easier to fly than the Standard-T, and require a smaller instrument scan by the pilot. The result of this stage was the first Tunnel-in-the-Sky Display flown in a single engine piston aircraft [5].

To investigate potential benefits of Tunnel Displays to reduce Controlled Flight into Terrain accidents, researchers at Stanford added a terrain skin and terrain alerting symbology to the display. The culmination of this work was a statistical analysis designed to quantify any gains in height above terrain awareness [1].

With the 3-D depiction of the tunnel and terrain and working flight symbology the next logical step was to investigate conveying traffic awareness. Choosing one of the most urgent safety hazards to test our traffic display we first implemented a Runway Incursion Monitor [12].

At each stage, researchers built on the previous work by incrementally adding functionality to the display. Care must be taken not to cause clutter. We must also be careful to ensure that various features do not interfere with each other. Our strategy to duplicate the out the window scene has proven itself thus far to produce displays without conflict between features. Despite past success it is always imperative to flight-test any changes or additions to ensure that they do mix seamlessly.

## Evolution of the Stanford Tunnel-in-the-Sky Display

The basic system architecture is common to each stage of development. Sensors feed a central computer, which fuses the data and databases. That computer renders the "out the window" view on the cockpit display. In various stages of the research, pieces of the system have been upgraded or changed. Differential GPS, however, has always been the primary position sensor. In the most challenging tests we used WAAS GPS [7] to power the display. Figure 2 shows the current block diagram.
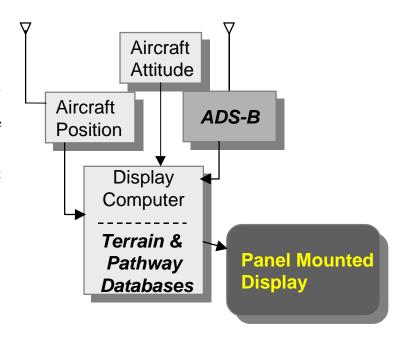


**Figure 2 - System Architecture**

### Stage 1:  First Development

**Display Content** – Figure 3 shows the baseline display. The display is intentionally designed to resemble an attitude indicator. The tunnel and runway are included in 3-D perspective. The tunnel is depicted as a series 100 m wide by 60 m tall hoops spaced at 200 m intervals. The field of view is 50 deg horizontal by 40 deg vertical. Additional important data, magnetic heading, distance to airport, groundspeed are included to reduce the distance of a pilot's scan. Airspeed could be included by adding an air data computer.

The flight symbology is similar to that used in Grunwald, 1996 [8]. A symbol shaped like a circle with wings and a tail indicates the aircraft position in four seconds. The prediction is based on current position, velocity, and lateral acceleration (estimated from bank angle). The nominal path symbol is shown as four corner marks. The square that these corner marks imply indicates the cross-section of the tunnel that is four seconds ahead of the aircraft. The task for the pilot is to keep the predictor symbol at the center of the square defined by nominal path symbol. This task is very similar to flying with a flight director since the higher derivatives, used to drive the predictor symbol, provide lead compensation. The pilot's ability to see the intended flight path provides further lead compensation thus adding to the display's ability to help pilots avoid oscillatory flight paths or "chasing the needles."
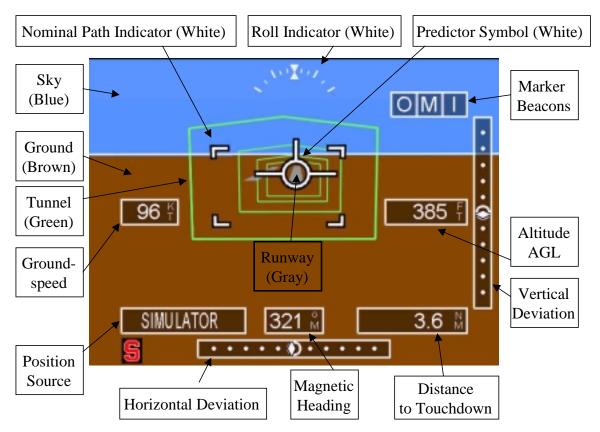
**Figure 3 - Baseline Tunnel-in-the-Sky**

**System** – Differential GPS was the sensor chosen to avoid high cost inertial sensors. Most often the DGPS data came from the National Satellite Test Bed prototype WAAS system. This provided 2 m, 95%, vertical accuracy [7]. Attitude information came from a complimentary filtering system that fused GPS with inexpensive inertial sensors. This system used a small triangular array of 3 GPS antennas mounted atop the fuselage [11].

The computing platform and display device have undergone the most change of any components. Commercial off-the-shelf (COTS) PC hardware was used to keep costs low. Over the course of time the capability of COTS hardware has increased significantly. The first platform, flown in a Piper Dakota in 1995, was an 80486 laptop running DOS. The right seat pilot held the laptop up to the instrument panel so the left seat pilot could fly the tunnel. This computer was capable only of gray scale images. In 1996, the computer was upgraded to a ruggedized 90 MHz Pentium PC running Windows NT. This computer could run the newly emerging color graphics hardware and software. A 5.5-inch diagonal color Active Matrix

Liquid Crystal Display (AMLCD) was attached to the Dakota's glaresheild, but flight tests showed the display was difficult to read in bright sunlight [4].

In 1997 we retired the Dakota and leased a Beechcraft Queen Air from Sky Research, Inc. We mounted a high brightness (1000 nit) AMLCD in the panel. Racks mounted to the passenger seat rails provided ample room to install research hardware. Results discussed in this paper were obtained from flights in the Queen Air.

**Results** – Flight Tests conducted in California in 1995-1997 took place at Palo Alto, Livermore, Truckee, and Moffett Field. In 1998, flight tests took place in Juneau, Sitka and Petersberg, Alaska. The goal was to verify that pilots could control the aircraft and, moreover, could fly very precise approaches. The left seat pilot kept their eyes inside the cockpit and relied on the display for vehicle control and guidance. The right seat pilot acted as a safety pilot. All flights were conducted during Visual Flight Rules conditions.
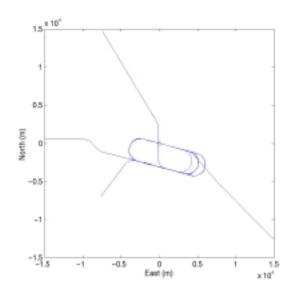
**Figure 4 - Approaches Flown into Juneau Alaska**

Figure 4 shows a top down view of four approaches into Juneau, AK. The runway is at coordinates (0,0). All approaches were flown with the pilot wearing view limiting devices and using the tunnel display for attitude reference and guidance [3].

To quantify the accuracy of the system in the Queen Air, a set of flight tracks was flown with controlled straight and curved tunnels. Turns of 30, 60, 90 and 180 deg were flown with radii ranging from 750 m to 3000 m. The tightest turn radii were smaller than normal instrument flying practice. In straight tunnels the horizontal and vertical RMS FTEs were 21.8 and 11.8 ft, respectively. On curved segments the corresponding FTEs were 38.2 ft and 15.8 ft. These results are better than the Instrument Landing System even at decision height [14].

*Stage 2: Adding Terrain*

**Display Content –** The baseline display in Figure 3 shows no information regarding local terrain. This isn't a shortcoming if the pilot can always fly within the tunnel. Upon seeing Tunnel Display, an American Airlines Captain commented, "It isn't *if* you fly outside the tunnel its *when* you fly outside the tunnel." In 1998 we added a textured terrain skin to the scene to give pilots some visual cues for proximity to terrain and geographic features for guidance. In this iteration it is difficult to make the analogy to an attitude indicator with integral guidance information as we did for the baseline display (Fig.3). Thus, the horizon line becomes a key indicator for roll and pitch.

The databases to generate the terrain came from the Digital Elevation Maps of the U.S. Geologic Society. Coastline information for the continental U.S. is from the USGS Land Use Land Coverage databases. The Alaska Department of Natural Resources provided the coastline data for our Alaskan Flight Tests. Data points of low curvature in both the elevation and coastline data were removed to reduce the number of polygons to be rendered. In some areas up to 70% of the data points were removed.

Performing a Delaunay Triangulation integrated the coastline and terrain data and transformed the mesh of individual points into a list of polygons to be rendered by the graphics hardware.

The left panel of Figure 5 shows the terrain for the Alaska Flight Tests. After flying the Tunnel Display for two weeks, pilots commented on the strengths and weaknesses. Bolding the symbology and augmenting the height above terrain cues were improvements that resulted directly from the test pilots' reactions. To give better height above terrain cues common sized objects, a new terrain texture, and a simulated radar altimeter were added [12]. In the right hand panel of Figure 5 the common sized trees stand 100 ft tall. These trees give pilots a virtual yardstick to measure their height above the terrain. The isotropic, mip-mapped texture reveals more detail as the vantage point approaches the terrain skin. This gives intuitive proximity cues. Lastly, the terrain database and GPS position make possible the calculation of AGL altitudes. This altitude is displayed above the MSL value.

**System** – To leverage advances in graphics rendering engines the display computer was upgraded to a 333MHz Pentium II PC with an Obsidian2 graphics card. This upgrade allowed the addition of terrain without suffering undue decreases in frame rate. While displaying 8,000 – 10,000 polygons and completing all the display computation we were still able to maintain refresh rates in excess of 20-25 Hz.

**Results** – Flight Tests of this display were performed in Southeastern Alaska in August of 1998 and California in August of 1999. The goal was to demonstrate curved approaches at airports severely constrained by terrain. A total of 12hrs 55 min were flown with the display running and a total of 4hrs 28 min were flown in the tunnel. In sum, 47 approaches were flown to Juneau, Sitka, and Petersburg many of which were simulated instrument conditions. In these days of flying the total horizontal and vertical FTE were

**Figure 5 - Terrain Skin Comparison '98 (Left), '99 (Right)**

76.5 ft and 35.8 ft [2]. These data support the claim that functional Tunnel-in-the-Sky displays can greatly increase the accuracy achieved when flying an approach.

### Stage 3:  Dynamically Updating Elements – Tunnels and Traffic

**Display Content** – A tunnel that is fixed in space serves well to represent standard procedures like visual and instrument approaches.  However, for a missed approach, it is advantageous to dynamically adjust the tunnel position in space.  We used GPS derived climb rate to raise or lower the tunnel to match the instantaneous performance of the aircraft.  The missed approach tunnel, nominally represented by magenta goalposts, turns amber if the aircraft climbs at or below the published minimum safe climb gradient for that runway.  The missed approach tunnel is fixed laterally so that it still provides navigation guidance while adapting to aircraft climb performance [12].

It should be noted that the addition of an air data computer would allow current airspeeds to be included in the numeric data.  Displaying current and best climb airspeeds would give the pilot vertical guidance.

Next, we developed a Runway Incursion Monitor for the Tunnel Display. An image of a bogey aircraft is presented on the display. The bogey aircraft can be programmed to perform any number of adversarial maneuvers.  To begin the study the bogey was programmed to taxi onto the runway as the Queen Air flew short final.

At large distances the life-sized image of the bogey is too small to see clearly.  Changing the scaling removes one of the cues that pilots use to judge distance to other aircraft.  Color coding the runways is an intuitive solution to indicate the position and intent of traffic that does not add clutter.

To decide when to color a runway warning (red) or caution (amber) each runway is surrounded by a series of protected zones.  When an aircraft shows intent to enter one of the zones (landing or taxiing) the Tunnel Display in every neighboring aircraft shows the runway as occupied by changing the color from gray to amber.  The display also shows the image of the aircraft.  When two aircraft show intent to enter the same zone the runway is colored red.  Figure 6 shows the view from the landing aircraft.  As we approach the threshold the bogey has taxied onto the runway (now colored red).  This system is meant to give advance warning to pilots.  The amount of advance warning will be quantified in flight tests later in 2000.
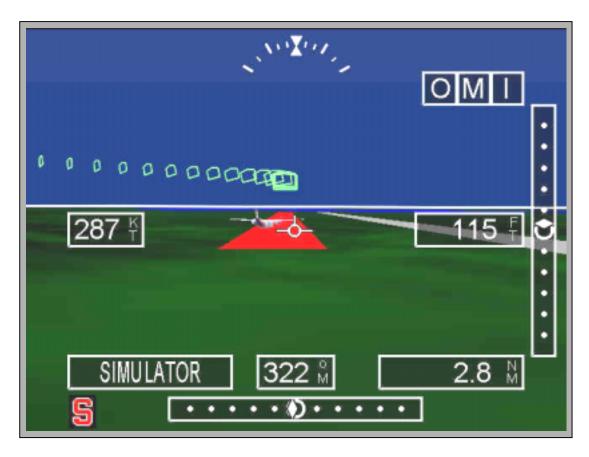
**Figure 6 - Runway Incursion Monitor - Warning**

**System** – Two changes mark this stage. First, a Honeywell HG1150 IMU delivered attitude. Second, a traffic sensor, ADS-B, is being added. ADS-B is a digital datalink between (air and/or land) vehicles, whereby each vehicle broadcasts its GPS derived position, ICAO aircraft identification number, whether the aircraft is climbing, descending, or turning, and airspeed. This sensor is currently being integrated into the flight display system for tests later in 2000.

**Results** – Pilots flying the missed approach tunnel appreciated the flexibility of the dynamic tunnel. In the flight tests, pilots were able to climb at best rate or best angle and easily stay within the tunnel.

In August of 1999 seven approaches were flown into Moffett Field to test the Runway Incursion Monitor. The bogey aircraft was a virtual aircraft and existed only within the display computer. It was programmed to taxi onto the runway as the Queen Air approached the threshold. The pilot was instructed to fly using the display and react as if the display was rendering an actual aircraft. Each time the virtual aircraft incurred,

the pilot of the Queen Air executed a missed approach. Subjective feedback from the two pilots suggested that the color-coding of the runway was more helpful in deciding whether or not to go around than the image of the bogey aircraft [12].

## Conclusions

The flight test team has flown with an active Tunnel-in-the-Sky Display for 41 hours with 2 aircraft and 9 pilots. We have flown 180 approaches into 6 airports in 2 states. Extensive operational experience has demonstrated that:

- Flight-testing has proven invaluable in that it led to solutions that did not appear in laboratory simulations.

- Flight-testing is also valuable in that it refocuses research efforts to help ensure that the displays developed are actually operationally useful to pilots.

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- A Tunnel-in-the-Sky Display can be implemented using low-cost technologies.

- The simple design yielded a flexible system that was readily expandable to incorporate terrain, dynamic tunnels, and traffic.

- Pilots learned to fly the tunnel with almost no training. Student pilots were soon able to fly instrument approaches more precisely than most instrument rated pilots.

- Results showed that adding the terrain skin gave pilots better awareness of their height above the ground.

- Subjective results indicate that the Runway Incursion Monitor can provide pilots with added warning of incursion conflicts.

In summary, the Tunnel-in-the-Sky Display shows promise for all segments of aviation from General Aviation to Civil Air Transport. Heightened situational awareness with respect to pathway guidance, height above terrain, and incurring traffic has been demonstrated. Prior art has shown that using synthetic vision technology provides effective ways to present primary flight control and guidance information [6][8][9][16][17]. In addition, prior and Stanford research has shown there is room in this representation to seamlessly integrate terrain and traffic information.

## Acknowledgements

## Biographies

Chad Jennings is a Ph.D. candidate in the Department of Aeronautics and Astronautics. Mr. Jennings did his undergraduate work in Physics and Astronomy at Vassar College. Mr. Jennings is a private pilot.

Andrew K. Barrows received his Ph.D. from Stanford University in June of 2000. His thesis is entitled, *GPS 3-D Cockpit Displays: Sensors, Algorithms and Flight Testing*. Currently, Dr. Barrows is President of Nav3D Inc., a company that develops synthetic vision systems for aviation. Dr. Barrows has been a private pilot for 14 years.

Keith Alter is a Ph.D. candidate in the Department of Aeronautics and Astronautics. He received his B.S. and M.S. degrees from Stanford and left to work for the Flight Deck Research Group at Boeing. After five years at Boeing Mr. Alter returned to The Farm to complete his Ph.D. Mr. Alter is an avid pilot and a Certified Flight Instructor.

J. David Powell is a professor emeritus of Aeronautics and Astronautics. Dr. Powell has co-authored two textbooks on control systems. His research deals with precision navigation and control of land, air and space vehicles. Dr. Powell is an avid pilot and owner of a Piper Dakota.

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