USING WIDE AREA DIFFERENTIAL GPS TO IMPROVE TOTAL SYSTEM ERROR FOR PRECISION FLIGHT OPERATIONS

A DISSERTATION

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Abstract

Total System Error (TSE) refers to an aircraft's total deviation from the desired flight path. TSE can be divided into Navigational System Error (NSE), the error attributable to the aircraft's navigation system, and Flight Technical Error (FTE), the error attributable to pilot or autopilot control. Improvement in either NSE or FTE reduces TSE and leads to the capability to fly more precise flight trajectories.

The Federal Aviation Administration's Wide Area Augmentation System (WAAS) became operational for non-safety critical applications in 2000 and will become operational for safety critical applications in 2002. This navigation service will provide precise 3-D positioning (demonstrated to better than 5 meters horizontal and vertical accuracy) for civil aircraft in the United States. Perhaps more importantly, this navigation system, which provides continuous operation across large regions, enables new flight instrumentation concepts which allow pilots to fly aircraft significantly more precisely, both for straight and curved flight paths.

This research investigates the capabilities of some of these new concepts, including the Highway-In-The Sky (HITS) display, which not only improves FTE but also reduces pilot workload when compared to conventional flight instrumentation. Augmentation to the HITS display, including perspective terrain and terrain alerting, improves pilot situational awareness. Flight test results from demonstrations in Juneau, AK, and Lake Tahoe, CA, provide evidence of the overall feasibility of integrated, low-

cost flight navigation systems based on these concepts. These systems, requiring no more computational power than current-generation low-end desktop computers, have immediate applicability to general aviation flight from Cessnas to business jets and can support safer and ultimately more economical flight operations. Commercial airlines may also, over time, benefit from these new technologies.

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Acronyms

3-D	Three-Dimensional
ADS-B	Autonomous Dependent Surveillance “B”
AGL	Above Ground Level
ANOVA	Analysis of Variance
ATC	Air Traffic Control
CDI	Course Deviation Indicator
CFIT	Controlled Flight Into Terrain
CRT	Cathode Ray Tube
DEM	Digital Elevation Model
DGPS	Differential GPS
DME	Distance Measuring Equipment
EGNOS	European Geostationary Navigation Overlay Satellite
EGPWS	Enhanced Ground Proximity Warning System
FAA	Federal Aviation Administration
FMS	Flight Management System
FTE	Flight Technical Error
GPS	Global Positioning System
GPWS	Ground Proximity Warning System
HSI	Horizontal Situation Indicator

HITS	Highway-In-The-Sky
IBLS	Integrity Beacon Landing System
IFR	Instrument Flight Rules
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
INS	Inertial Navigation System
L1	L-Band 1st (GPS Frequency, 1575.42 Mhz)
LAAS	Local Area Augmentation System
LADGPS	Local Area Differental GPS
LCD	Liquid Crystal Display
LOD	Level Of Detail
LTI	Lateral Terrain Indicator
MAD	Mean Absolute Deviation
MSAS	Multifuncitonal-Transport Satellite Augmentation System
NSE	Navigational System Error
PFD	Primary (Perspective) Flight Display
RNP	Required Navigation Performance
RTK	Real Time Kinematic
SA	Selective Availibility
TERPS	Terminal Procedures
TIN	Triangular Irregular Network
TSE	Total System Error
VFR	Visual Flight Rules
VHF	Very High Frequency
VMC	Visual Meteorological Conditions
VOR	VHF Omnidirectional Range
WAAS	Wide Area Augmentation System
WADGPS	Wide-Area Differential GPS

Chapter 1

Introduction

In general, civil aircraft spend a significant amount of time flying through clouds, at night, or in other meteorological conditions that preclude the pilots' capability to see anything out the windows. Some might find this surprising, and perhaps disconcerting, but pilots' capability to operate aircraft without any external visual references has existed for many decades. On September 24, 1929, in a fully hooded cockpit, U.S. Army Air Corps Lt. James H. Doolittle made the first completely blind flight in history, taking off, flying over a predetermined course, and landing at the point of departure, all by instruments alone (Johnston, 1980). In the decades following, gyroscopic instruments and radio navigation aids became common in aircraft cockpits. This equipment, along with carefully designed and standardized flight routes and flight procedures, enabled civil flight in poor weather conditions.

The U.S. Department of Transportation's Federal Aviation Administration (FAA) has long held the responsibility to regulate and enforce the rules for safe civil aircraft operation in the United States. The FAA also has the obligation to evaluate new flight procedures and to assess the flightworthiness of new aircraft equipment (a process called *certification*). The FAA must certify new procedures and equipment before aircraft operators can use them legally in civil flight operations.

Except for a few special cases, all civil flight operations must be conducted under one of the following sets of flight rules:

- *Visual Flight Rules (VFR).* Pilots fly mainly by reference to visual cues viewed through the aircraft windows. Pilots hold the responsibility to maintain adequate terrain and traffic separation via these visual cues. VFR flight is only allowed in *Visual Meteorological Conditions* (VMC; sometimes called *visual conditions*), typically one to three miles of flight visibility or greater.

- *Instrument Flight Rules (IFR).* Pilots fly mainly by reference to cues from the aircraft instruments or instructions from Air Traffic Control (ATC). External visual cues are only required for taxi, takeoff, and landing. ATC is responsible for traffic separation, while pilots and ATC share joint responsibility for terrain separation. Aircraft may fly under IFR in either VMC or *Instrument Meteorological Conditions* (IMC; sometimes called *instrument conditions*), which are conditions where visibility is less than 1 mile. Flight under IFR requires the use of certified aircraft navigation equipment and instrumentation commensurate with the IFR flight procedures to be flown.

The work described in this dissertation demonstrates and evaluates navigation systems and flight display concepts that allow pilots to fly aircraft along very precise trajectories by reference to flight instruments. Previous work in this area has utilized expensive inertial navigation equipment and flight display computers. The cost of such equipment has been one of the impediments in moving these advanced displays from the

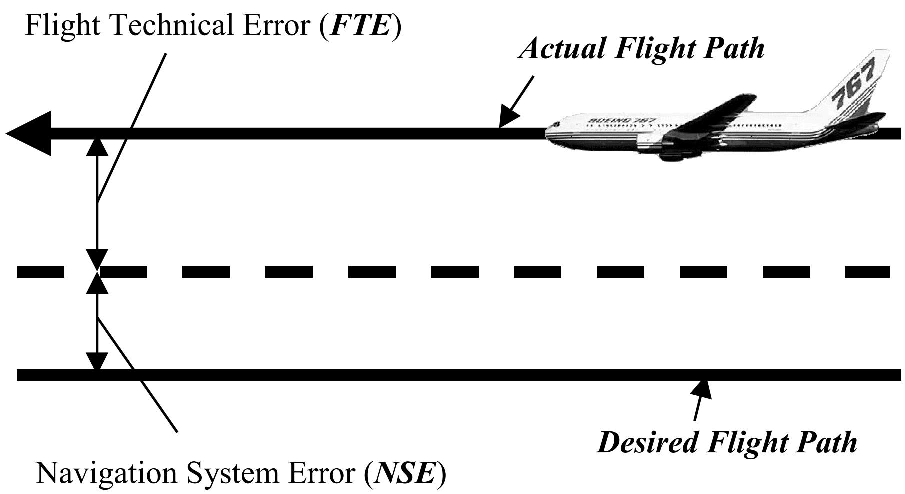


Figure 1. Total System Error.

laboratory to the flight deck. High-accuracy satellite navigation systems (described in sections 1.2 and 1.3), along with new low-cost computing and display technologies, can significantly reduce the expense of this technology and perhaps enable production flight displays.

1.1 Total System Error

Terrain clearance requirements for IFR navigation procedures are based on the expected relative perpendicular distance between the desired flight path and the actual aircraft position. This relative error is called *Total System Error* (TSE) (Figure 1). TSE is usually separated into horizontal and vertical errors. TSE is composed of two distinct components (U.S. Department of Transportation, 1999):

- *Navigation System Error (NSE).* The error attributable to the navigation system in use. It includes the navigation sensor error, receiver error, and path definition error.

- *Flight Technical Error (FTE).* The contribution of the pilot or autopilot in using the navigation information to control aircraft position.

TSE is related to NSE and FTE by the equation:

$$TSE = NSE + FTE$$

where *TSE, NSE,* and *FTE* are the respective error components. Also:

$$\sigma_{TSE}^2 = \sigma_{NSE}^2 + \sigma_{FTE}^2$$

where σ_{TSE}, σ_{NSE}, and σ_{FTE} are the standard deviations of the respective error components. Note that some definitions of TSE separate path definition error, which is the difference between the modeled path through space in the relevant coordinate system and the true desired flight path, from NSE as a distinct third component.

Both newer, more accurate navigation systems and new flight instrumentation or autopilots that can produce smaller tracking errors are beneficial to instrument flight. Reduction in either NSE or FTE yields a reduction in TSE, which allows for lower required terrain clearance requirements for instrument flight procedures. This, in turn, results in approach procedures that allow arrivals in poorer visibility, closer runway spacing for parallel approaches in IMC, and instrument approaches into airports that could not have any before.

Reduction in TSE can be advantageous for VFR flight as well. Certain operations that are typically conducted in VMC, such as aerial survey or firefighting, often require precise knowledge of where the aircraft is, as well as precise and repeatable aircraft positioning along desired flight paths. In these cases, systems that improve TSE may prove advantageous.

1.2 Global Positioning System

The Global Positioning System (GPS) (Figure 2) is a U.S. Department of Defense satellite navigation system approved for civilian use. GPS consists of a nominal constellation of 24 satellites in a 55 degree inclination with orbital periods of 12 sidereal hours. User receivers use ranging and range rate information from these satellites to trilaterate 3-D position and velocity. In addition, GPS includes ground monitor stations located throughout the world, which monitor the orbits and the health of GPS satellites, uplink system navigation data to the satellites for broadcast, and command orbital maneuvers when necessary.

GPS navigational accuracy is generally better than that of older ground-based navigation systems such as VHF Omnidirectional Range (VOR) and Distance Measuring Equipment (DME). Average GPS horizontal position repeatable accuracy is 15 m. (2 drms) (U.S. Department of Transportation, 1999). The Department of Defense can choose to enable (and has in the past enabled) Selective Availability (SA), an intentional GPS satellite clock error for the purpose of degrading the accuracy of civil satellite navigation. With SA on, GPS horizontal position accuracy is 100 m. (2 drms) (U.S. Department of Transportation, 1999). Unlike older radio navigation systems for civil aircraft, GPS can be used to determine an estimate of user altitude as well as horizontal position. Vertical GPS errors tend to be roughly 50% greater than horizontal errors.

Beyond accuracy improvement, GPS shows further promise over older radio navigation systems for civil aviation because it allows flexible routing with worldwide coverage. With satellite navigation, instrument flight routes can be set up anywhere, in any orientation. In contrast, ground-based navigation systems transmitting from fixed locations must have instrument procedures designed about the transmitter station itself, typically on straight paths intersecting the station. On average, GPS NSE is generally uniform everywhere in the U.S. GPS procedure paths and profiles can be straight, curved, or any 3-D trajectory that the aircraft can follow.

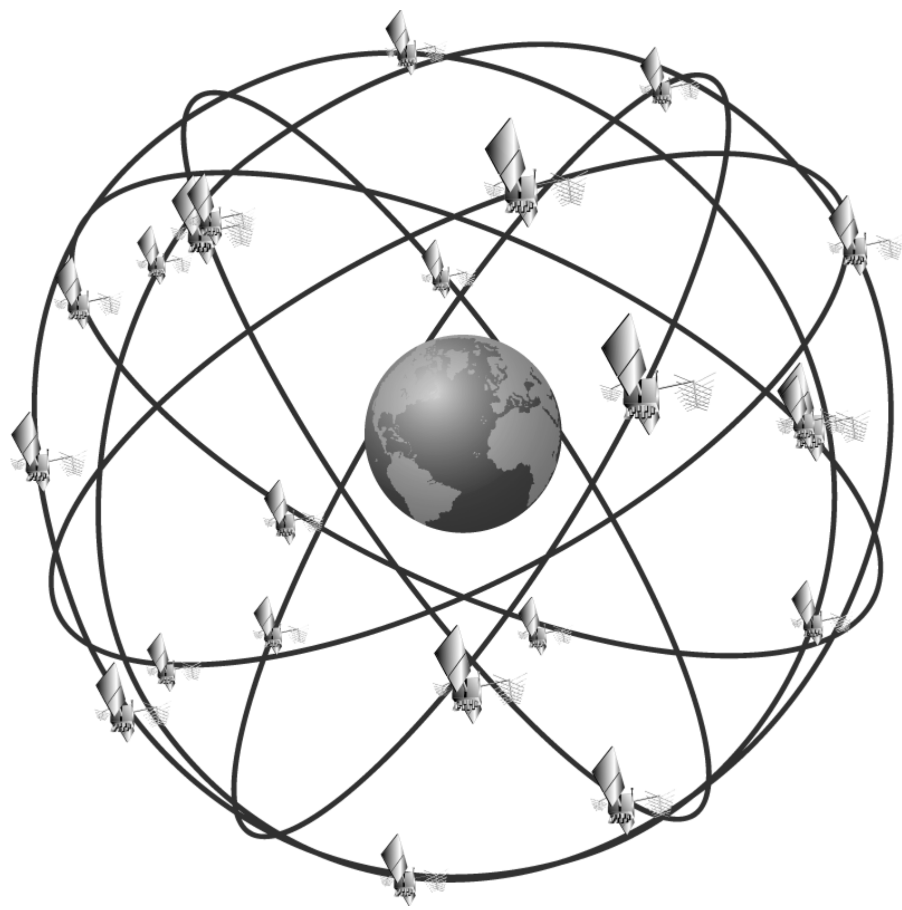


Figure 2. Global Positioning System.

1.3 Wide-Area Differential GPS

Wide-Area Differential GPS (WADGPS) is the concept of using an array of multiple ground stations to estimate GPS ionosphere, ephemeris, and satellite clock errors across a region. While currently SA is off, if SA were turned on, WADGPS could very accurately estimate SA error as well. Corrections for these errors are sent to the user receiver, which applies these estimated corrections to the pseudorange measurements. Position and user clock bias are then estimated from the GPS ranging measurements in the standard method. In contrast, the conventional method for

Differential GPS (DGPS) (also called *Local-Area DGPS)* utilizes a single ground reference station to almost completely cancel out ionospheric, tropospheric, and satellite orbit and clock errors for nearby user receivers. Local area DGPS is limited to roughly a 50-100 km. radius about any reference station. Particular issues arise when utilizing a series of local area DGPS reference stations to navigate across a region, such as which differential corrections to use and how the corrections from each individual station are transmitted. Unlike local area DGPS, WADGPS is seamless across the coverage region and is, in concept, extendable through the addition of reference stations. This feature makes WADGPS ideal for navigation for aircraft, which in many cases fly hundreds or thousands of miles on a single flight.

The FAA has committed to the installation of a WADGPS system with a coverage region that includes the entire United States. Called the Wide Area Augmentation System (WAAS) (Figure 3), the system is currently scheduled to be

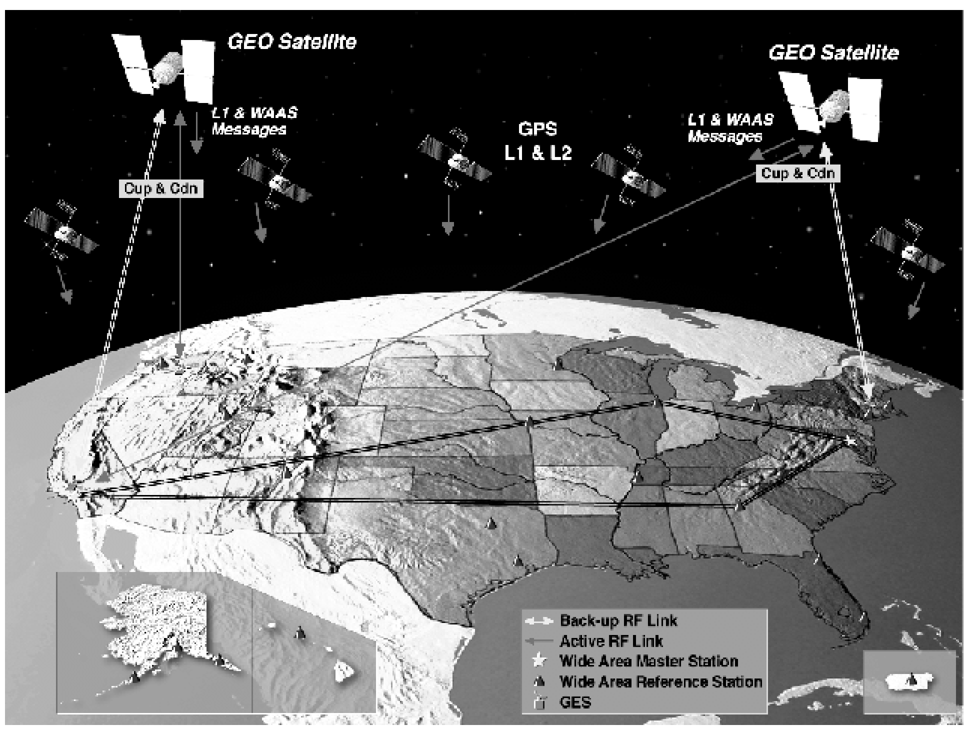


Figure 3. Wide Area Augmentation System.

operational for safety-critical operations in 2002. A prototype version of the WAAS system has been created to evaluate and research WAAS implementation issues. This system is called the National Satellite Test Bed (NSTB), and has demonstrated 2 m. accuracy (95%) over continental areas (Tsai, 1999). Most importantly, the WAAS system is designed to provide the integrity to alert users when the guaranteed accuracy of the system is exceeded. This capability should enable 3-D IFR navigation service in the coverage region to allow for aircraft approaches in IMC to approximately 300-350 ft. above ground. With future enhancements, WAAS will likely enable instrument approaches down to 200 ft. above ground, which is similar in capability to most installations of the Instrument Landing System (ILS), a traditional radionavigation system for final approach guidance.

Simultaneous with the U.S. development of WAAS, other nations are implementing their own WADGPS navigation systems. The European WADGPS system is called the European Geostationary Navigation Overlay Satellite system (EGNOS). Japan is developing a similar system called Multifuncitonal-Transport Satellite Augmentation System (MSAS). In all cases, the WADGPS correction signal is broadcast on the same frequency and in a similar format to the GPS signal itself. A WADGPS receiver uses the same antenna and very similar receiver hardware and software to range and decode the WADGPS signal as a stand-alone GPS receiver. Within a few years, the price of WADGPS receivers and stand-alone GPS receivers may be very close. Since IFR-certified GPS receivers currently cost several thousand U.S. dollars, navigation with low-cost WADGPS receivers likely will be practical even for general aviation aircraft, whose owners typically have a budget for instrumentation that is considerably less than what is spent on airliner cockpits.

As described above, WADGPS reduces TSE through NSE improvement. Perhaps more importantly, however, is the capability of WADGPS to reduce FTE for general aviation aircraft as a low-cost yet high-accuracy navigation system essential for an electronic flight display incorporating new guidance symbology (Figure 4). Perspective flight displays as discussed in section 1.4.2, have been shown to improve

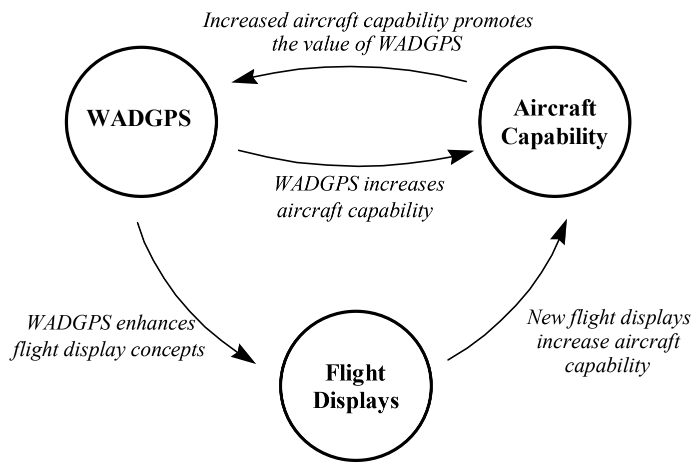


Figure 4. Value of WADGPS to general aviation aircraft capability.

pilots' ability to fly precise trajectories when compared to more conventional flight instrumentation. These new display systems also increase aircraft capability through improved pilot situational awareness and decreased workload, and by improving aircraft navigation through curved approaches and missed approaches.

The greatest potential for perspective flight instrumentation may be for general aviation pilots, who in most cases do not have the same high level of training and expertise with older flight guidance instrumentation. However, until very recently perspective displays have been infeasible for general aviation due to the high cost of electronic graphics computer and display hardware. Further, the cost of inertial navigation systems that provide both accurate and precise 3-D position and velocity has been prohibitive. Less expensive radionavigation systems like ILS and Distance Measuring Equipement (DME), could provide accurate position but not precise 3-D velocity. Even stand-alone GPS might not provide necessary 3-D position and velocity. As shown in the work of Barrows (2000) and in this dissertation, WADGPS adequately provides precise 3-D position and velocity for these new display concepts. The display research described in this work was motivated through the consideration that research into these flight displays also illustrates the value of WADGPS.

1.4 Associated Work

Significant prior research has been conducted in the areas of GPS and WADGPS navigation, perspective display flight guidance, and terrain displays and warning systems. This section surveys this prior art.

1.4.1 Wide-Area Differential GPS

The WADGPS concept was developed at Stanford University (Kee, 1993). This original work showed that the WADGPS concept could provide very accurate positioning with reference stations hundreds of kilometers from the user. In particular, the document contains a detailed list of nine specific GPS error sources that the WADGPS user must estimate. Hypothetically, if all of these were estimated correctly, only multipath and receiver noise would remain as error sources. Enge (1996) contains a thorough overview of the implementation of WADGPS.

A version of differential GPS called *kinematic DGPS* utilizes only the carrier phase measurement of the GPS signal to determine very precisely user position. The phase range measurement (in wavelengths) from the user to a GPS satellite can be divided into a fractional component (which is measured) and an integer component (which is initially unknown). Resolution of the integer component (also called *ambiguity resolution)* for kinematic DGPS is discussed in detail in section 2.3. Traditional ambiguity resolution methods provide the basis for a similar methodology used for kinematic WADGPS (a novel concept for high accuracy positioning utilizing GPS carrier phase and WADGPS corrections, discussed in Chapter 2 of this dissertation). Lawrence (1996) provides specific algorithms and results from experimentation with kinematic DGPS for an aircraft landing system. Raquet and Lachapelle (1997) have hypothesized and tested a system of multiple reference stations which can be used to provide centimeter-level precision across a larger region than can be serviced by a single reference station. This system requires carrier phase measurements from each of the reference stations, and thus at least requires that the user have a separate receiver from the GPS receiver for differential corrections. In contrast, with the kinematic WADGPS concept, the user receives differential correction information on L1 from WAAS (or equivalent), but does not have access to reference station carrier phase measurements.

1.4.2 Perspective Flight Display Guidance (Highway-In-The-Sky)

A number of studies have been conducted investigating the use of a perspective display for flying instrument approaches. Relatively recent work in examining the Highway-In-The-Sky (HITS), or tunnel, concept includes the work of Watler and Logan (1981), Wickens, Haskell, and Harte (1989), Theunissen (1993, 1994), in which different features of the tunnel were compared and evaluated. In particular, a number of studies compared the HITS display to other flight displays in terms of pilot precision and capability during manually flown approaches. Dorighi, Ellis, and Grunwald (1993) demonstrated an advantage in using HITS over conventional instrumentation with an electronic map display in identifying azimuth to geographical targets during manually flown approaches. Reising, *et. al.* (1995) determined that using tunnel symobology on a Head-Up Display (HUD) to fly curved approaches was advantageous compared to using conventional military HUD symbology. Parrish, *et. al.* (1994) found that flying manual curved approaches with HITS results in lower horizontal and vertical errors from the desired flight path and profile as compared to flying with conventional electronic instrumentation (EFIS) with the flight director (pilot guidance cue for manual flight) either on or off. In a more recent study, Regal and Whittington (1995) found that using a tunnel for straight-in approaches resulted in lower pilot workload than using a conventional flight director. Given this, they determined that flying straight-in approaches using either flight director or the HITS display resulted in similar horizontal and vertical errors. However, Regal and Whittington recorded similar results to the Parish study for curved instrument approaches, with increased flight precision and decreased workload available through flight with the HITS display for more complex curved approaches.

In contrast to the large number of studies investigating the merits of HITS displays, few investigations have been done recently to examine the possible advantages of adding incremental information to conventional flight instrumentation. Knox (1993) documented the advantages of manual flight with a flight director over conventional instruments for straight-in approaches (and curved approaches). When Boeing developed the integrated primary flight display (PFD) for the 747-400, their engineers assessed via piloted simulation that adding a track symbol to the horizontal situation indicator (HSI) at the bottom of the PFD allowed pilots to fly smoother approaches; however, this assessment was based on informal pilot evaluations. While Haskell and Wickens (1993) examined 2-D velocity-based predictor information for flying approaches, the examination was done in comparison to a perspective display, rather than conventional instruments.

The past few years have seen a number of flight demonstrations of HITS (Swenson, *et. al.,* 1993; Theunissen, 1997; Below, *et. al.*, 1997). These demonstrations, for the most part, had somewhat limited results, and utilized graphics technology which at the time was relatively expensive. Barrows, *et. al.* (1996, 1997) developed hardware using inexpensive commercially available components and algorithms for using differential GPS to drive a HITS display. He demonstrated the display in flight at several airports in two aircraft, a Piper Dakota and a Beechcraft Queen Air. The work described in this dissertation was specifically intended to extend the work of Barrows and other previous researchers through the evaluation of complex curved approaches and missed approaches, including approaches in mountainous areas with a perspective terrain display.

1.4.3 Terrain Display and Terrain Alerting

The study of graphical terrain generation is fairly extensive. Most of this work is centered on the creation of realistic terrain scenery for flight simulators, other vehicle simulators, and computer games. Methods of terrain representation and options for the generation of 3-D terrain are discussed in Lorriman, *et. al.* (1991). Prior research that discusses elements of terrain graphics that improve pilot performance includes Stevens (1995), who examines the issue of optimal terrain texturing for pilot depth perception. Kleiss and Hubbard (1993) and Kleiss (1995) conducted piloted simulation comparing terrain surface object (e.g., trees) type and density. The results from this study seem to indicate that increasing object density on the terrain surface, which requires more graphics processor power, may result in limited improvement in pilot performance beyond a certain density.

Theunissen (1997), Möller and Sachs (1994), Sachs, *et. al.* (1998), and von Viebahn (1998) describe both the development and flight demonstrations of perspective terrain display concepts. These studies exhibit the capability of modern graphics to provide realistic scenery to pilots. However, in general, results from these works do not compare pilot performances based on display implementation options.

The ongoing effort to counter controlled flight into terrain (CFIT) accidents includes the investigation into warning systems that alert pilots to imminent hazards. Kuchar and Hansman (1993) compared perspective terrain display to plan and profile terrain display concepts. Results suggest advantages for plan (top-down) and profile (cross-section from the side) terrain representation over perspective terrain; however, the perspective display utilized was somewhat rudimentary, and arguably provided poor distance and height above terrain cues. Bateman (1999) discusses Honeywell's successful Enhanced Ground Proximity Warning System (EGPWS), which includes a plan display of terrain about the aircraft. Several 2-D map displays with terrain are commercially available from UPS Aviation Technologies and Bendix/King. Universal Avionics now offers a flight display that can show terrain in both plan and perspective views. These new displays support very good pilot awareness of high terrain in the vicinity around the aircraft. However, perspective displays with clearly rendered 3-D terrain may better support maneuvering to avoid close terrain hazards in from of the aircraft. This topic is discussed in more detail in section 4.4.

1.5 Contributions

The objective of this work includes the investigation of features of GPS and WADGPS that yield improvement or increased functionality for NSE. Further, this work explores the use of novel, low-cost perspective display concepts that improve FTE and pilot situational awareness. The contributions presented in this dissertation are:

- *Development of Glideslope Predictor Concept.* Developed novel glideslope predictor symbol for improved vertical path following when flying straight-in instrument approaches. Examined several different symbols representing immediate closure rate to glideslope to determine the most intuitive graphical depiction.

- *Evaluation of Advanced Flight Display Concepts for FTE Improvement.* Conducted simulator study to determine the effectiveness of candidate display options. This study was one of only a few highway-in-the-sky studies that included an objective measurement of pilot workload. Results indicated a significant improvement in vertical FTE with the glideslope predictor over conventional instrumentation. Results further showed significant improvements in both horizontal and vertical flight technical error as well as workload reduction with the highway-in-the-sky.

- *Piloted Inflight Demonstration of Complex Curved Approaches in Alaska.* Developed and demonstrated extremely complex, curved approaches to help civil aircraft fly in and out of airports with restrictive airspace or mountainous terrain. Collected inflight data showing that the use of a view-limiting device does not increase flight technical error, suggesting that pilots are not utilizing external visual cues to conduct the high-precision curved flight operations with the highway-in-the-sky. Showed how to achieve smoothly animated perspective displays with low-cost navigation and graphics hardware. The high frame rates on the flight displays are preferred by pilots and reduce their workload.

- *Variable-Slope Tunnel for Missed Approach.* Developed novel algorithms for a variable-slope tunnel for missed approach; this more closely matches the pilot's functional requirements for missed approach guidance than a static tunnel. The algorithms include restrictions and alerts for minimum required climb gradient and maximum altitude restrictions. Demonstrated this display concept inflight, including evaluation of this concept under simulated engine-out conditions. Results suggest that this concept is feasible, but that it requires more pilot training than the static highway-in-the-sky.

- *Perspective Terrain Display for Improved Pilot Situational Awareness.* Developed a high-resolution textured 3-D perspective terrain display at significantly lower cost as compared to other display concepts demonstrated inflight in earlier research. Iterated display color contrast scheme to optimize readability of terrain display on Liquid Crystal Display (LCD) in actual flight conditions. Demonstrated feasibility and precision of display inflight utilizing the NSTB Wide Area DGPS positioning system. Pilot feedback from Alaskan flight testing revealed the need for improved terrain surface representation. Based on prior research, common-sized surface objects were added to the terrain.

Determined the optimal density for trees to maximize pilot terrain awareness without sacrificing high frame rates. Incorporated prior research and capabilities of state-of-the-art graphics cards to develop a homogeneous, isotropic terrain texture that increases in resolution as the pilot approaches the terrain; this was accomplished while keeping the overall (low) cost of the hardware the same as in the prior iteration. This improved work was accomplished by taking advantage of graphics card technology that became available in 1998. Demonstrated improved terrain in flight testing in the Lake Tahoe area; pilot feedback from flight tests revealed that improved terrain texturing yields better pilot ability to estimate height above terrain.

- *Perspective Terrain Alerting to Show Hazardous Terrain.* Developed novel algorithms for alerting the pilot to hazardous nearby terrain and for presenting this information on the perspective terrain display. Developed algorithms for a minimum altitude bounding surface for pilot alerting based on maximum aircraft climb gradient. Created the Lateral Terrain Indicator (LTI) concept and algorithms. These indicators were designed specifically to address pilot feedback that while the perspective terrain display provides good awareness of terrain in front of the airplane, the display does not provide adequate information on potentially hazardous terrain to the sides of the airplane. Conducted piloted simulator study on alerting concepts, which revealed significant performance improvements with terrain alerting when compared to no alerting.

- *WADGPS Velocity Estimation.* Conducted initial quantification of WADGPS velocity from flight test results. Results indicate an approximate order of magnitude improvement for WADGPS velocity over stand-alone GPS velocity with Selective Availability on.

- *Kinematic Wide Area Differential GPS for NSE Improvement.* Created novel concept of using carrier phase measurements with a single receiver to achieve high accuracy 3-D position by utilizing the NSTB differential corrections. Developed the algorithms for static survey. Results from test runs with actual GPS measurements suggest a horizontal positioning accuracy of approximately 50 cm or less (1 sigma).

Chapter 2 of this dissertation contains details of WADGPS velocity estimation as well as a description of the kinematic WADGPS concept. Chapter 3 discusses results from simulator and inflight research demonstrating improvement in FTE due to primary flight instrumentation concepts. Chapter 4 examines flight display concepts, including perspective terrain display, that increase functionality of the basic HITS display. Finally, Chapter 5 concludes the work and offers suggestions for further research.

Chapter 2

Navigational System Error Improvement

2.1 Introduction

Significant research and validation testing has confirmed the capability of WADGPS to improve NSE over older radio navigation aids and stand-alone GPS (see section 1.4) by over an order of magnitude. Once implemented, the operational versions of WADGPS (including WAAS in the United States and EGNOS in Europe) should provide this improvement with a high-level of continuity and integrity.

In this chapter, we investigate some additional advantages of WADGPS for navigation beyond estimated position improvement with standard (carrier-smoothed code-based) WADGPS. While much of the original research into WADGPS centered on position improvement, it was recognized early on that the same underlying concept could yield significant velocity improvement over stand-alone GPS (with SA on). Having accurate velocity as well as accurate position measurements is beneficial to WADGPS users, including the aviation segment. For example, the velocity information can drive a velocity vector, which indicates the instantaneous flight path of an aircraft (see section 3.2.4), on a flight display. Section 2.2 describes this improvement, as well as a simple algorithm that yields smooth, high-rate position output from lower-rate WADGPS position and velocity estimates. Section 2.3 examines a navigation technique with utilizes GPS carrier phase ranging (as opposed to carrier-smoothed code) to further improve WADGPS NSE. Finally, section 2.4 explores how GPS NSE and WADGPS NSE affect the utility of perspective flight display concepts.

2.2 3-D Velocity Estimation

The instantaneous velocity of a GPS user can be estimated using the doppler (range rate) measurement for each satellite in view. As with GPS position, the velocity measurement accuracy in any direction is subject to satellite geometry, and typically the more satellites in view, the better the user velocity estimate. The method to determine GPS velocity is virtually identical to the common iterative algorithm used to solve for GPS position, except that doppler is used as measurements instead of pseudorange or carrier smoothed code. This method is described in detail in Enge (1996).

While user velocity can be estimated with significant accuracy using stand-alone GPS carrier phase measurements, user velocity can be calculated with increased accuracy utilizing the WADGPS correction message. Carrier phase cycle slips and changes in the number of satellites in view affect the accuracy of the WADGPS-corrected velocity in a similar manner to stand-alone GPS velocity. However, selective availability (SA) rate (when SA is on) can be removed from the stand-alone GPS velocity to provide a significantly more precise velocity estimate. Smaller velocity errors due to ionospheric changes and satellite orbit errors could, in theory, also be removed utilizing WADGPS corrections.

As an initial examination of the possible improvements in user velocity, Stanford GPS code created for the evaluation of WADGPS on mobile user platforms (e.g., golf carts, airplanes) was modified to calculate velocity as well as position. In this initial study, GPS doppler measurements were not used. Instead, both stand-alone and WADGPS-corrected velocities were calculated using carrier phase difference over the sampling period (in this case 0.2 sec.). This provided solutions with lag, but in general the accuracy of these estimates were expected to be very similar to the accuracies of velocity solutions that utilized doppler. WADGPS corrections were generated by the Stanford WAAS Testbed (Chao, 1997) with reference stations in Arcata, Elko, and San Diego.

For the work described in this section, user-to-satellite range rate was determined through differencing carrier phase over the sampling period, then subtracting out the satellite velocity component along the line of sight vector for each satellite, as follows:

$$V_{user}^{j} = los^{j} \cdot V^{j} - [\phi^{j}(t) - \phi^{j}(t - \Delta t] / \Delta t$$

where:

V_{user}^{j} = user velocity toward or away from satellite *j*.
los^{j} = line of sight vector from user to satellite
V^{j} = satellite position difference over Δt
$\phi^{j}(t)$ = phase range at time *t*.
Δt = sample time

The user velocity was then obtained by using a weighted least square estimate based on the measured velocity terms for each satellite. (McLoughlin, *et. al.*, 1995).

The corrected user velocity was calculated in the same method as above, except the relative velocity terms were corrected using data from the WADGPS correction signal as follows:

$$V_{user,corr}^{j} = V_{user}^{j} - [B(t) - B(t - \Delta t) + T(t) - T(t - \Delta t) - (I(t) - I(t - \Delta t))]$$

where:

B(t) = WADGPS satellite clock correction term (includes SA, when on)
T(t) = WADGPS troposphere correction term from model

I(t) = WADGPS ionosphere correction term

For this work, the weighted least squares velocity estimate V is calculated as:

$$V = (G^T W G)^{-1} G^T W V_{user,corr}$$

where:

$$V_{user,corr} = \begin{bmatrix} V^{(1)}_{user,corr} \\ V^{(2)}_{user,corr} \\ \vdots \\ V^{n}_{user,corr} \\ \dot{b} \end{bmatrix}$$

$$G = \begin{bmatrix} (los^{(1)})^T & 1 \\ (los^{(2)})^T & 1 \\ \vdots & \\ (los^{n})^T & 1 \end{bmatrix}$$

$$W = \begin{bmatrix} snr^{(1)} & & & 0 \\ & snr^{(2)} & & \\ & & \ddots & \\ 0 & & & snr^{n} \end{bmatrix}$$

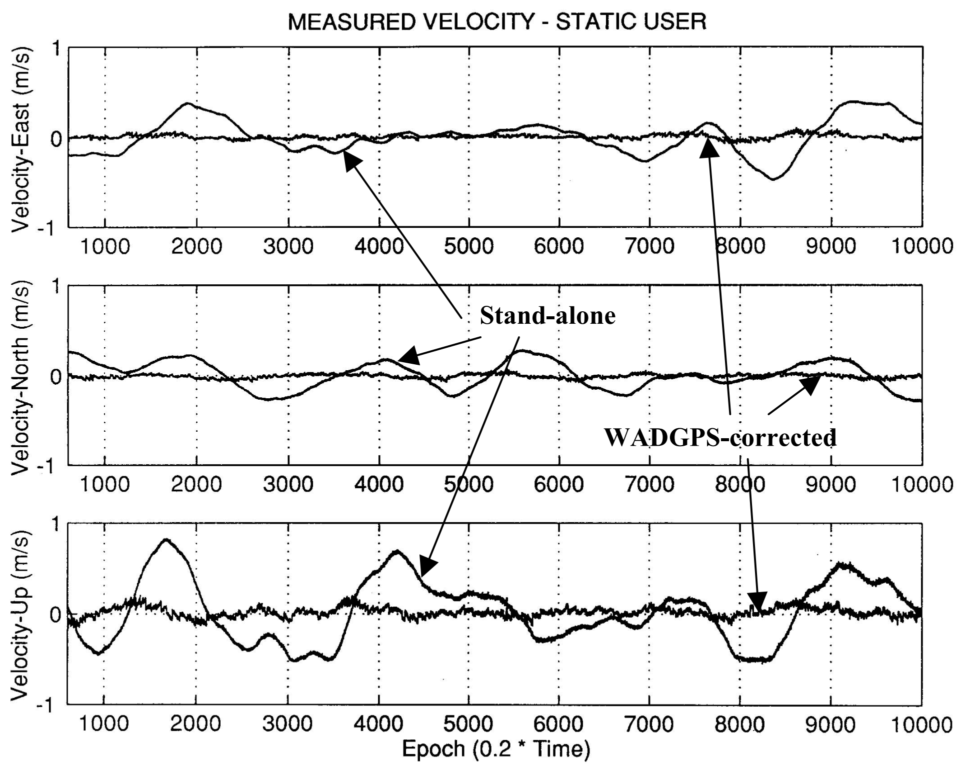
The term $\dot{b}$, above, refers to the receiver clock error rate of change.

For comparison, the stand-alone user velocity is obtained using the same least-squares method as used for the raw velocity, except that the stand-alone line-of-sight velocities are utilized.

The actual code developed for WADGPS-corrected velocity did not include the velocity error corrections for the troposphere and for the ionosphere. These terms were deleted as 1) these correction terms are typically extremely insignificant (e.g. on the order of 0.0001 m/s) when compared to the SA rate correction term, and 2) due to existing features in the code, differencing of ionosphere and troposphere terms resulted in regular undesirable spikes in the velocity estimate. For the purposes of determining the effectiveness of the WADGPS velocity correction algorithm, data for a static user was collected from a antenna on the roof of the Durand building at Stanford University over a continuous period of approximately 30 min. A velocity estimate was also collected from a data file generated on a November 7, 1995 test flight of a Piper Dakota at Palo Alto airport, in which the recorded information included GPS measurement data (including WADGPS correction terms) from taxi start through one complete right hand traffic pattern. For each epoch (0.2 second time interval), both stand-alone and WADGPS-corrected user velocity were calculated. Data from the flight test was reviewed to determine if any obvious problems existed for velocity determination in a non-static environment.

In general, both stand-alone and corrected velocity terms were fairly precise. However, results indicate a significant improvement in velocity estimation when utilizing WADGPS-corrected velocity. Figure 5 shows the east, north, and up components of user velocity from the static test, and the mean error and the standard deviation of the stand-alone and WADGPS-corrected data. The stand-alone velocity clearly shows the effect of SA rate-of-change, which can vary significantly from one minute to the next. One possible drawback of the corrected velocity is a characteristic “sawtooth” output due to SA drift between regularly spaced WADGPS messages (here 6 seconds, or 30 epochs, apart) (Figure 6). However, the “sawtooth” activity can be smoothed somewhat with filtering at the expense of lag. No reference of actual airplane velocity (“truth”) was available in flight. However, measured velocity error can be examined while the aircraft was stationary on the ground. Figure 7 shows measured aircraft northward and eastward velocity while the airplane is stationary on the ground over a period of approximately 3.5 minutes. While the raw velocity error tends to drift (due to SA rate) over this short period from northerly to southerly, the corrected velocity clusters around zero.

Figure 8 shows user velocity and track over the entire inflight portion of the data. Differences between raw and corrected velocity are not apparent at this scale.



Velocity bias	East (m/s)	North (m/s)	Up (m/s)
Stand alone (SA on)	0.0083	0.0044	0.0273
WADGPS-corrected	0.0066	-0.0088	0.0188

Velocity rms error	East (m/s)	North (m/s)	Up (m/s)
Stand-alone (SA on)	0.1934	0.1529	0.3481
WADGPS-corrected	0.0244	0.0226	0.0539

Figure 5. WADGPS-corrected vs. stand-alone GPS velocity.

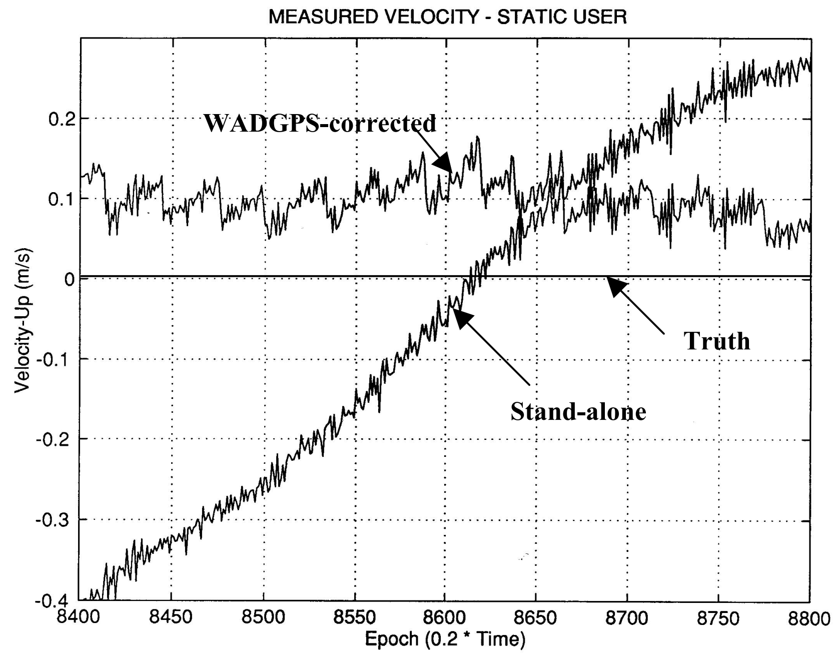


Figure 6. Close-up of user velocity.

Figure 9 shows measured vertical velocity during flare and landing. During this period of time the corrected velocity shows roughly a 0.5 m/s bias from the raw velocity. The corrected vertical velocity is considered more accurate as the value after landing remains centered about zero vertical velocity.

Figure 10 shows airplane track on final approach (calculated from eastward and northward velocity). In this form, stand-alone velocity error is apparent as an approximately 0.5 deg. angle error between raw and corrected track. This error is significant when compared to the magnitude of heading changes required on final approach (approximately +/- 1 deg. on this approach). Track calculated from WADGPS-corrected velocity yields less error.

These results suggest that the WADGPS correction effectively removes the slowly changing velocity error due to SA in all axes. While the WADGPS correction does not completely eliminate velocity errors, a filtered velocity signal will have a number of useful applications. Examples of aviation-related uses for velocity include a ground track and ground speed indication, a glideslope predictor symbol for improved glideslope following, and a flight path vector for HITS displays.

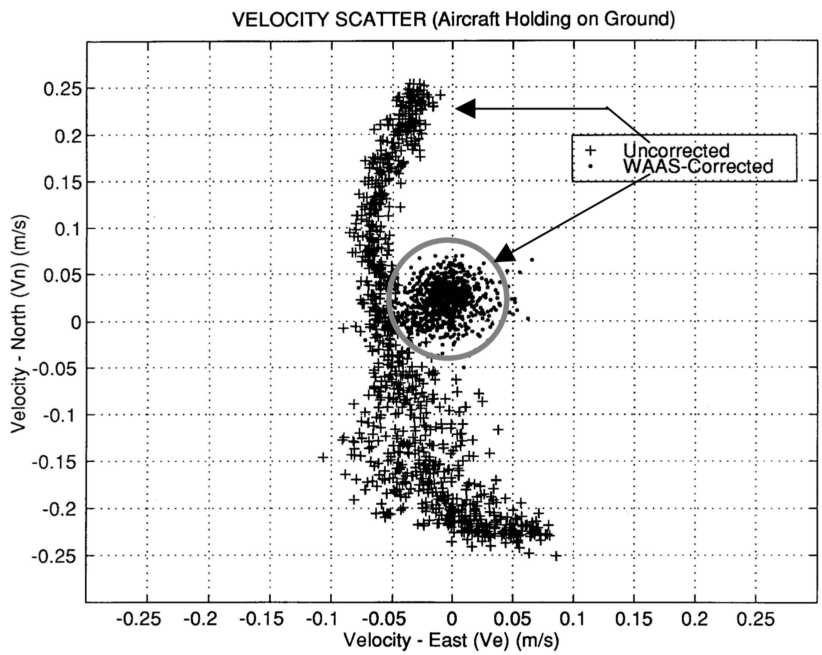


Figure 7. Aircraft stationary on ground.

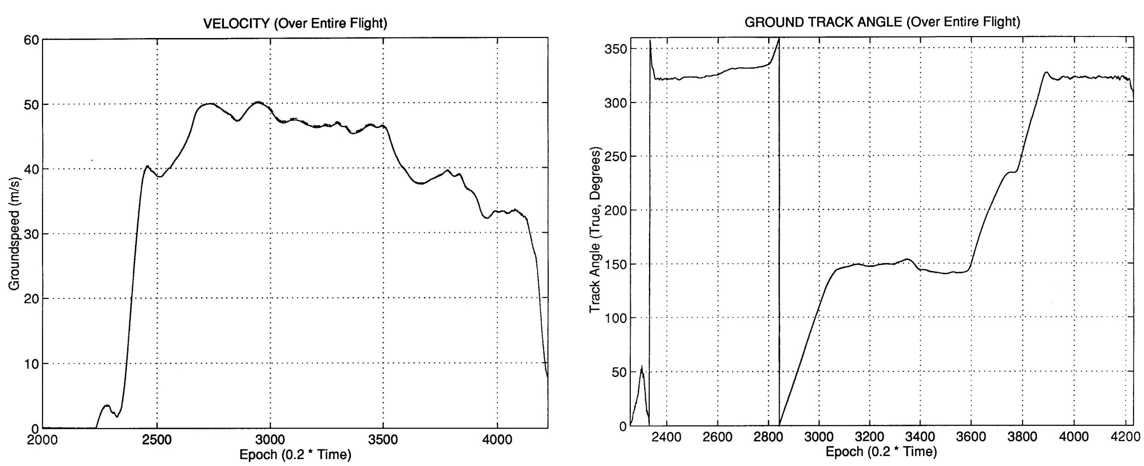


Figure 8. Flight test velocity and ground track angle.

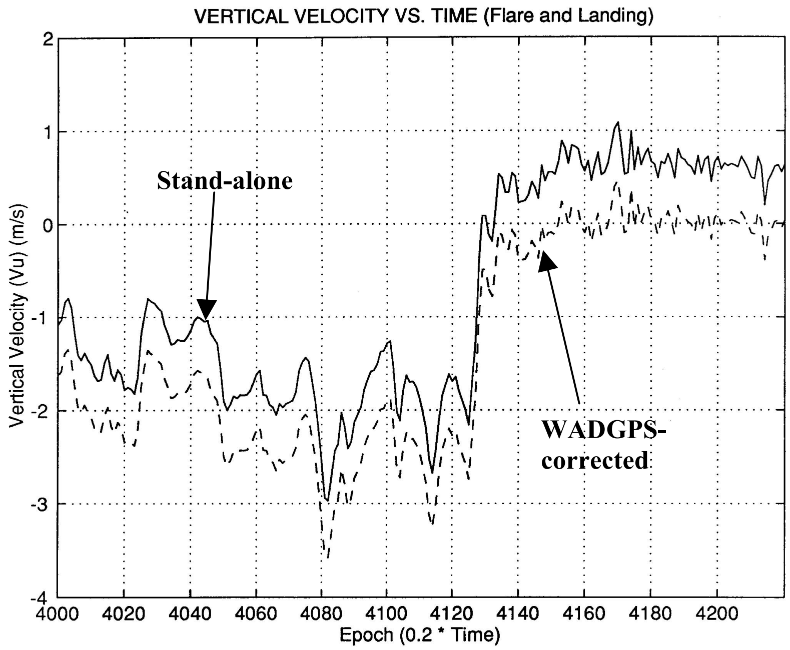


Figure 9. Vertical velocity on final approach.

2.2.1 3-D Position Aided with Velocity

Many GPS receivers provide position and velocity output at data rates ranging from 1-10 Hz. Partly due to frame rate limitations of the graphics technology used, initial flight demonstrations of the HITS display utilizing NTSB WADGPS used a 5 Hz display position update. This increased to 10 Hz for later testing, when the WADGPS computer output increased from 5 Hz to 10 Hz. While the 5 Hz display utilized some filtering of WADGPS positioning, neither incorporated WAAS velocity for position updating. The resulting display, while functional, had noticeable jerkiness between frame updates (Barrows, 1997).

In contrast, a smoothly animated flight display using this data must update at least 18 Hz, and nominally should update at 30 Hz or more (see section 4.3.3). Given the accuracy of the WADGPS velocity estimate, for civil aircraft maneuvering normally

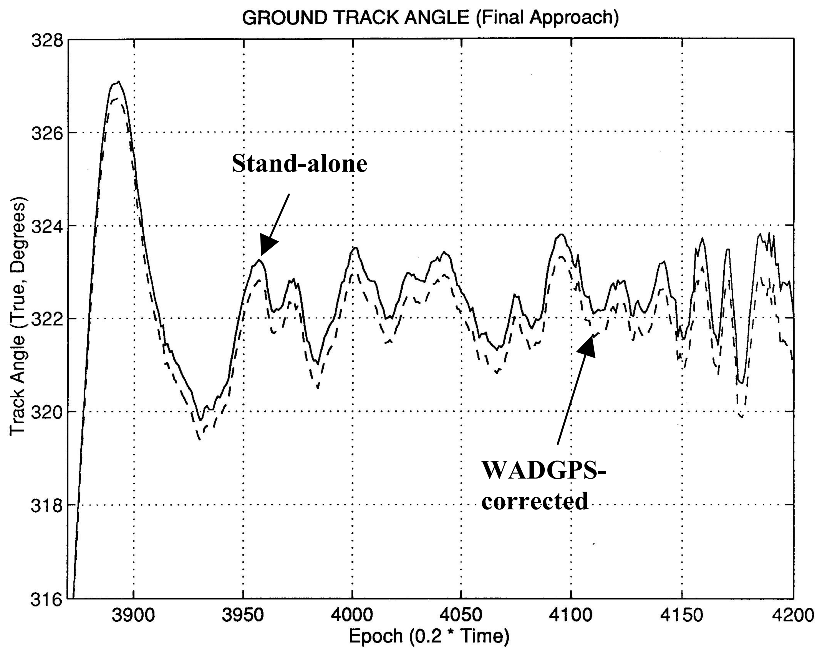


Figure 10. Ground track on final approach.

we can generate a functional estimate of current aircraft position using 10 Hz WADGPS position and velocity with the equation:

$$\vec{x}_{user}(t_0 + \Delta t) = \vec{x}_{user}(t_0) + \vec{v}_{user}(t_0)\Delta t$$

where t_0 is the time the most recent valid GPS position and velocity was measured.

Δt for the current frame must be estimated using measured frame periods from prior frame updates. For the 3-D display concepts tested, frame period changed very little from frame to frame, and thus this method for estimating Δt worked well. Note that here Δt never exceeded 0.1 sec.

Flight test experience demonstrated that this estimator yielded a very smoothly animated display for frame rates from 20 Hz to 60 Hz. In general, pilots noticed very few observable position jumps due to the estimator.

2.3 Kinematic Wide-Area Differential GPS

Standard WADGPS utilizes GPS pseudorange measurements to determine range from GPS satellites. Estimated WADGPS position is significantly more accurate and smooth when pseudorange measurements are filtered with GPS carrier phase measurements. Given this, while less so than pseudorange measurements only, carrier-smoothed code measurements remain susceptible to multipath and receiver noise. Pseudorange multipath error, which is typically much greater than phase range multipath error, remains apparent in carrier-smoothed code due to the finite averaging time (typically approximately 100 sec.) used in the smoothing filter.

Kinematic WADGPS is similar to WADGPS, except that kinematic WADGPS utilizes carrier phase measurements to estimate position. This is analogous in concept to kinematic DGPS, in which carrier phase is used instead of pseudorange or carrier-smoothed code. Unlike kinematic DGPS, kinematic WADGPS provides an absolute position, not position relative to a single reference station (Figure 11).

Carrier phase ranging requires the resolution of ambiguity for each satellite in view. These ambiguities are constant unless a loss-of-lock (cycle-slip) occurs on the tracking loop for any particular receiver channel. For local-area kinematic DGPS, these ambiguities are always integers, and this knowledge can be used to improve ambiguity resolution. In contrast, the ambiguities for kinematic WADGPS are not necessarily integers, but still can be estimated as real constants. Estimating these kinematic WADGPS non-integer ambiguities as real values is very similar in nature to proven local-area kinematic DGPS techniques which estimate the ambiguities as float values rather than rounding these estimates to the nearest integer.

It is hypothesized that kinematic WADGPS is worthwhile due to the fact that carrier-smoothed WADGPS user systems can estimate SA, satellite clock and ephemeris errors, ionosperic errors, and (to a lesser extent) tropospheric errors extremely well. Given this, the remaining multipath error and receiver noise constitute a significant percentage of the overall WADGPS ranging errors. Carrier-only ranging is much less

Examples of DGPS		Local Area DGPS	Wide Area DGPS
		Characterized by: ▪ Single reference station ▪ Solving for relative position from ref. station ▪ Most error sources cancel ▪ Solution more accurate "close" to ref. station	***Characterized by:*** ▪ Multiple reference stations ▪ Solving for absolute position (e.g. WGS84 position) ▪ Must solve explicitly for error sources (I, T, etc) ▪ Solution accurate over wide area
Carrier-smoothed code	***Characterized by:*** ▪ Higher receiver and multipath noise ▪ No ambiguity	LAAS	WAAS
Carrier phase only	***Characterized by:*** ▪ Lower receiver and multipath noise ▪ Ambiguity resolution required	IBLS, RTK survey	Kinematic WADGPS

Figure 11. Examples of DGPS.

susceptible to multipath error and code-phase receiver noise than carrier-smoothed code. Thus kinematic WADGPS, which uses carrier only for ranging, should demonstrate accuracies similar to a hypothetical WADGPS positioning with the aforementioned multipath and receiver noise errors removed.

The kinematic WADGPS system should be realizable using only a single-frequency (L1) WADGPS receiver with additional software. However, kinematic WADGPS requires the estimation of the ambiguities described above to be useful. Hypothetically, a static survey could be used to estimate these ambiguities prior to taking position measurements; this technique was investigated (see section 2.3.2). Given this, there is no reason why an "on-the-fly" estimation process, in which the ambiguities are estimated while the user is moving, is not also theoretically possible.

2.3.1 Measurement Residuals and Kinematic WADGPS Accuracy

Investigation into the feasibility of kinematic WADGPS centered on the observation of phase residual, as phase residual (once the user clock error is removed) must be reasonably constant for this concept to be practical. For this analysis, phase residual for a static user at a pre-surveyed location is defined as:

$$res^j = \phi^j - \left\| \vec{X}^j + d\vec{X}^j - \vec{x} \right\| + (B^j + dB^j) + I^j - T^j \qquad (2.1)$$

where all the terms on the right side of the equation are measured or known, i.e.:

Measured:	ϕ^j, I^j
Broadcast:	$\vec{X}^j, B^j$
Estimated from WAAS, sat. elevation:	$d\vec{X}^j, dB^j, T^j$
Known user position:	$\vec{x}$

Note that in this work the ionospheric error term was measured using a dual-frequency receiver, but in practice a WADGPS ionospheric estimate for an L1-only receiver should be very close to the real error. Further investigation into single-frequency kinematic WADGPS is warranted (see section 5.1). Since phase range consists of the following components

$$\phi^j = \left\| \vec{X}^j + d\vec{X}^j - \vec{x} \right\|_{actual} + b - (B^j + dB^j)_{actual} - I^j_{actual} + T^j_{actual} + N^j \lambda + \nu \qquad (2.2)$$

where $(\bullet)_{actual}$ are the true, unknown values for the indicated parameters. When we plug *(2.2)* into *(2.1)* we see that

$$\begin{aligned} res^j = & \left\| \vec{X}^j + d\vec{X}^j - \vec{x} \right\|_{actual} + b - (B^j + dB^j)_{actual} - I^j_{actual} + T^j_{actual} + N^j \lambda + \nu \\ & - \left\| \vec{X}^j + d\vec{X}^j - \vec{x} \right\| + (B^j + dB^j) + I^j - T^j \end{aligned}$$

or, when similar terms mostly cancel

$$res^j = N^j \lambda + b + noise$$

where $N^j \lambda$ is the constant ambiguity bias commonly associated with the GPS phase range measurement, *b* is the user receiver clock error, and *noise* is the residual between the measured/broadcast/estimated and actual values for terms plus the receiver noise ν.

The value $res^{j1} - res^{j2}$, the difference in phase residual between satellites *j1* and *j2*, then contains the difference between constant ambiguities and noises. The user clock error, *b*, cancels out completely. If kinematic WADGPS is to be an improvement over carrier-smoothed code WADGPS, $res^{j1} - res^{j2}$ must be relatively constant with noise errors of less than one meter. (Note: in the analysis of local area DGPS, the term "double-differencing" refers to the subtraction of differential range measurements from two different satellites. The same subtraction is utilized here, except that there is no "first" difference between the reference station and user range measurements). For clarification, we will refer to $res^{j1} - res^{j2}$ as the "satellite-to-satellite" single difference (Figure 12).

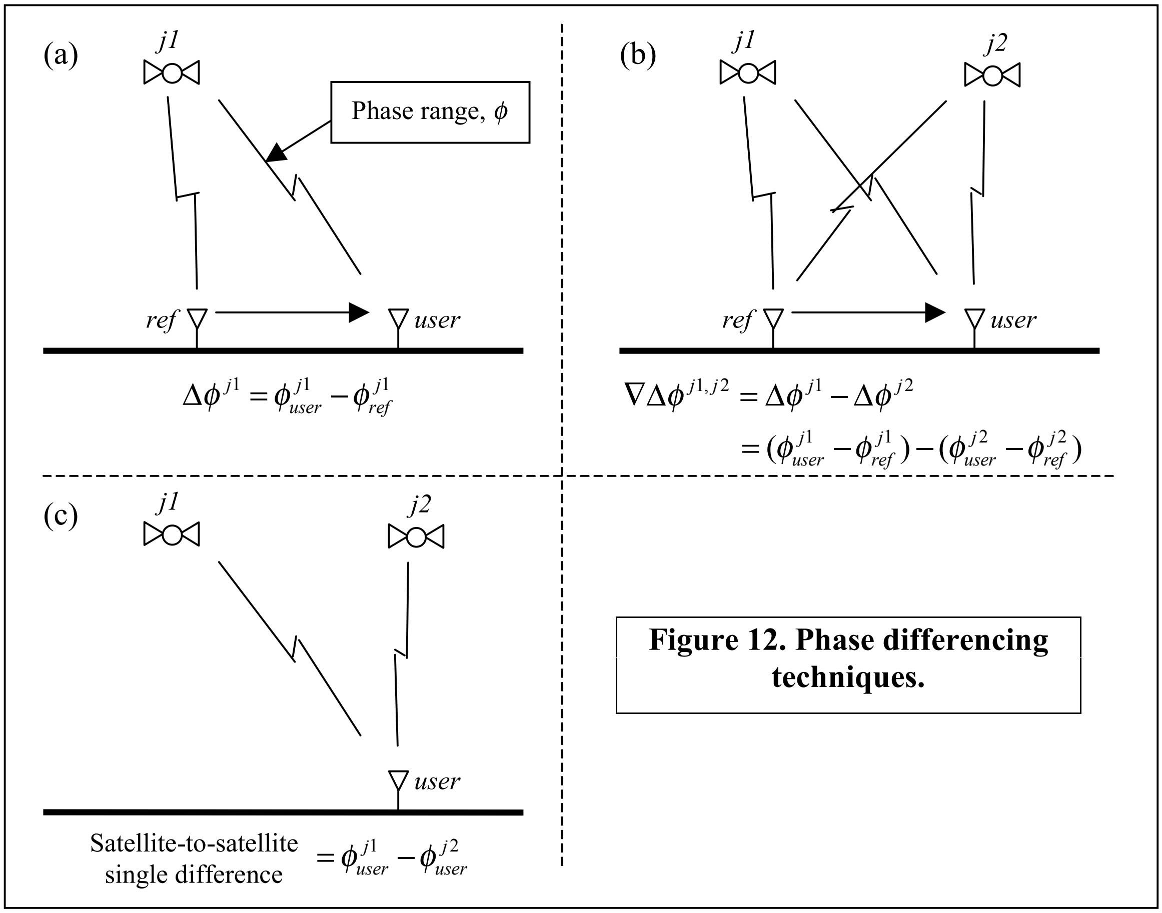


Figure 12. Phase differencing techniques.

Figure 13 contains a characteristic plot of $res^{j1} - res^{j2}$ (with the satellite-to-satellite ambiguity $N^{j1}\lambda - N^{j2}\lambda$, which is a constant, removed for clarity) and the elevation of the respective satellites over an approximately 5 hour period. The black and the gray lines represent the same satellite passes over two sequential sidereal days. On both days, the satellite-to-satellite single difference phase noise is, over most of the pass, well contained by +/- 0.5 m. bounds. This measurement difference is extremely smooth over periods of tens of minutes, in most cases with little drift. The gradual departure of the measurement difference from a relatively constant value toward the end of the pass was seen in just about every test case. It was ultimately concluded that these end-of-pass departures were most likely the result of the GPS receiver's limited capability to precisely track the carrier phase measurements at low satellite elevations.

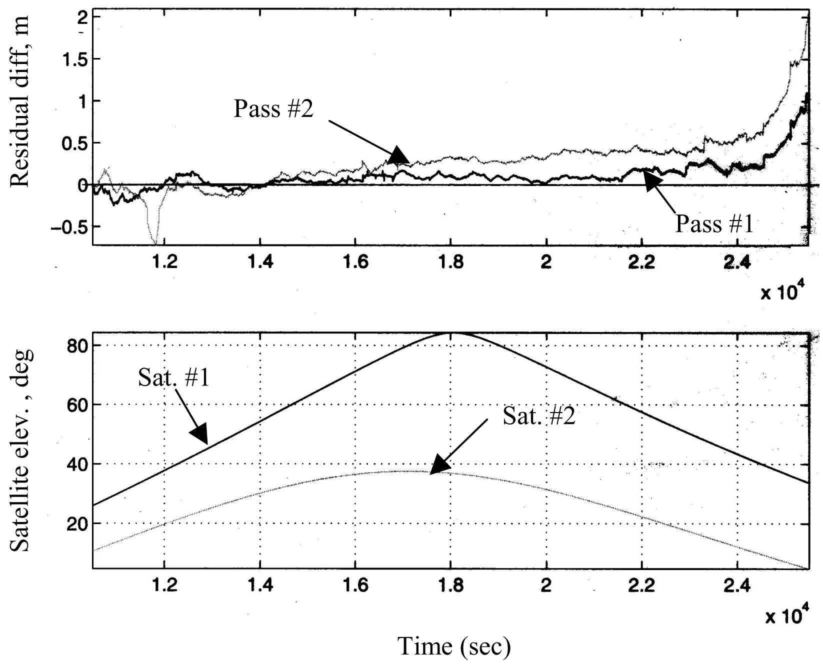


Figure 13. Satellite-to-satellite single difference residual (2 passes) and satellite elevation.

In the effort to further reduce error in $res^{j1} - res^{j2}$, it was recognized that the wavelength of the measured L1 carrier is generally not constant but in fact varies based on the doppler between the user and the satellite. When the satellite is rapidly approaching the user, the wavelength is shorter than the L1 wavelength. Similarly, when the satellite is moving away from the user, the wavelength is slightly longer than normal. For kinematic LADGPS, wavelength is typically considered constant for carrier-based range measurements: given the total number of wavelengths between the user and the relatively close-by reference station, the effect of considering variable wavelengths is significantly less than one millimeter.

In contrast, the change in the total number of wavelengths between a satellite on the horizon and at zenith is significantly more dramatic. It was thus hypothesized that actual (non-constant) wavelength would need to be factored into the carrier-based range. However, further analysis indicated that the correction factor is on the order of only a few centimeters. Ultimately, the kinematic WADGPS algorithms worked no better with this correction included.

Overall, the results from the examination of satellite-to-satellite single difference phase noise suggested that the WADGPS-corrected phase range to the satellites in view was very precise and accurate once the ambiguity bias was taken into account. A preliminary analysis of the kinematic WADGPS was conducted to evaluate user position accuracy over a five-hour period. For this analysis, it was assumed that the ambiguity biases could be correctly estimated prior to using the phase range measurements for position estimation. The method used for position estimation was identical to the standard method used to calculate GPS position, except that the WAAS-corrected phase range measurements (with the fixed biases removed and cycle-slips repaired) were used instead of carrier-smoothed code range measurements. Figure 14 shows a histogram of position error over time. In each axis, the 1 sigma position error for kinematic WADGPS is approximately 1/3 the error for carrier-smoothed code WADGPS. The improvement is not particularly dramatic, especially given the complexity of required ambiguity estimation prior or concurrent with position estimation. Nevertheless, the potential for some improved positioning accuracy by adding kinematic WADGPS software to the same hardware utilized in many WADGPS receivers has been demonstrated. Note that such a receiver would require utilization of carrier phase measurement, while WADGPS receivers do not necessarily require the use of carrier phase.

2.3.2 Ambiguity Resolution Through Static Survey

For effective position estimation utilizing either kinematic DGPS or kinematic WADGPS, the ambiguity biases in the phase range measurement must be resolved for each satellite in view. A number of techniques can be utilized to observe and estimate these biases. One of the simplest methods for this resolution is through a static survey,

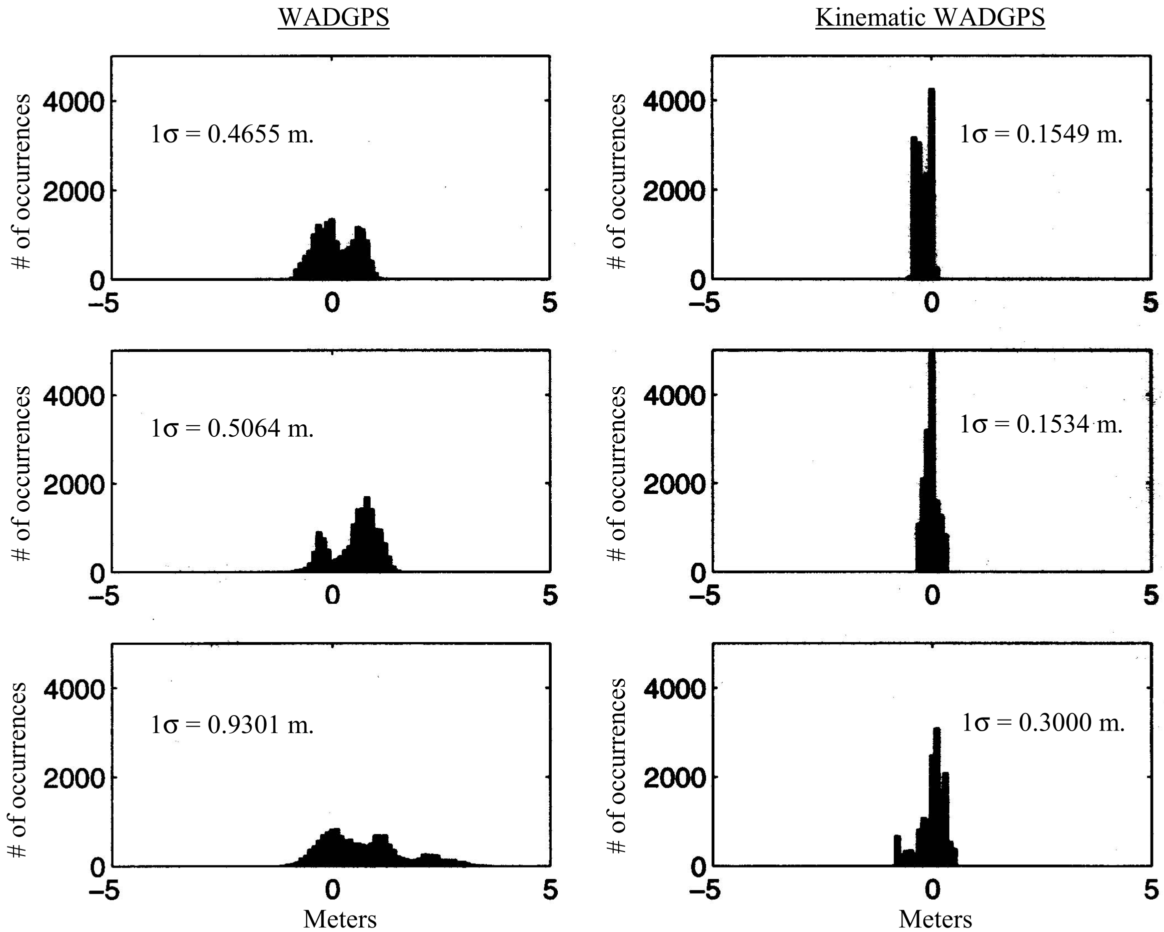


Figure 14. WADGPS vs. kinematic WADGPS position.

in which the user position is known to be constant in the ECEF reference frame. Over time, the satellite ambiguities become observable through satellite geometry change.

This method was utilized to examine its effectiveness for kinematic WADGPS. A Kalman filter was implemented to estimate user position and carrier-phase ambiguity. This implementation is described in Appendix A. Figure 15 shows post-static survey static position error for 67 trials. The filter used had some limited success. In 31% of the trials, position was estimated to within 0.5 m. horizontally. In 43% of the trials, position was estimated to within 0.5 m. vertically. However, in 38 of 67 trials, the estimated static survey position was over 1 m. from the actual user position. These

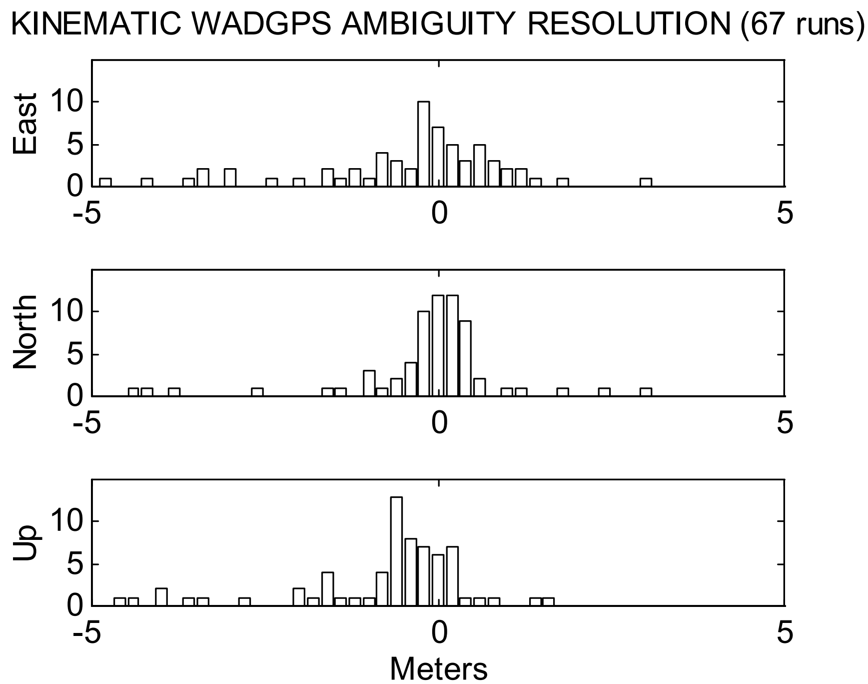


Figure 15. Static survey filter results.

results from static testing are promising. However, additional testing in moving vehicles (especially aircraft) would be valuable to determine whether this technique is robust enough for practical purposes.

2.4 GPS Options for Perspective Flight Displays

Aircraft navigation systems that use GPS are generally ideal for providing 3-D position and velocity information to perspective flight displays. This is especially true for stand-alone GPS and WADGPS. The relative value of each system for promoting TSE improvement lies in the NSE:FTE ratio; that is, given a GPS system with a typical NSE value, how much does that error ultimately affect TSE once FTE is also taken into account?

Using a horizontal FTE of 23 meters for a HITS perspective display (see section 3.4.2), typical horizontal NSE:FTE ratios for GPS, and associated issues, follow:

- *Stand-alone GPS, SA on (NSE:FTE approx. 2:1).* Navigation errors, primarily due to SA, are somewhat larger than errors due to pilot precision. When comparing the image on the perspective display to the outside world, during periods when position error due to SA is high, pilots will certainly notice the position error. Errors due to SA drift may be noticeable in some situations, such as lateral motion as the aircraft is on final approach to a narrow runway. Since the vertical errors are higher, augmentation with an altitude sensor (such as a barometric altimeter) is particularly advantageous to GPS, SA on (see below).
- *Stand-alone GPS, SA off (NSE:FTE approx. 1:4).* Pilot precision is somewhat to significantly worse than navigation error. Errors due to navigation error would be small and would only be noticeable when comparing the image on the perspective display to close objects. Velocity errors would be negligible. Given this, lack of integrity for GPS, SA off, make this navigation system infeasible for precision IFR operations. On rare but possible occasions where GPS error could be very large, a guidance system that typically yields accurate FTE values (e.g., highway-in-the-sky) may not sufficiently reduce TSE enough for safe precision flight guidance.
- *WADGPS (NSE:FTE approx. 1:20).* FTE dominates over NSE, except in cases of extreme WADGPS error.. For most practical purposes, an accurate visual scene on a perspective display would effectively match the outside world.
- *Kinematic WADGPS (NSE:FTE approx. 1:60).* As with WADGPS, FTE dominates over NSE. This navigation system would yield no effective improvement for aircraft TSE over WADGPS. However, certain flight

applications (e.g. aerial photogrammetry) require good aircraft positioning accuracy, but even more importantly require an extremely precise record of position error during the flight. In these cases kinematic WADGPS could prove worthwhile, especially if the application requires flights over large areas.

Local area DGPS should have a similar NSE:FTE ratio to WADGPS, so long as the user remains within 50-100 km. of the reference station, and as with WADGPS the perspective display would effectively match the outside world. However, this navigation system could drive the display only in the coverage area of a local area DPGS.

Other navigational sensors, such as accelerometers, radar altimeter, and barometric altimeter can be used to augment GPS user receivers to improve a perspective display. Such sensors, depending on bandwidth, can help smooth the animation on the display, or can improve accuracy.

2.4.1 Navigation System Jitter Effects on HITS

As discussed in this chapter, accuracy of the navigation system is important for TSE improvement. Given this, precision of the navigation system is also very important for FTE improvement. Jitter due to noise errors in the GPS navigation system, even if zero mean, can adversely affect pilot ability to smoothly fly a Highway-In-The-Sky (HITS) display. In addition, long-term errors with high amplitude, such as SA, may affect pilot ability to track the desired flight path.

An initial examination of this issue was conducted with a single test subject. Further evaluation with multiple subjects would be expected to reveal similar results. Jitter was modeled as sinusoidal noise added to the horizontal position of the aircraft using the HITS flight simulator. The amplitude and frequency of the added noise was varied, and the subject's tolerance of the noise (a subjective yes/no determination of whether or not the noise would substantially affect HITS centerline tracking) was recorded.

As expected, results indicated that, in general, increasing jitter amplitude for any given frequency eventually resulted in a level of noise that was unacceptable. The maximum tolerated amplitudes varied with respect to jitter frequency (Figure 16). Lower frequency noise was progressively more difficult to track up to approximately 2 Hz. At higher frequencies, a blurring effect made it progressively easier for the subject to mentally filter out the zero mean noise and track the centerline of the tunnel, but the subject explicitly commented that the high-frequency motion was unpleasant to watch.

Given this result, jitter or jumps in displayed aircraft position due to the navigation system should not be excessive for a HITS display. Any excessive noise in a GPS position solution must be filtered out before the solution is used. Given this, lower frequency components of the position solution should not be filtered out as these components may reflect actual aircraft motion. Stand-alone GPS positioning may, on occasion, yield position error motion that exceeds the maximum tolerated jitter frequency (although the use of integrated navigation systems such as GPS/INS may alleviate the potential for this to occur). In contrast, WADGPS errors are typically small enough such that even a rapid change in WADGPS position error would not result in much display jitter. As reflected in Figure 16, good aircraft control is, for the most part, guaranteed by low WADGPS errors in all frequency ranges, including the roughly 1-4 Hz range which reflects aircraft dynamics. It follows directly that pilot control of the airplane when using a HITS display can benefit from the use of WADGPS over stand-alone GPS.

2.5 Conclusion

GPS, and in particular WADGPS, show great promise for civil aircraft operations due to precise and continuous position availability in the coverage region. Utilizing WADGPS for more than just pseudorange-based position can be advantageous for

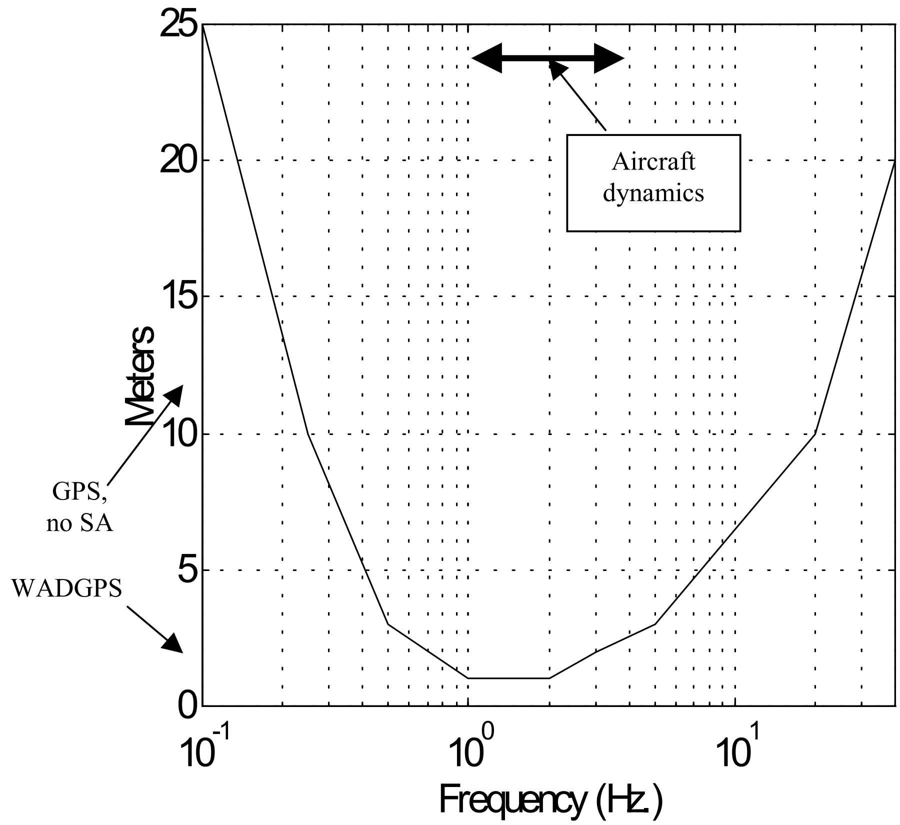


Figure 16. Maximum tolerated jitter amplitude.

aviation (and, indeed, any and all users of WADGPS). WADGPS velocity, which is extremely accurate regardless of whether SA is on or off, is obviously useful for guidance systems which directly utilize vehicle velocity, such as flight instrumentation for aircraft track or glide path angle. As shown earlier in this chapter, WADGPS velocity can further be used to construct high-frequency position estimates in receivers that output data at slower rates.

In particular, while perspective displays benefit from frame update rates in excess of 10 Hz (typically at least 24 Hz is desirable; see section 4.3.3), most GPS and WADGPS receivers only output position data at 5 Hz or less. Many output data at only 1 Hz. Using high data-rate inertial measuring units in combination with low data-rate GPS receivers can alleviate this problem, but this solution adds to the cost of the navigation system. For many applications, the technique described in this chapter is an effective, low cost solution.

Kinematic WADGPS, which requires further investigation and improvement to be viable as a practical navigation system, has the potential to increase the functionality and value of systems like WAAS and EGNOS. Kinematic WADGPS could fill a niche market as a “poor man’s” precision positioning system. As stated earlier, kinematic WADGPS has the potential to support aviation applications such as aerial surveying.

Finally, in this chapter we discussed how WADGPS significantly enhances use of the HITS guidance display. In subsequent chapters, we will investigate how perspective flight displays reduce FTE and increase pilot situational awareness. WADGPS will make such displays smoothly animated, making HITS accessible and functional for general aviation users.

Chapter 3

Flight Technical Error Improvement

3.1 Introduction

As stated in Chapter 1, new navigational technologies, such as Wide Area Differential GPS systems, will have horizontal and vertical accuracies of considerably better than 10 meters. These accuracies are significantly better than those achievable with older navigation technologies such as Distance Measuring Equipment (DME) and VHF Omnidirectional Range (VOR). As noted previously, the required terrain and obstacle clearances for instrument flight procedures are based on total flight error from the desired flight path. This includes both the errors due to the navigation system and pilot capability to keep the airplane on the centerline of the path provided by the navigational system. If flight instrumentation were available which took advantage of digital technology to improve FTE, instrument procedures could be developed for airports that currently have none.

3.2 Flight Instrumentation

All modern manned aircraft have instrumentation in the cockpit that provides the pilot with information about the current position and state of the aircraft and its systems. Specific instruments are generally considered to be necessary for the control and navigation of the aircraft; these instruments are called the *primary flight instruments.* During visual flight operations, the pilot of the airplane primarily uses the visual scene through the windows for aircraft control. The primary flight instruments provide supporting information to the pilot. However, in instrument flight conditions, clouds, fog, or night obscure vision through the aircraft windows. In this case, the primary flight instruments are the sole means for aircraft navigation.

Many aircraft have autopilots, which control the vehicle based on strategic commands entered by the pilot. However, even when the aircraft is under automatic control, the primary flight instruments are critical, as the pilot must continuously monitor these instruments to verify that the aircraft is not deviating from the desired course. Many aircraft, especially older models, do not have autopilots. In this case, or in the case of an autopilot-equipped aircraft flown manually, the pilot's primary task is to integrate all of the information presented on the primary flight instruments into a mental model of the aircraft state for aircraft control. This is not an easy task, even for an experienced pilot. Consequently, the Federal Aviation Administration requires an instrument rating and a minimum number of recent instrument flight hours and recent instrument approaches for pilots flying under instrument flight rules.

Primary flight instrumentation has not changed significantly in the past fifty years, most likely because the navigation systems used have not changed either. Recent advances in electronic display technology have yielded configurable flight displays of reasonable size, good sunlight readability, high reliability, and low cost. With this new capability to present the primary flight information in just about any format, and with accurate 3-D navigation systems now available, it is worthwhile to investigate alternate concepts for aircraft primary flight displays, which may improve FTE.

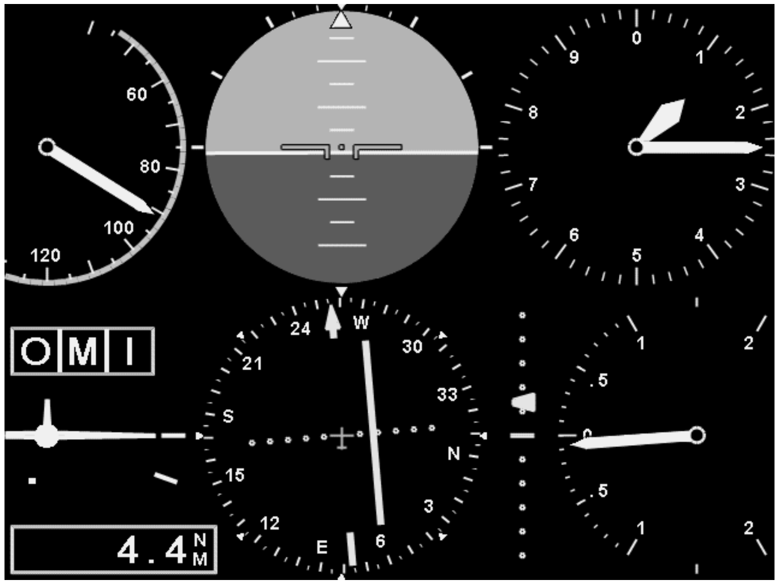


Figure 17. Conventional instrumentation.

3.2.1 Conventional Instrumentation

Conventional primary flight instrumentation includes six indicators described below (Figure 17).

- *Airspeed indicator.* A dial that shows airspeed based on the difference between total (static plus dynamic) air pressure and static air pressure. Change in indicated airspeed indirectly indicates airplane acceleration or deceleration.
- *Attitude indicator.* An artificial horizon line, typically with a brown area below the line and a blue area above the line. A gyroscopic instrument.
- *Altimeter.* A dial that shows altitude above sea level based on static pressure. Change in indicated altitude indirectly indicates a climb or a descent.
- *Turn coordinator.* A gyroscopic instrument showing a combination of roll rate and yaw rate. Indicates when aircraft is in a standard (2 minute) turn rate.

- *Directional gyro.* A gyroscopic instrument showing current airplane heading. Since the gyroscope in this instrument precesses over time, this instrument must occasionally be reset to the magnetic compass heading
- *Vertical speed indicator.* A dial which shows aircraft climb or descent rate. When based on changes in static air pressure, indicated vertical speed lags a few seconds behind actual vertical speed.

In addition to the instruments described above, flight instrumentation includes Course Deviation Indicator (CDI) needles, which indicate current left or right error from the desired route. For Instrument Landing System (ILS) approaches, a second deviation needle exists that indicates up/down error from the approach profile. This indicator of vertical path error is called a *glideslope deviation indicator.*

When originally engineered, the primary flight instrumentation were mechanical devices designed to indicate raw information provided by gyroscopes and static and ram air pressure. Many less expensive aircraft models are still manufactured with this mechanical instrumentation essentially unchanged in basic design for decades. Even in modern airliners with electronic displays, the primary flight display simply shows an electronic representation of these mechanical instruments (although the airspeed indicator and altimeter are shown as tapes, not dials). Instrument-rated pilots have been trained to mentally fuse these indications to control the aircraft and to cross-check between instruments to identify if any are not working properly.

3.2.2 Horizontal Situation Indicator with Track

A Horizontal Situation Indicator (HSI) is an electromechanical instrument that combines the directional gyro with the course deviation indicator. The resulting arrangement intuitively depicts the orientation and position of the desired course relative to the aircraft as if the pilot were looking down at the airplane from above.

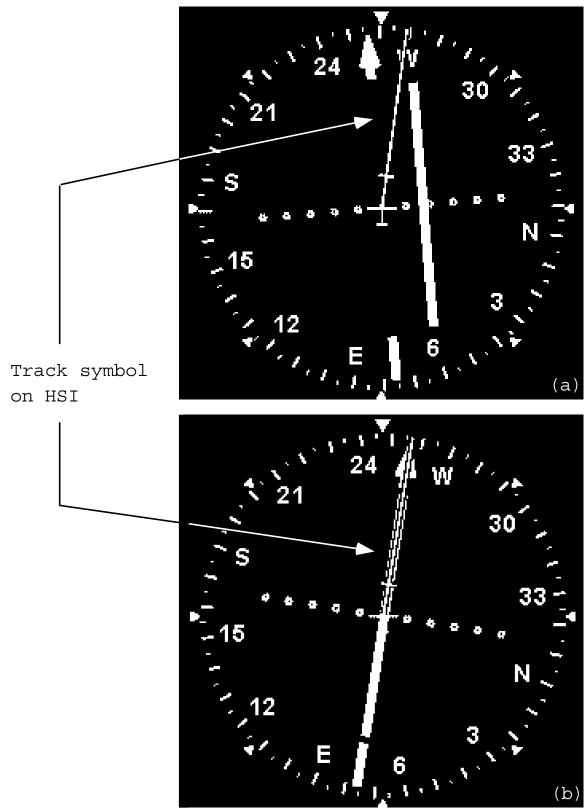


Figure 18. Track symbol on HSI.

While the inverted white triangle at the very top of the HSI shows current airplane heading, the track symbol shows instantaneous path of airplane with respect to the ground. Note the left crosswind in the case shown above. (a) The airplane is offset to the left of the desired course and is correcting (b) The airplane is on course.

Modern aircraft equipped with inertial navigation systems typically have a pointer or a line included on the HSI to indicate instantaneous track (path flown over the ground). Most current general aviation HSI installations do not have a track line. However, with an inexpensive GPS or WAAS receiver, the track line could also be included. This obviates the need for the pilot to estimate the wind correction angle. Regardless of aircraft heading or wind, the track symbol clearly indicates whether the aircraft is correcting to or diverging from the course centerline (Figure 18).

3.2.3 Glideslope Predictor

WADGPS provides the user with a very precise measurement of the current aircraft velocity in three dimensions. Previously, this precise velocity was only available on aircraft with expensive inertial navigation units. Inexpensive instantaneous velocity enables a concept called a *glideslope predictor* (Figure 19). This symbol, placed adjacent to the glideslope deviation indicator, is simply instantaneous vertical velocity with respect to the glideslope, which is intended to provide the pilot with an indication of rate of closure to (or divergence from) the glideslope regardless of current airplane airspeed or wind velocity. The symbol moves up and down like vertical speed, and thus the pilot can control the position of the glideslope predictor by adjusting the airplane's rate of descent. Since vertical speed indicators move up when the aircraft climbs and down when the airplane descends, it is critical to implement the glideslope predictor in the same fashion. If the glideslope predictor symbol is placed on the same side of the center of the glideslope display as the glideslope deviation indicator, the airplane is correcting to the glideslope. If the glideslope predictor is on the opposite side of the glideslope display as the deviation indicator, the airplane's deviation from the glideslope is increasing. If the glideslope predictor is placed in line with the center of the glideslope display, the airplane is neither converging to nor diverging from the glideslope (i.e., if the airplane is two dots low, it will remain two dots low). Placing the glideslope predictor adjacent to the deviation indicator allows the airplane to correct smoothly (exponentially) to the glideslope without overshoot.

The glideslope predictor has several interesting features. The design is independent of airplane dynamics, and is thus the same for all aircraft. Since the glideslope predictor is a raw indication of aircraft trend and is arguably not a guidance cue, possible certification advantages exist. Finally, the glideslope predictor could be as easily implemented in an electromechanical glideslope indicator as on an electronic display.

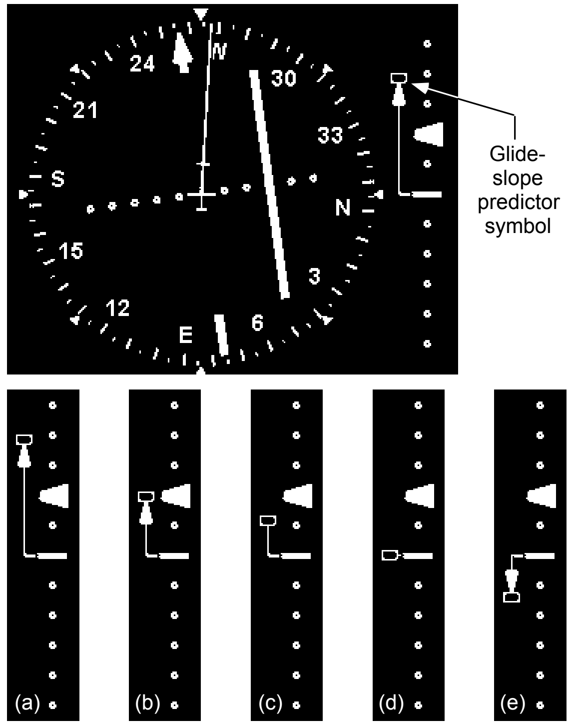


Figure 19. Glideslope predictor.

Glideslope predictor symbol adjacent to the glideslope deviation scale, shown in the top panel. In all five cases shown, the airplane is two dots low. (a) The airplane is correcting rapidly to the glideslope (b) The airplane is correcting smoothly to the glideslope (c) The airplane is correcting slowly to the glideslope (d) The airplane is not correcting to the glideslope and will remain two dots low as long as the glideslope predictor symbol is neutral as shown (e) The airplane is diverging from the glideslope.

3.2.4 Highway-In-The-Sky (HITS)

In recent years, avionics developers have shown renewed interest in the concept of a perspective flight display. A perspective flight display (occasionally called a *synthetic vision display*) is an electronic representation of the 3-D world outside of the airplane, typically shown from the point of view of the pilot looking forward. The primary advantage of this concept is its intuitive nature: pilots (and even non-pilots) are used to operating vehicles while looking forward at the world ahead. The perspective display effectively replaces the attitude indicator. Since the display is electronic, it is possible to include indicators such as airspeed and altitude directly on the perspective flight display. This minimizes the number of dials in the cockpit, and reduces the pilot scan time.

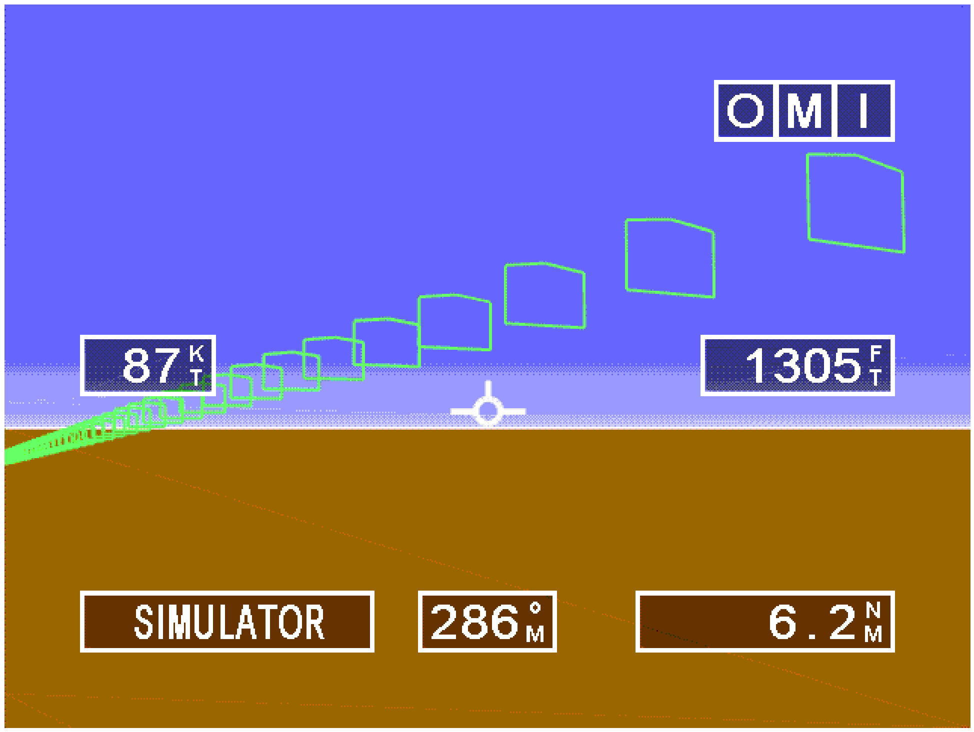


Figure 20. Highway-In-The Sky.

The Highway-In-The-Sky (HITS; also called *pathway-in-the-sky*, *tunnel-in-the-sky*, or *tunnel*) is a three dimensional representation of the desired flight path on a perspective flight display. The tunnel is often presented as linked rectangular hoops, but can also be represented with brackets, goalposts, or a series of rectangles showing a "road" underneath the desired route (Figure 20). Each of these concepts essentially presents the same guidance cues, and no format has been shown to be particularly advantageous over the others. Again, the primary value of this perspective symbology is its intuitiveness. Our experience indicates pilots flying the HITS display require very little training to understand the HITS symbology.

A valuable addition to the HITS display is a symbol that indicates instantaneous aircraft velocity. This velocity vector assists the pilot in determining whether he is flying toward or away from the center of the tunnel. Quickening of the velocity vector in the lateral axis based on current aircraft bank improves pilots' ability to fly curved trajectories with the tunnel. Corner tick marks or a rectangle displayed on a plane perpendicular to the tunnel and in line with the velocity vector symbol further improves tracking of the desired path (Williams, 2000). Many pilots have expressed the desire for indications of raw deviation from the horizontal and vertical path in addition to the tunnel. These indicators, typically displayed as needles or marks on a scale, are very similar to the deviation indicators on conventional flight instruments, and assist the pilot in determining whether the aircraft is on the path and profile centerlines. The indicators also provide an easier transition for pilots accustomed to flying with CDI needles only (Barrows, 2000).

3.3 Simulator Study: Display Symbologies for Instrument Approach

In an attempt to quantify potential improvement in flight technical error with newer primary flight display concepts described above, the primary flight instrumentation concepts were compared through a flight simulator study. The study focused on aircraft FTE under pilot control, as opposed to autopilot control. The study only examined straight-in instrument approaches with vertical guidance (similar to Instrument Landing System (ILS) approaches). Through quantitative measurements of pilot performance for each of the flight display concepts, the study affirmed advantages of the novel display symbology over conventional primary flight instrumentation

3.3.1 Display Concepts

The control condition tested in the simulator study was an electronic representation of conventional primary flight instrumentation. A conventional HSI replaced the directional gyro. Dials and needles were antialiased for realistic and smooth instrument animation. The control display concept included DME distance to touchdown and marker beacons, although neither was required for the approach flown. The three experimental concepts tested were:

- Conventional primary flight instrumentation with HSI with a track symbol (represented as a green line).
- Conventional primary flight instrumentation with HSI with a track symbol and glideslope predictor.
- Highway-In-The-Sky display. The HITS display as tested included digital airspeed, digital altitude, digital heading, DME, and marker beacons. However, horizontal and vertical deviation indicators, which are typically included in the HITS display, were removed for this study to test the capabilities of the tunnel by itself.

3.3.2 Apparatus

Instrumentation concepts were displayed on a CRT and rendered by a Pentium 90 Mhz industrial computer with a high-end Glint 3-D graphics card. The display update rate (15 Hz) was considered smooth enough for this investigation. An FS-100 PC-based simulator manufactured by Jeppesen, Inc., emulating a Beechcraft Bonanza, generated the real-time airplane model. The pilot had a conventional control yoke. Since all flight was autocoordinated, rudder pedals were not used. A slider lever controlled throttle, and a rocker switch controlled elevator trim. No other flight controls were used or required for airplane control during the experiment.

For the secondary workload task (described below), the pilot controlled a push-button on the yoke. The workload task indicator used was a sunlight-readable green indicator light placed approximately five feet to the left of the flight display, roughly at the edge of the of the subjects' peripheral field of view.

3.3.3 Subjects

Eight pilot subjects participated in the study. The total flight time for each subject varied between 270 and 3300 hours; the mean total flight time was approximately 800 hours. Each subject was instrument rated; three were certified instrument instructors. All were familiar with the operation of an HSI, and 7 of the 8 had flown an airplane equipped with one. None had prior experience with the apparatus used or the experimental flight instruments; however, each pilot received simulator training prior to experimental data collection (see below). Each pilot who served as a test subject volunteered for the experiment, and each was either a Stanford University graduate student, a pilot from the local Palo Alto Airport, or both.

3.3.4 Experiment Design

The simulator experiment was divided into three phases: simulator training, practice with each of the experimental flight instrument concepts, and data collection. In each phase the subjects were asked to fly straight-in, "ILS-like" instrument approaches starting just prior to localizer intercept approximately 6 nm. from touchdown and ending at a 200 ft. (above ground level) decision height (Figure 21).

In the training phase, each pilot was introduced to the flight simulator and advised on some of the handling qualities of the simulator used. Each subject was then allowed to fly up to ten approaches using the conventional instrument suite to gain familiarity with the flight simulator. Once the subject flew three approaches without deviating more than two dots from either localizer or glideslope between glideslope intercept and decision height, the subject proceeded to the second phase of the study. If a subject had flown ten approaches without staying within the deviation limits specified, that subject would have been disqualified from the study. However, none of the subject group tested was disqualified. The subject group tested flew an average of 6 training approaches before proceeding to the next phase of the study.

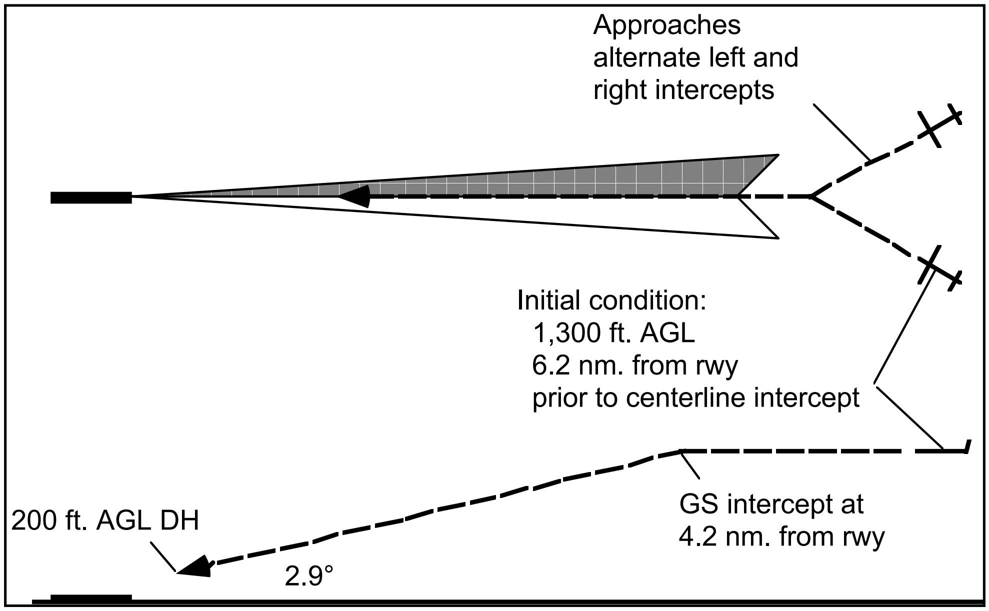


Figure 21. Straight-in approaches flown.

In the second phase of the study, the pilots were introduced to each of the three experimental instrument suites and allowed to fly one approach using each of the three display concepts. At this point, the subjects were introduced to the secondary workload task. In this task, the pilot was asked to fly while simultaneously attempting to match the state of the secondary task indicator using the push-button on the control yoke (i.e., push and hold the button when the workload light is on, and release the button when the light is off). The workload light alternately illuminated for a random period of 1 to 4 seconds, then turned off for a random period of 1 to 4 seconds. The pilots were then allowed to fly four more practice approaches, one approach for each of the control and experimental display concepts, while simultaneously conducting the secondary task as much as possible.

In the third (data collection) phase, each subject flew each of the four control and experimental display concepts six times, for a total of 24 approaches per subject. The sequence of display concepts flown was random, although at any given point in the study the subject would have flown approximately the same number of approaches using each of the display concepts. Each approach was flown with a constant wind from a random direction and with a random velocity from 0 to 18 knots. For each case, the subject was given a "surface wind observation," which was a random approximation of the winds aloft direction within +/- 20 degrees and magnitude between 1/4 to 3/4 of the winds aloft (since surface wind velocities are typically less than winds aloft). The subjects were instructed to attempt to fly approaches without deviating more than one dot from localizer or glideslope. The subjects were asked to conduct the workload task simultaneously with flying the approach, but were emphatically told to concentrate on flying first and to conduct the workload task only as much as was possible given the constraints of the primary flying task.

During the third phase, position and altitude of the airplane were collected 5 times per second. In addition, status of the workload light (on/off) and status of the pilot-controlled push-button (depressed/released) were also collected 5 times per second.

The data collected yielded horizontal root mean square error from localizer, vertical root mean square error from the glideslope, and workload score for each approach between glideslope intercept and decision height. Workload score was calculated as time the subject matched the push-button state divided by the total time of the approach, all multiplied by 100. Thus a workload score of 100 corresponded to perfect performance matching the push button state to the light; no activity on the workload task would result in a score of approximately 50, since, on average, the workload light was illuminated half of the time.

3.3.5 Results and Conclusions

On average, pilots performed better with each incremental addition to the display suite. Data was analyzed using the Statistics Toolbox in Matlab™. Output from this analysis (Multivariate ANOVA) is in the form of a variance ratio, F. Based on the number of conditions being compared and the total number of measures taken, the F value yields the probability, p, that the differences in the conditions are purely due to

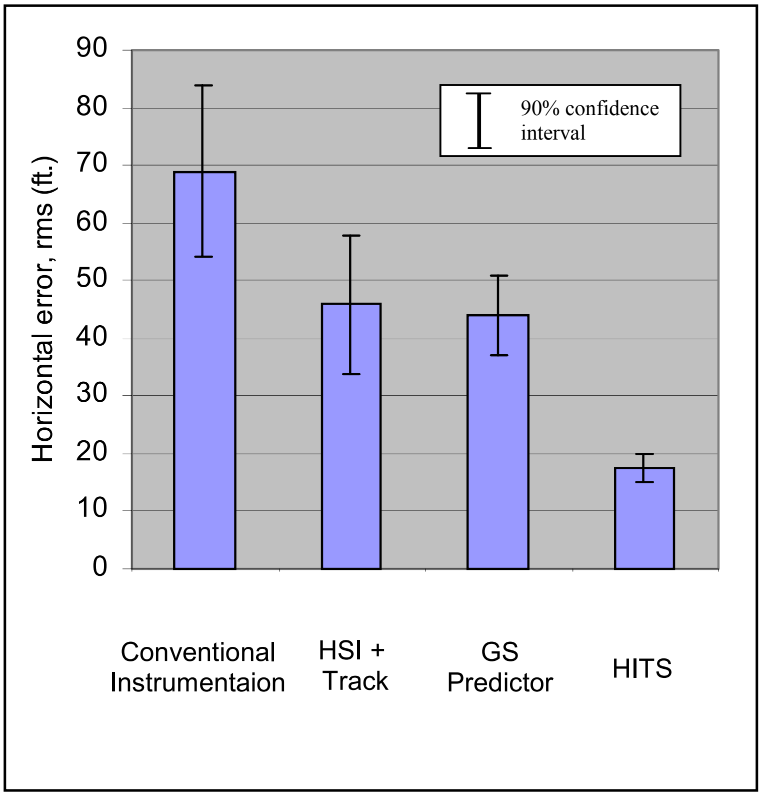


Figure 22. Horizontal FTE.

chance. Higher values for *F* result in lower values for *p* (Hayes, 1994). When this probability is 0.1 or less, the results are considered somewhat significant; values of *p* less than 0.01 are considered statistically significant and suggest that the comparison being investigated is meaningful (see Appendix B). Results revealed a significant main effect for display symbology with respect to both horizontal rms error ($F(3,160)=55.36$, $p<0.001$) (Figure 22) and vertical rms error ($F(3,160)=15.25$, $p<0.001$) (Figure 23).

HITS symbology showed a marked improvement in flight precision over all other symobologies examined. In particular, across all subjects one-way ANOVA indicated significant improvements in both horizontal error ($F(1,47)=95.38$, $p<0.001$) and vertical error ($F(1,47)=30.82$, $p<0.001$) for the tunnel when compared to conventional instruments. The glideslope predictor and track symbology also yielded improved horizontal ($F(1,47)=7.90$, $p<0.01$) and vertical ($F(1,47)=8.64$, $p<0.01$) errors when

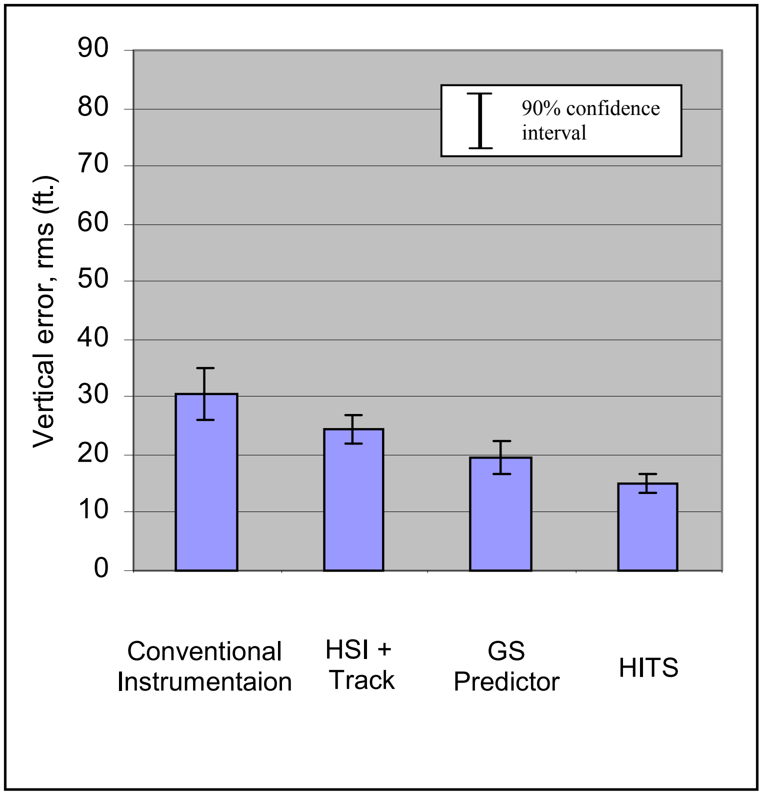


Figure 23. Vertical FTE.

compared to conventional instruments. The track symbol augmentation alone showed a lesser but still somewhat significant improvement in horizontal rms accuracy when compared to conventional instruments without the track symbol ($F(1,47)=3.54$, $p<0.1$).

Multivariate ANOVA also revealed a main effect for display symbology with respect to workload score ($F(3,160)=7.62$, $p<0.001$). Across all subjects, one-way ANOVA showed a significant improvement in workload score for HITS when compared to conventional instrumentation ($F(1,47)=5.57$, $p<0.05$) (Figure 24).

One additional result of note was the significant improvement in vertical flight precision when using the glideslope predictor and track symbol combination over using the instruments with the track symbol alone. This suggests that the glideslope predictor symbol *by itself* may also improve vertical precision over installations that include an unaugmented glideslope indicator.

Based on the four significant results stated above, this study clearly suggests that the tunnel display has possible merits over conventional general aviation flight instrumentation. This is likely due to the "out-the-window" representation of

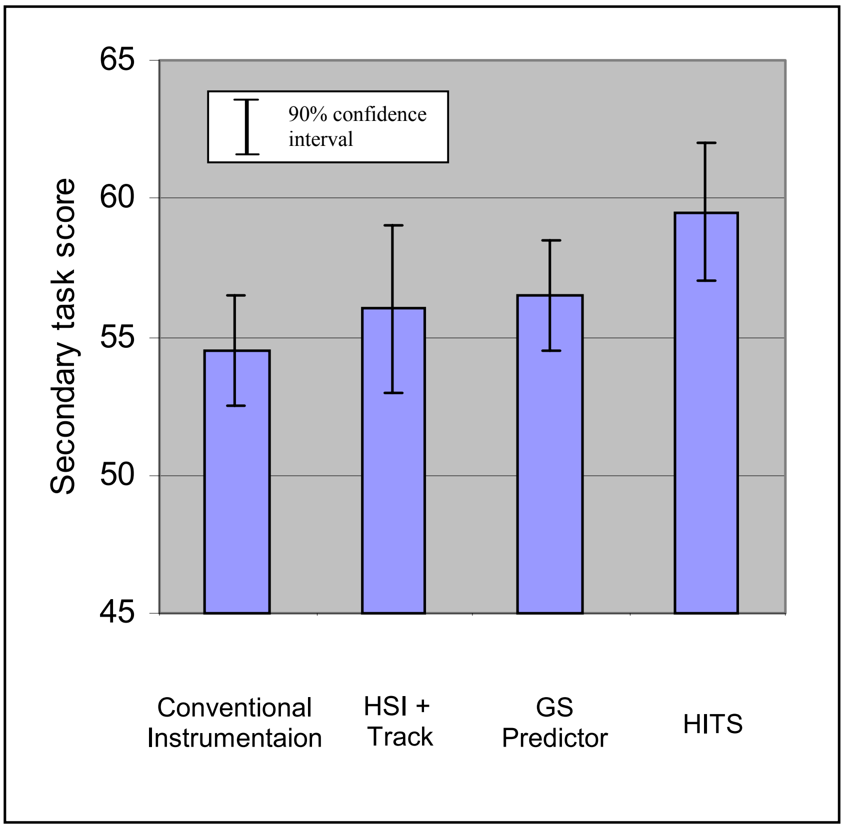


Figure 24. Workload score results.

information on the HITS display, and that the integrated HITS display requires less scanning (as opposed to the scan of separate instruments required to fly conventional instruments). One could argue that the improvement in precision errors using the tunnel display over conventional instruments is mainly due to a lack of resolution in the conventional HSI, and by simply increasing the sensitivity of the HSI needles, much lower precision values could be achieved. Even so, a valid counter argument would suggest that such an increase in sensitivity in the conventional flight instruments would most certainly result in even poorer workload scores in the conventional flight instrument case. This would retain the result that the pathway remains significantly easier to fly when considering the availability of residual attention.

It is interesting that the results of this study differ from the similar study conducted by Regal and Whittington (1995). In their study, they found no significant accuracy improvements when using the tunnel display for straight-in approach compared to using a flight director, an electromechanical or electronic guidance cue for manual flight included on the attitude indicator of many current-generation aircraft (they did find the pathway better for curved approaches). Regal and Whittington's study was slightly different from this study in that 1) they were comparing pathway to a flight director, 2) the simulated aircraft was a 737, not a general aviation airplane, and 3) the subjects in the prior study were mostly Boeing flight test pilots. These overall conclusions suggest that even if the HITS display were not desirable to airliner manufacturers, it may be valuable to the general aviation community in which pilots are generally less proficient than airline pilots.

The significance of vertical FTE improvement using the glideslope predictor and track instrument suite over conventional flight instruments suggests that improvements in flight precision are achievable using such instrumentation. For general aviation, these improvements were not previously realizable due to a lack of an economical source of precision positioning and velocity. As stated earlier, track information is available economically from stand-alone GPS. As an estimate, the glideslope predictor should have a vertical velocity input accurate to 100 ft./min or better. This precision velocity is available from inertial measuring units and will shortly be available more economically from WADGPS receivers. In addition, the 3-D position and velocity information required for pathway-in-the-sky are also available from WADGPS (see section 2.4). Each of the symbology enhancements presented in this study may be at lower risk for certification, since arguably neither enhancement provides command guidance and the original raw deviation from localizer and glideslope are still presented to the pilot.

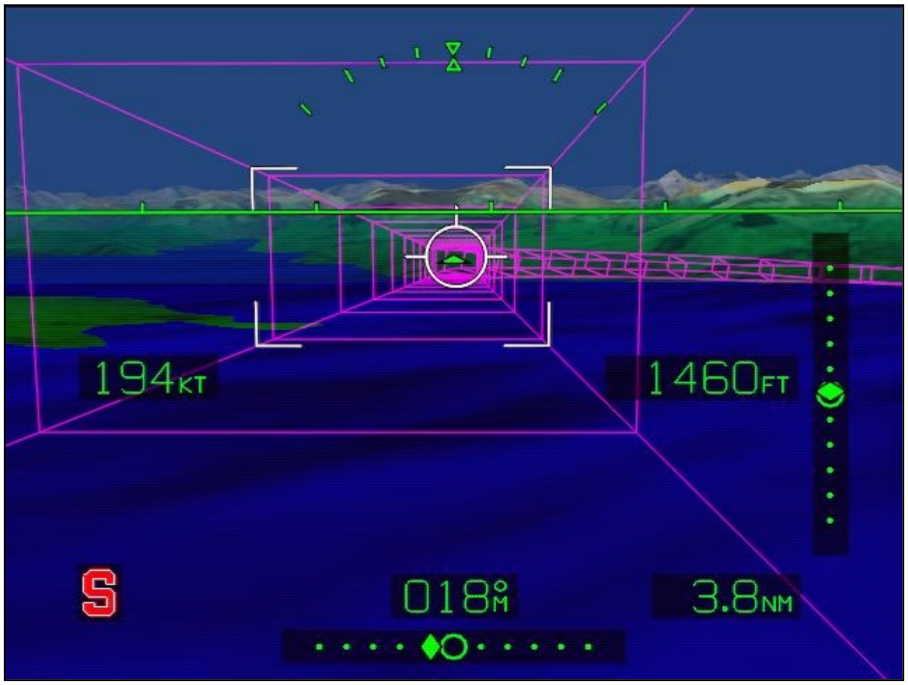


Figure 25. HITS display flown in Alaska.

3.4 Flight Test

Based in part on the promising results from the simulator study, and in part on the desire to evaluate and quantify the capability of new navigation technologies, significant inflight testing of the HITS concept followed the study described in the previous section (Figure 25). Most of the flight testing was conducted in an area around Juneau, AK, that included airports at Sitka, AK, and Petersburg, AK (Figure 26). This area was selected due to the challenges associated with WAAS navigation at the edge of the coverage region, and due to the difficulty in conducting approaches in a mountainous area. Instrument approach procedure design, which with traditional navigation systems technology requires ample terrain clearance requirements, is typically problematic in such a highly mountainous region. Often the Minimum Descent Altitude (MDA) on such approaches must be set very high to allow enough terrain clearance during missed approach. This limitation results in pilots being unable to fly instrument approaches into these airports in weather conditions acceptable for airports situated in flat terrain. For some mountainous airports, it is simply not feasible to create a useful instrument approach procedure with older technology as the terrain precludes a straight in approach required by precision approach systems such as ILS. Horizontal errors associated with other older technologies besides ILS may require very high MDA's on approach to guarantee clearance above terrain, which would preclude the use of such an approach in weather conditions where the bases of the clouds are below the MDA's.

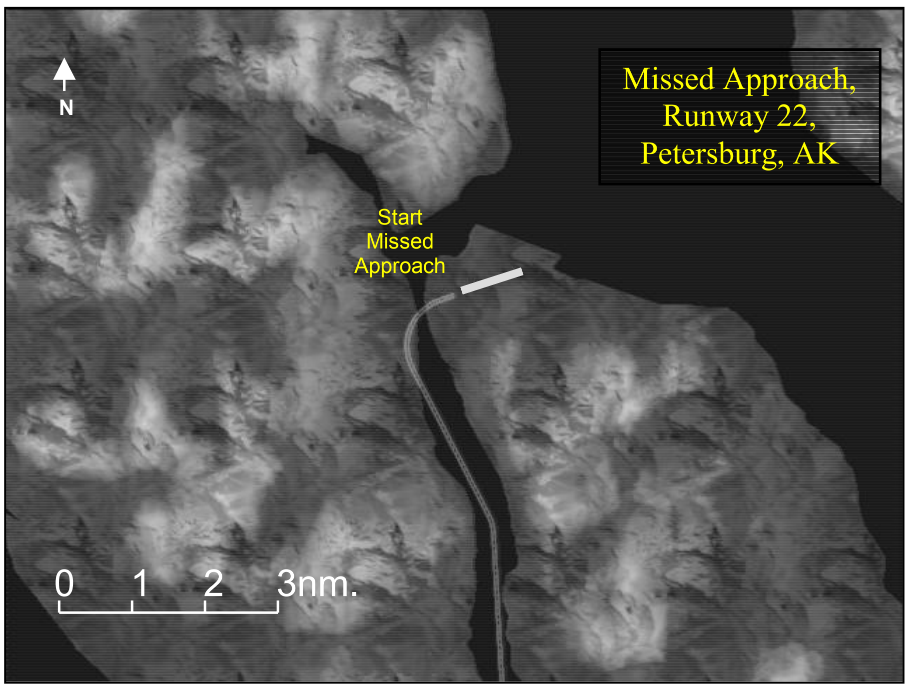


Figure 26. Complex missed approach flown in Petersburg, AK.

In addition to the performance benefits for straight approaches described in the prior section, HITS display technology has been shown to significantly reduce FTE for manual flight on curved paths as compared to more conventional flight guidance instrumentation. Navigation systems such as WADGPS allow precision positioning along curved trajectories for approach and missed approach. These trajectories can take advantage of lower terrain (such as valleys and notches in ridgelines) that is not necessarily in line with airport runways. Thus, the main objective of the Alaskan flight trials was to demonstrate inflight the potentially beneficial capabilities of WAAS when combined with HITS.

The Alaskan flight tests required the development of specialized software for the rapid prototyping of HITS. Curved paths flown included combinations of straight and constant-radius arc segments. The software facilitated the placement of tunnel segments over important arrival fixes (e.g., the runway threshold) and around higher terrain. By this method, some complex trajectories including multiple and alternating turning segments were designed and flown.

3.4.1 Flight Test Aircraft, Pilots, and Equipment

Flight testing was conducted utilizing a 1965 Beechcraft Model BE65-A80 Queen Air piston twin engine airplane (Figure 27). The airplane used had a large cabin interior capable of holding two full racks of equipment and multiple GPS antennae installed on the fuselage and wings for test purposes. The airplane, owned and operated by Sky Research, Inc., was always commanded by one of two pilots with significant experience with the Queen Air and other aircraft.

A total of 9 pilots flew the pathway-in-the-sky display from the left pilot seat. Pilot experience ranged from approximately 200 hours to 15,000 hours total time. All pilots were instrument rated. Some pathways were flown with the flying pilot wearing view-limiting goggles designed to simulate flight in instrument meteorological conditions. The right seat of the airplane was always occupied by the pilot-in-command of the aircraft, who verified terrain and traffic separation during the flight trials and was responsible for the overall safety of each flight.

Figure 27. 1965 Beechcraft Queen Air.

Precision positioning for the flight display was provided by prototype WADGPS user equipment developed by the GPS Laboratory at Stanford University (Comp, *et. al*., 1998) (Figure 28). Raw GPS position and velocity measurements were provided at 10 Hz by a Novatel GPS card inside the Pentium 90 rack-mount personal computer which ran the differential GPS software. Differential corrections for the GPS equipment were generated on a DEC Alpha master station located at Stanford University using information from the FAA National Satellite Test Bed (NSTB) ground reference stations. Corrections were sent to the airplane either via phone line and VHF ground-to-air datalink, or by a geostationary satellite broadcasting correction information on L1. For VHF communication, the experiment utilized Pacific Crest RFM96 radio modems. When the geostationary satellite was broadcasting, corrections were received by a Novatel Millenium GPS unit on board the airplane. Real time attitude for the HITS display was provided by a Stanford GPS/inertial system (Hayward & Powell, 1998). Attitude information was provided at approximately 20 Hz.

A dedicated Pentium II 333 Mhz industrial personal computer system, with an Obsidian 200SB-8440 3-D graphics accelerator card manufactured by Quantum3D, Inc., generated the HITS display. This lower-cost graphics system is capable of drawing many thousands of textured polygons per frame while maintaining approximately 30

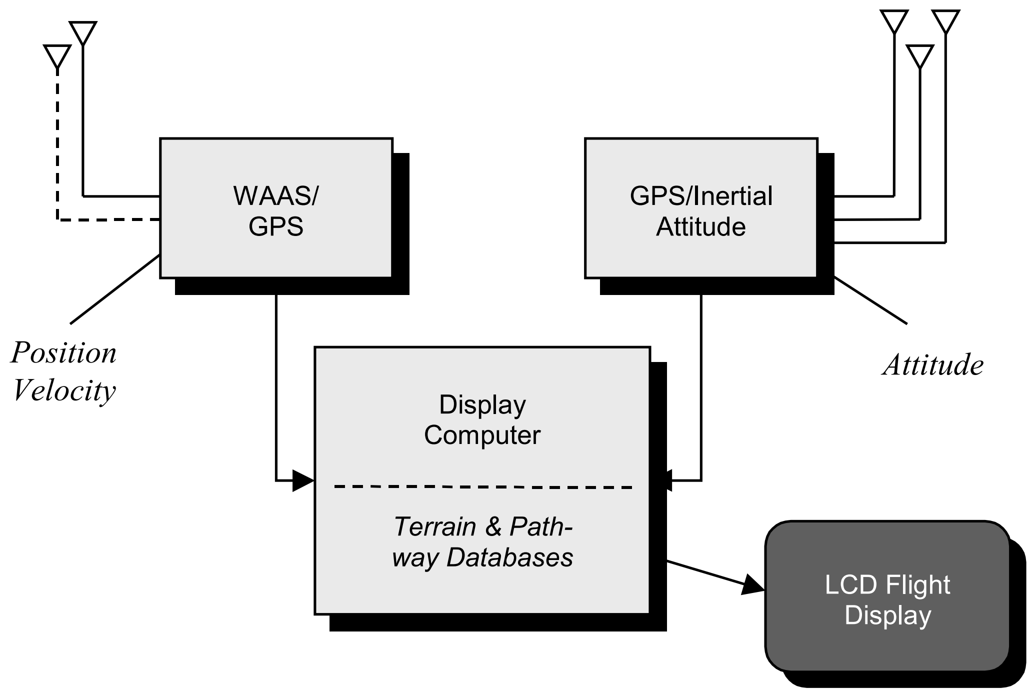


Figure 28. Flight test hardware.

frames per second or more. All lines on the display, including the pathway, were drawn antialiased, or smoothed. The HITS display (Figure 29) used in the airplane was a 6.4-inch diagonal sunlight readable AMLCD display.

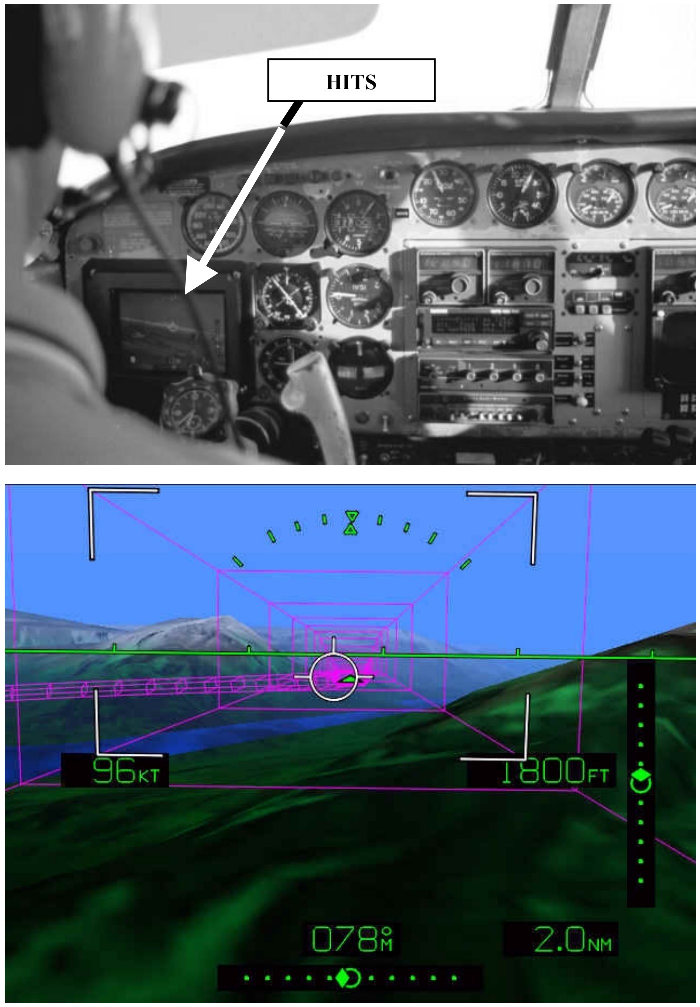


Figure 29. (Top) LCD on left side of instrument panel (Bottom) Close-up of HITS display.

3.4.2 Flight Test Results

38 different pathways were programmed for flight test, with most of these paths (24) for flight operations around Juneau. Seven paths were created for operations around Sitka; the remaining seven paths were created for operations around Petersburg. Pathways included closed traffic patterns, overlays of existing IFR arrivals into Juneau and Sitka, and overlays of certain visual arrival procedures into Juneau. Additionally,

pathways included overlays of Alaska Airlines RNP arrivals into Juneau, as well as variants/combinations of approach procedures, such as LDA Runway 8 Circle to Land Runway 26 at Juneau. Completely novel pathways were flown, such as a base entry to runway 11 at Sitka and a missed approach path from runway 22 at Petersburg. In general, the paths flown were relatively complex. Most of the paths flown contained at least two curved segments.

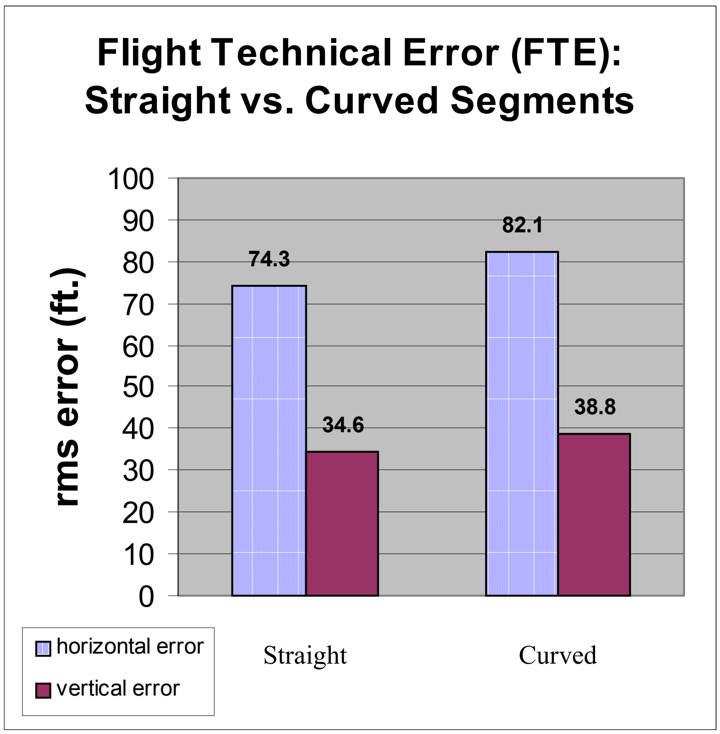


Figure 30. Straight vs. curved segments.

During flight trials, the HITS display was operational for 12 hours 55 minutes; of this time, 4 hours 28 minutes were spent flying inside the tunnel. The remainder of the time was, in general, spent repositioning the airplane for additional approaches. A total of 57 paths were flown, of which 47 were approaches to landings. Three missed approaches were flown at Sitka and Petersburg. The remainder included partial approaches and racetrack paths. Data are shown in Figure 30 and Figure 31.

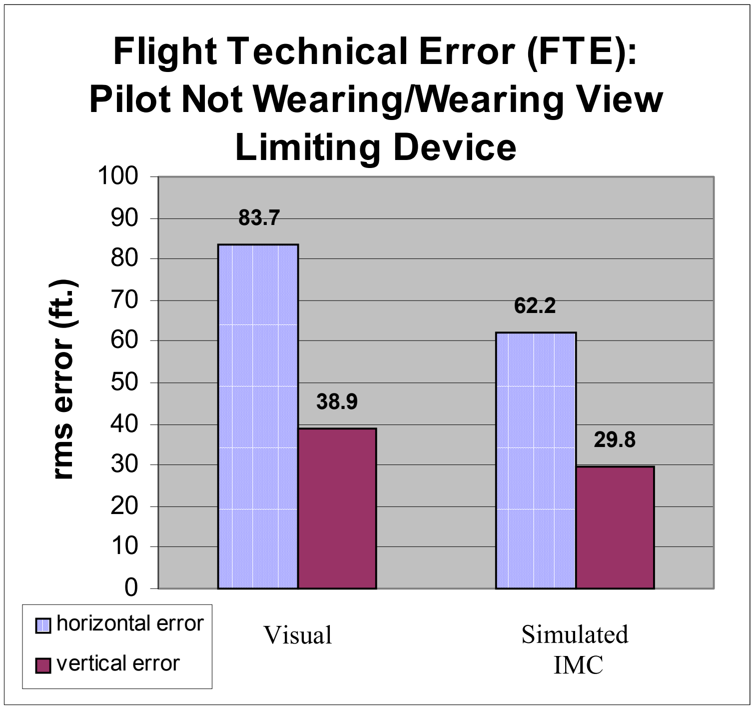


Figure 31. Effect of view-limiting device.

Overall, FTE was 77 ft. rms horizontally and 37 ft. rms vertically. These FTE values are higher than those reported in the simulator study (18 ft. rms horizontally and 15 ft. rms vertically, see section 3.3) because the pilots in the flight study were only instructed to "fly inside of the tunnel". In contrast, the pilots of the simulator study were specifically instructed and encouraged to fly as closely as possible to the center of the tunnel. Still, it remains impressive that even without instructions to zero path errors, pilots nevertheless flew very accurate horizontal and vertical profiles. The result that the horizontal errors were over twice the vertical errors can be explained partly by the fact that the tunnel is wider than it is tall, and in part that the pilot has more direct control over altitude than horizontal path error. However, further investigation into this anomaly could be conducted.

Most pathways were made up of both curved (constant radius) and straight tunnel segments. Pilots flew a total of 281 segments in the 57 paths flown, or 4.9 segments per tunnel. Of these 281 total segments, 182 were straight and 99 were curved. Measured FTE is comparable between curved and straight segments, suggesting that (given the turn radius selected) complex approaches can be flown without concern that curved segments might exacerbate errors from pathway centerline.

While all approaches were flown under VFR for legal and safety reasons, it was important to evaluate the HITS display inflight in simulated no visibility conditions to validate the effectiveness of the display in IMC. Seventeen of the 57 tunnels were flown with the pilot wearing a view-limiting device to simulate IMC, and to verify that pilots did not use any external cues to fly which would not be available to the pilot in IMC. Results show that pilots do not fly any less precisely while flying under simulated instrument conditions. In fact, the results shows a slight improvement in simulated IMC flight, possibly due to less distraction from out-the-window visual cues.

3.5 Conclusion

Study results confirm that new flight instrumentation concepts made economical in part by an inexpensive 3-D navigation system, such as WADGPS, significantly improve FTE. In particular, the highway-in-the-sky display radically improves FTE. Flight testing of practical, complex instrument approaches and missed approaches further validates HITS as a valuable flight guidance system (Figure 32). Very low FTE, without increased pilot workload, has been demonstrated, not only for straight flight segments but also for curved flight segments. This ability to fly precise curved flight paths in IMC can have significant economic advantages for aircraft operators in mountainous regions, as well as other regions with constrained airspace.

Given this, flight information displayed is clearly tactical in nature, and it should be evident that such a perspective display provides very limited strategic flight information. A HITS display as described in this paper would be well complemented with a map display or other strategic flight display which provides intuitive

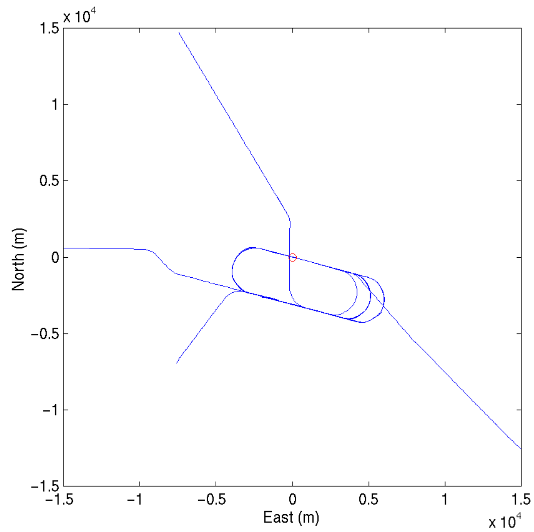


Figure 32. Actual flight position data from multiple approaches to runway 26, Juneau, AK.

route/navigation information in all directions about the airplane and about the planned flight path.

While there is evidence that the HITS display enables precise and easy manual flying of curved flight paths, such a display may not be necessary to fly curved approaches and missed approaches. Autopilots could use WAAS position and velocity to fly curved trajectories; pilots need only the flight information required (such as horizontal and vertical path deviation and a map display) to retain an acceptable level of situational awareness throughout the approach. Alaska Airlines currently flies curved paths into and out from Juneau using a system that requires a combination of GPS, INS, Flight Management System (FMS), a map display, and Enhanced Ground Proximity Warning System (EGPWS), although this implementation costs approximately $300,000 per aircraft.

Nevertheless, the HITS display seems to demonstrate excellent guidance for flying curved approaches in actual flight conditions. There may be flight operations or aircraft that are better suited for using this technology to fly manual curved approaches and missed approaches. It remains to be seen whether better FTE in flying curved approaches can be achieved with a pilot flying a tunnel display or an autopilot, or whether one technology will have significant cost advantages over the other. Even so, the economical HITS concept seems promising for general aviation.

Chapter 4

Perspective Display Augmentation

4.1 Introduction

Advances in navigation system technology for NSE improvement and flight display technology for FTE improvement yield TSE improvement and the potential for more precise instrument approach procedures. This new precision could allow instrument approaches and departures at airports with severe restrictions due to terrain or conflicting airspace. In the last chapter, we investigated how the HITS display provides significant advantages in flight precision over older flight instrumentation, and how HITS enables complex curved approaches and missed approaches. While the tunnel display is intuitive, easy to fly, and beneficial in promoting pilot situational awareness, the basic HITS concept can easily be improved upon.

In this section, we will discuss flight display technology that augments the basic highway-in-the-sky display. The augmentations selected for further study (variable-slope tunnel and perspective terrain) promote pilot acceptability and flight safety, and are arguably fundamental to the viability of the overall HITS concept. These augmentations are particularly advantageous in that they are relatively easy and inexpensive to implement. Furthermore, concepts such as perspective terrain and other 3-D objects that present the outside world as the pilot would see it through the aircraft windows are intuitive. Pilots can view pictorial objects provided with the perspective HITS concept as an integrated scene and can arguably perceive the additional information with little or no increased cognitive workload. Finally, the intuitive nature of perspective scenery may require significantly less pilot training than more abstract display symbology.

4.2 Variable-Slope Tunnel for Missed Approach

Most prior HITS implementations have had tunnels fixed in space. While tunnel trajectories that are independent from aircraft performance are appropriate for instrument approach procedures and may be suitable for enroute procedures, fixed tunnels are not functionally correct for climb procedures. When a civil aircraft climbs, typically the power setting is constant and the airspeed is constant. In this configuration, the climb gradient achieved is a function of aircraft weight, air temperature, wind direction and speed, and other factors. Even if these variables were known and a fixed climb tunnel estimated, any deviation from the tunnel profile would require a speed and/or power adjustment to reacquire the profile. It is commonly accepted among pilots that this is improper procedure for climbs. For example, if a tailwind caused the aircraft to climb below the precomputed climb profile, a pilot would not slow the airplane to climb steeper and force a recapture of the profile. Rather, the pilot would maintain the appropriate climb airspeed and replan his flight accordingly.

While a fixed tunnel may not be appropriate for climbs, the tunnel representation of the desired flight path on a perspective display remains intuitive. Further, most climb trajectories follow a fixed horizontal flight route, even though the profile varies. Given this, a HITS display in which the tunnel is fixed horizontally but varies in real-time vertically is ideal. For example, the horizontal route could be designed to guide the airplane over a path that has the lowest maximum terrain altitude in the departure quadrant; the vertical profile would vary as required by aircraft performance, with a minimum gradient as required.

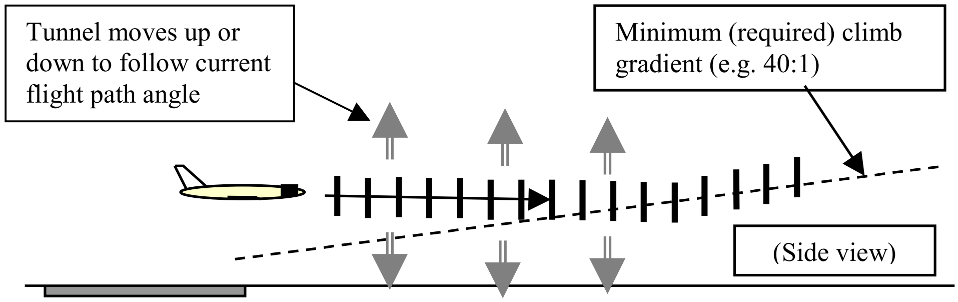


Figure 33. Variable slope HITS tunnel.

4.2.1 Tunnel Design

As with the fixed HITS tunnel described in this work, the variable-slope tunnel is referenced to an East-North-Up coordinate frame centered at a reference point on the active airport. The horizontal (East-North) coordinates for the hoop vertices of the tunnel remain fixed and can be precomputed prior to real-time tunnel display. The vertical coordinates of the vertices are adjusted each frame based on the current altitude and the flight path angle of the aircraft (Figure 33). Except in cases where the tunnel altitude is limited above or limited below (see next paragraph), the tunnel altitude at the current location of the aircraft is identical to the current altitude of the aircraft. The gradient of the tunnel is derived from aircraft flight path angle using a digital first-order filter with a 5-second time constant. The filter is utilized to assure that quick short-term changes in airplane climb gradient, due to turbulence or pilot action, do not cause the tunnel to move about excessively. The time constant of 5 seconds was determined through simulator and flight testing to be a good intermediate value that allows the tunnel to move smoothly based on pilot action without excessive lag. The variable-slope tunnel hoops have a custom shape to distinguish them from fixed tunnel hoops (Figure 34).

While the missed approach tunnel has a variable vertical profile, the lower extent of the tunnel must be constrained to make certain that the pilot is never shown guidance symbology that would take the airplane below the minimum altitude for the climb or missed approach. For example, missed approaches are designed with a minimum climb

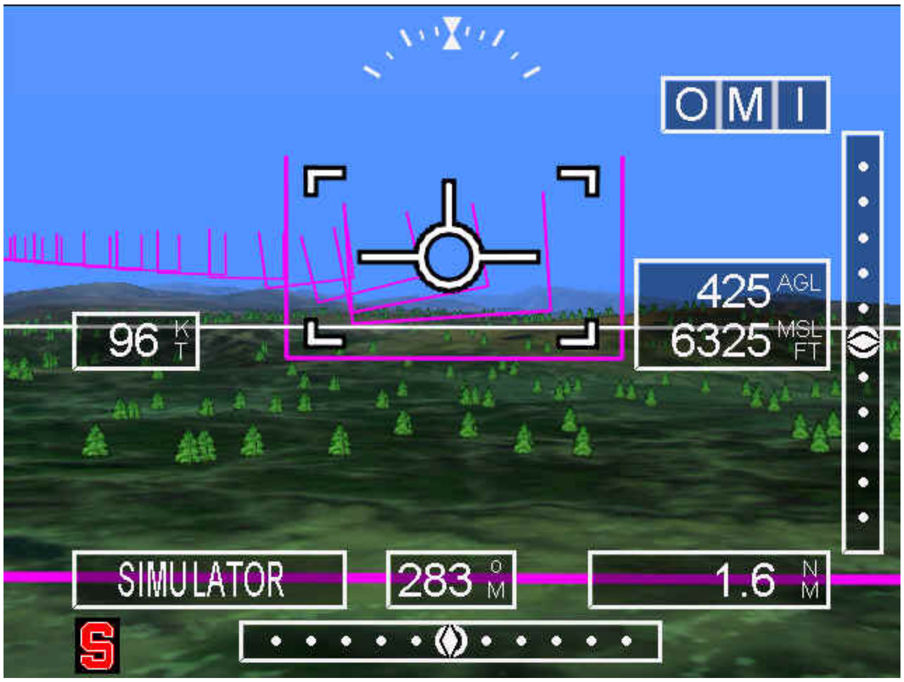


Figure 34. Custom-shaped hoops for missed approach tunnel.

gradient from the missed approach point (typically 40:1); pilots flying at least this gradient are guaranteed to avoid obstacles and terrain. Given this functional constraint, the missed approach tunnel is designed such that if the tunnel profile intersects the minimum climb gradient required, the tunnel profile will be adjusted to make certain that the tunnel guidance always shows a profile which is at or above the minimum requirement. The tunnel segments which are constrained are indicated on the display as yellow-colored hoops (instead of the nominal magenta-colored hoops for the missed approach tunnel) to advise the pilot that he is approaching the minimum climb gradient required for the missed approach. Note that if this display concept were implemented, it would remain the pilot's responsibility to plan the flight such that any required minimum climb gradients would be within the performance capability of the aircraft flown.

In addition, the variable-slope tunnel can be constrained by an upper limit, such as a maximum-altitude crossing restriction or the level-off altitude. In this case, the tunnel reverts to a fixed (level) tunnel at the point where the variable-slope tunnel intersects the constraint altitude.

4.2.2 Flight Test Results and Conclusions

The variable-slope tunnel was test flown at Moffett Field, CA, and Truckee, CA. The variable-slope tunnel successfully provided missed approach guidance for multiple missed approaches flown. As was the case with test flights of the fixed tunnel, pilots reported that following the tunnel was easy. However, an interesting contrast in required training existed between the fixed and variable-slope HITS displays. While in general pilots required surprisingly little training in symbology and flying technique for the fixed tunnel display, pilots desired more thorough instruction on the algorithms behind the variable-slope HITS display, including detail on when and how the hoops moved and on the color and hoop shape changes. This is probably more a credit to the intuitiveness of the fixed tunnel display than a limitation of the variable-slope tunnel. Adding vertical guidance cues may increase pilot acceptance of the variable-slope tunnel. Future versions should include explicit display of commanded climb airspeed, and could include alerting symbology (e.g., the airspeed turns yellow) for situations where the pilot does not maintain the required airspeed.

4.3 Perspective Terrain Display

Currently, aircraft flying under IFR guarantee separation from terrain and fixed ground obstacles by flying approved flight routes, which are guaranteed to provide adequate separation from the ground. When pilots err from these routes, the results can be catastrophic, and many accidents have occurred in this manner. The frequency of these accidents is high enough that this category of accident has been given a name: Controlled Flight Into Terrain (CFIT). CFIT is a serious problem for aviation and is particularly unnerving as, by definition, accidents in this category involve aircraft that are fully controllable by the pilots up until the time of the accident. CFIT is especially problematic at the commercial operations level (jets and turboprops), where it is the leading cause of accident fatalities. Between 1980 and 1996, 120 fatal approach-and-landing accidents occurred worldwide. On average (for Western-built turbine-powered airplanes) 51 fatalities occurred per approach-and-landing accident (Flight Safety Foundation, 1999). Some notable recent CFIT accidents include:

- *January 20, 1992: Strasbourg, France.* The flight crew of an Airbus A320 apparently incorrectly set the autopilot, and the aircraft descended into a mountain on approach.
- *December 20, 1995: Cali, Columbia.* The pilots of a Boeing 757 on approach through a valley lost situational awareness, in part due to distractions while making inputs to their Flight Management System (FMS). Approaching to the south, the airplane turned left and impacted terrain on the east side of the valley at the 8,900 ft. level (Simmon, 1998).
- *August 6, 1997: Agana, Guam.* A Boeing 747 on a straight-in approach descended below the minimum prescribed altitude for the approach flown. According to the cockpit voice recorder, the flight crew continued accomplishing normal checklist items even as the airplane descended through 500 feet above the ground about 5 miles from the airport. The airplane impacted a hill about 300 ft. above runway elevation approximately 3 miles from the runway (Tullo, 1999).

CFIT almost always occurs in IMC or at night. Under daytime weather conditions with good visibility, pilots have the capability to see terrain about the aircraft through the aircraft windows. However, until very recently, civil pilots have had no display available in their cockpits to display the location of hazardous terrain relative to their aircraft in instrument conditions. As of mid-2000, several “low-cost” terrain warning systems were available for commercial or general aviation aircraft, including:

- Honeywell’s GA-EGPWS: Based on their Enhanced Ground Proximity Warning System (EGPWS) for commercial aircraft, this general aviation unit is housed in a more compact and light weight avionics box than the commercial version. Using GPS for position data, the unit costs about $10K.
- UPS Aviation Technologies’ Apollo MX20: This multifunction display unit connects to the GPS unit and includes a terrain database. The unit continuously monitors aircraft altitude, current position, groundspeed and route of flight, and provides a terrain advisory if the aircraft is within two minutes of a close encounter with the ground. The unit cost about $7K.
- Universal Avionics’ Terrain And Warning System (TAWS): This terrain alerting system is similar to the EGPWS. It utilizes input from the FMS, air data computer, radio altimeter, ILS, and a terrain database to generate warnings if a potential conflict with terrain is imminent.

Each of these units can be connected to a dedicated or multifunction display unit to provide a 2-D graphical representation (like a map) of the terrain about the current position of the aircraft.

In hypothesizing the appropriate display presentation of local terrain, researchers have debated the value of 2-D plan (top-down view), 2-D profile (cross-section view from the side), and 3-D perspective terrain displays. In their experiments, Kuchar and Hansman (1993) determined that a terrain display with both a plan and profile display provided better situational awareness than a perspective display concept. Until roughly the early 1990's, however, the technological capability to display realistic-looking perspective terrain with good resolution and adequate depth cues was very limited. In particular, the perspective terrain display concept tested by Kuchar and Hansman was arguably not very realistic and provided poor depth cues. Further, the capability to design perspective terrain graphics systems with low-weight equipment (less than 100 lbs.) at a reasonable cost for civil aircraft (less than $100,000) was nonexistent. In contrast, by 2000, graphics technology has advanced to the point where it is possible to build a practical perspective terrain display system for less than $10,000.

Certified pilots test-flew and evaluated perspective terrain display concepts described below in and around San Jose, CA, Juneau, AK, and Lake Tahoe, CA. These 3-D display concepts were generated by the Pentium II-333 MHz industrial computer described in section 3.4.1.

4.3.1 Generation of 3-D Terrain

Many algorithms and modelling techniques exist for the generation and display of high-resolution, realistic-looking, smoothly animated 3-D graphical terrain. No attempt was made in this work to create new methods to depict perspective terrain, nor to advance the state-of-the-art in the discipline of graphical terrain rendering. A thorough discussion of all issues associated with 3-D graphical terrain depiction is available at URL http://www.vterrain.org, a non-profit industry resource managed by Mr. Ben Discoe of Intel, Corporation. The different methods for digitally representing terrain models are described in Lorriman, *et. al.* (1991).

4.3.1.1 3-D Graphics and Rendering

The most common graphical method for visually representing (or *rendering)* any irregularly shaped 3-D object or 3-D surface (such as terrain) on a 3-D graphics display is to divide the surface (or *skin*) of the object up into a collection of representative triangles. If the triangles are small enough, as required by the complexity of the surface, and enough of these small triangles are used, the skin of the rendered object will look smoothly curved, even though it is constructed from flat triangles. Fewer larger triangles can be used to render a curved surface if a simple technique called *smooth shading* (or *Gourad shading*) is used. In this technique, the colors of vertices of each triangle are determined based on the color of the surface itself and the ambient and incident lighting (as modeled by the graphics system). The color across the rendered triangle is smoothly varied between the vertices. This method hides the edges between adjacent triangles, and creates the illusion of curvature over flat surfaces. Whether triangles are Gourad shaded or not, as of mid-2000 several inexpensive (approximately a few hundred dollars or less) graphics chips exist which are designed with high-speed hardware specifically for the 3-D display of colored, textured triangles. These low-cost graphics systems can draw roughly 10,000 textured triangles per frame while still maintaining a 20-30 Hz frame update rate.

4.3.1.2 Rendering of a 3-D Terrain Skin

Generation of a 3-D terrain skin for use on a perspective display is very easy if display speed is not important and memory limits are not a factor. Terrain elevation data for the United States can be acquired for free from the United States Geological Survey (USGS) as 1:250,000 Digital Elevation Model (DEM) databases. These databases provide gridpost elevation data for the United States at 3 arc second (roughly 90 meters) latitudinal and longitudinal intervals (6 arc second longitudinal intervals between 50-70 degrees north latitude, 9 arc second longitudinal intervals north of 70 degrees north latitude) (U.S. Geological Survey, 1993). This elevation data is not certified for IFR flight operations, but has proven to be very accurate for the purposes of 3-D terrain representation and is adequate for flight demonstration purposes (certified terrain and obstacle data guidelines for IFR flight are being developed by RTCA, Inc. Special Committee 193, which will recommend requirements for the accuracy and integrity of terrain and obstacle databases). Terrain skins associated with DEM data can be easily

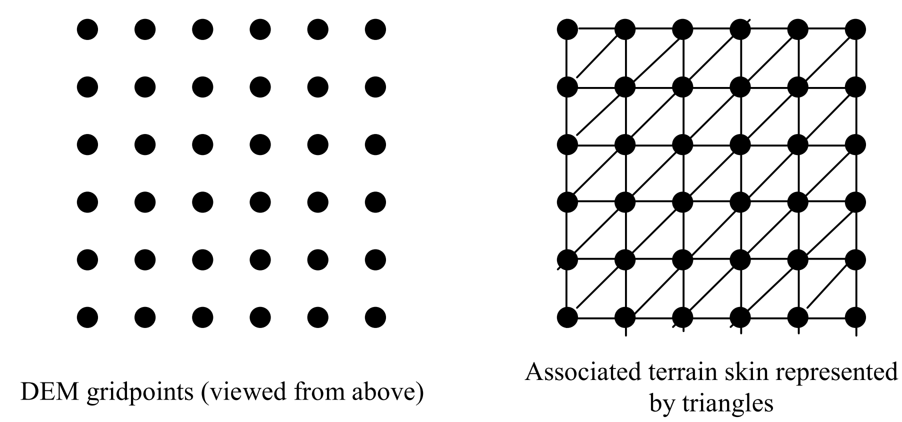


Figure 35. Regular triangularization of gridpoints.

rendered by graphics chipsets described in the previous section via the simplistic method of identifying squares whose corners are defined by DEM gridpoints, dividing each square into two triangles, and rendering those triangles (Figure 35). While this terrain skin generally looks very good, this method of representation requires a huge number of triangles. Less expensive graphics chipsets, such as those used in this work, may take several seconds to draw just one frame with 3-D terrain. This refresh rate is unacceptable for a smoothly animated display.

To reduce the number of triangles in order to increase display frame rate, two techniques were adopted:

- *Generate the terrain with fewer total triangles.* A large, mostly flat area can be effectively rendered with only a few dozen triangles and still retain reasonably good representative accuracy (the average absolute difference between height of the terrain skin the DEM height at each gridpoint). In contrast, the same flat area may require thousands of triangles using the method described above. Methods to reduce the number of triangles generally involve creating a subset of points from the DEM which are

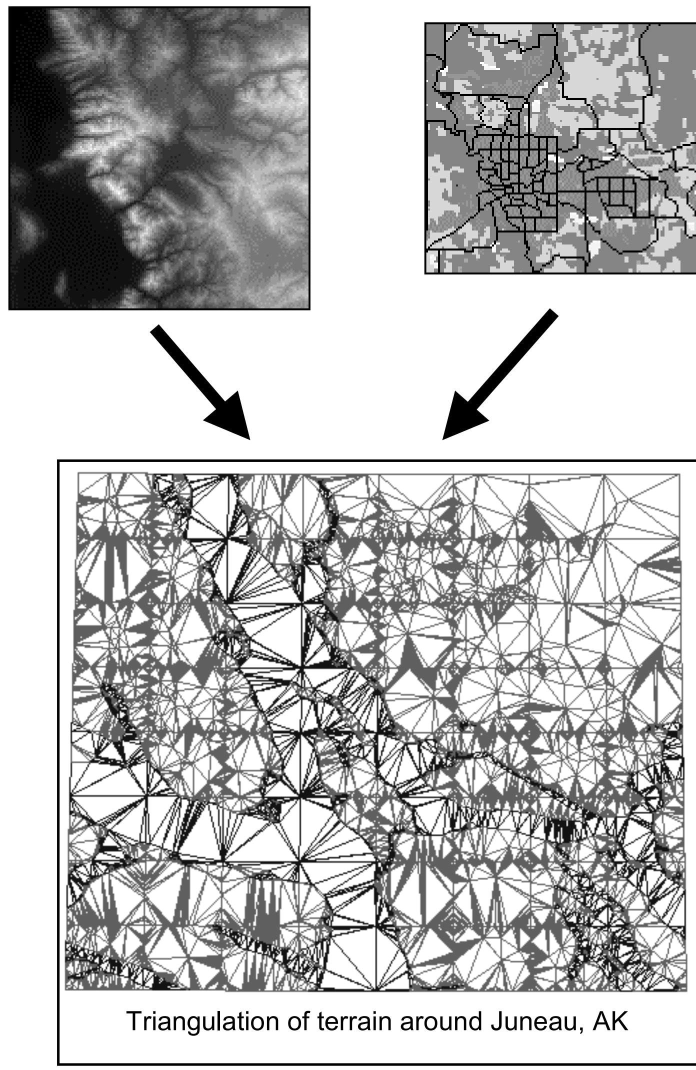


Figure 36. DEM data and coastline data for TIN.

representative of peaks, ridgelines, and valleys. A triangular mesh is then constructed from this subset. Since it is made up of unequally-sized triangles, this mesh is called a *Triangular Irregular Network* (TIN) (Figure 36). A straightforward yet effective version of the method described in this paragraph was utilized in this work (see section 4.3.1.3).

- *Use fewer triangles for terrain that is far away from the viewpoint.* While perspective terrain close to the aircraft should be rendered in high detail, terrain distant from the aircraft, which is of less concern to the pilot, does not have to be rendered as accurately. Perhaps more importantly, details of the terrain in the distance would only show up as minute differences in a few pixels on the display screen. Thus, significantly decreasing the number of triangles used in rendering terrain distant from the aircraft has little effect on the overall scene, yet decreases the total number of triangles drawn per frame. This results in higher frame rates and smoother animation.

  A practical method for controlling the detail of terrain in the distance is to divide the overall area rendered into many smaller areas. For each of the smaller areas, the terrain is rendered at multiple levels of complexity, with the most complicated level utilizing the greatest number of triangles but having the most accurate terrain with representative features. This technique is called varying *Level Of Detail* (LOD), and details of this method along with a discussion of some associated issues and solutions can be found in Willis (1998).

  Carefully adjusting both the level of complexity for each LOD and the distance at which the LOD's switch is part of the design process. The methodology and parameters used in this work are discussed below in the next section.

In addition to the TIN representing the terrain skin itself, terrain features such as roads, buildings, power lines, railroad tracks, etc., could be overlaid on the terrain. For the most part, these cultural features were not included in this work in order to preserve homogeneity of the terrain texture (see section 4.3.2), although in later versions trees were added for depth cues (section 4.3.3). However, major bodies of water (large lakes, channels, bays, and oceans) were included in the TIN for purely aesthetic reasons (pilots shown the 3-D terrain graphics without water were dissatisfied with the representation). Coastline data for 3-D terrain within the continental US came from USGS Land Use Land Coverage (LULC) data (U.S. Geological Survey, 1986). The lake, bay, and ocean coastlines from these datasets are low accuracy but are representative enough to provide good pilot awareness of aircraft location relative to important coastline features. Specifics on the format of LULC data can be found in Mitchell, *et. al.* (1977). LULC data was not available for Alaska. The Alaska Department of Natural Resources specially provided coastline data for the demonstration flights around Juneau.

4.3.1.3 Algorithm for TIN Generation

The process implemented for generating a terrain skin is described in detail in the following steps. This process was used to generate terrain databases for regions about Palo Alto, Monterey, and Lake Tahoe, CA; Juneau, Sitka, and Petersburg, AK, and Seattle, WA. Note that not all terrain databases were flown during flight tests.

1. Select the overall dimensions of the area of terrain to be rendered. Datasets generated were typically 0.8 deg. latitude by 0.8 deg. longitude. Select the northern and southern boundaries of the area, by latitude, and the eastern and western boundaries of the area, by longitude.

2. Retrieve all DEM datasets required for the area to be rendered. Note that the DEM datasets utilized were all 1 deg. latitude by 1 deg. longitude. DEM data from adjacent areas is easily added together to create an amalgamated dataset.

3. Extract the data for terrain altitude (above sea level) across the prescribed area from the DEM gridpoints.

4. Divide the overall area into *blocks* for LOD. Typically, the 0.8 deg. latitude by 0.8 deg. longitude area was divided into 64 blocks, each 0.1 deg latitude by 0.1 deg.

longitude on each side. Each block will have a separate TIN for each level of detail. For this work, 3 levels of detail were generated.

5. Determine the curvature of the terrain at each gridpoint. While more complex discriminators of curvature could and have been used (Garland and Heckbert, 1995), it is simplest to use a discrete version of the 2-D Laplacian (the “del2” function included in Matlab™). For any gridpoint, this curvature is:

$$c(i,j) = \frac{h(i+1,j) + h(i-1,j) + h(i,j+1) + h(i,j-1)}{4} - h(i,j)$$

   where c is the computed approximation of terrain curvature; i and j are the latitude and longitude indices, respectively; and h is the altitude of the terrain at the DEM gridpoint specified. In other words, the curvature at any point is the difference between the altitude at that point and the average of the altitudes of its four neighboring gridpoints.

6. Select minimum absolute curvatures, $c_{\min,LOD1}$, $c_{\min,LOD2}$, and $c_{\min,LOD3}$ for *each* level of detail. These values are design parameters, and were adjusted as necessary to adjust the frame rate of the display (see section 4.3.1.4). Adjusting these values upward will decrease the number of triangles generated for the respective level of detail. $c_{\min,LOD1}$ (for the most detailed LOD) should be less than $c_{\min,LOD2}$, and $c_{\min,LOD2}$ should be less than $c_{\min,LOD3}$.

7. Copy the terrain elevation data three times, once for each LOD

8. For each LOD, remove gridpoints of low curvature. In other words, for each LOD, check each gridpoint to see if:

$$|c(i,j)| < c_{\min,LODi}$$

If so, remove that gridpoint. The remaining gridpoints are representative of the ridgelines and valleys at that level of detail.

9. Copy any gridpoints from LOD 1 (the most detailed LOD) that are on the edges of blocks (blocks are defined in step 4, above) into each of the less detailed LOD's. This guarantees that if two adjacent blocks of different LOD's are rendered there will be no gaps in the seam between the terrain skins for each block.

10. For each LOD, add in points defining water (coastlines of lakes, channels, and bays), as necessary. Note that coastline points for bays and oceans are automatically set to 0 ft. above sea level. No attempt was made to model tidal effects (i.e., sea level moving up and down).

11. Transform remaining terrain (and water) points from latitude, longitude, and altitude to local east, north, and up coordinates. This transformation is discussed in Barrows, 2000. East, north, and up coordinates are used by the flight (graphics) computer.

12. Create a TIN for each LOD from the points in each block. A Delaunay triangulation function transforms the terrain points into a terrain skin. A Delaunay triangulation is a process by which a series of points is turned into a TIN, with the given points serving as vertices for the triangles. The Delaunay triangulation has the property that the circumcircle of every triangle does not contain any points of the triangulation. (Kramer, 1995) (Figure 37). This feature results in few, if any, long and skinny triangles in the TIN, giving the TIN a less jagged appearance. An algorithm for Delaunay triangulation can be found in O'Rourke (1994).

The final output is a series of triangles defining the terrain skin for each block at multiple levels of detail. The output is stored in a file, which is subsequently read into the flight computer. Since terrain heights are, for the purposes of this work, static, terrain skins can be generated once and used on multiple flights.

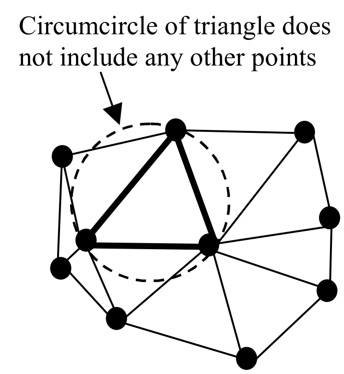


Figure 37. Delaunay triangulation of points.

4.3.1.4 Adjusting Design Parameters for "Best" Display

When utilizing TIN-represented terrain on a low-cost system care must be taken to model the terrain appropriately and to keep the total polygon count from exceeding a maximum. If the terrain contains too few triangles, the terrain may not be accurate. If the terrain contains too many triangles, frame rate will suffer. Between the terrain generation software and the flight display graphics software, there were a number of design parameters that could be adjusted to alter frame rate (assuming no hardware changes). The adjustable design parameters consisted of the minimum absolute curvature for each LOD in the terrain generation algorithm (previous section, Step 6), and the distances from the viewer at which the terrain blocks changed from a higher to a lower LOD.

The process for the adjustment of these parameters was a subjective "trial-and-error" process. First, the minimum absolute curvature for the most detailed LOD was decreased until the rendered terrain was considered reasonably representative (i.e., such that detailed terrain features were recognizable in the rendered terrain). Then, the maximum distance at which the terrain would be drawn at this highest LOD was set to 11,500 m. 11,500 m. is approximately equivalent to 3 minutes of flight at approach speed for the Queen Air used in flight tests. 3 minutes is an arbitrary number, but it can be considered a reasonable time period for the pilot to recognize detailed terrain features as they appear and adjust the aircraft's flight path, if necessary. Finally, the minimum absolute curvatures and drawing distances for the remaining LOD's were adjusted such that terrain in the distance "looked good" without the frame rate dropping so low as to not look smoothly animated.

In the system described in this work, the resultant minimum absolute curvatures were ultimately selected such that once gridpoints of low curvature were removed there were, on average, 9.9 points per sq. km. for finest LOD (LOD 1), 1.8 points per sq. km. for the mid LOD (LOD 2), and 0.48 points per sq. km. for the coarsest LOD (LOD 3). Terrain 0-11,500 m. from the aircraft was rendered at LOD 1; terrain at 11,500-26,000 m. was rendered at LOD 2; terrain at 26,000-35,000 m. was rendered at LOD 3. Terrain more than 35,000 m. from the aircraft was not drawn; haze (see section 4.3.4) was set such that this "edge of the world" was not visible to the user. This implementation resulted in representative terrain that could be animated at 24 frames per second or greater. Flight testing of the perspective terrain display with these settings yielded positive pilot feedback with regard to frame rate and terrain detail. As a complementary analysis, Figure 38 shows data from Garland and Heckbert (1995) showing overall elevation accuracy of the resulting TIN as compared to the underlying data from the original DEM prior to decimation vs. density of selected terrain points utilizing a similar terrain generation method to ours. In this figure, the curve from the Garland and Heckbert data is specific to a TIN generated from the mountainous terrain in Oregon shown in the Figure 38 insert; however, the Alaskan and Lake Tahoe areas are similarly mountainous. The densities of the levels of detail described above and the resulting elevation accuracies are overlaid. For the finest LOD, the level of accuracy is approximately 7.5 meters rms error. This is on the same order of magnitude as the vertical NSE for WADGPS, suggesting the accuracy is reasonably good. More importantly, the figure indicates that any increase in TIN density from the chosen value will have limited return on further elevation accuracy improvement.

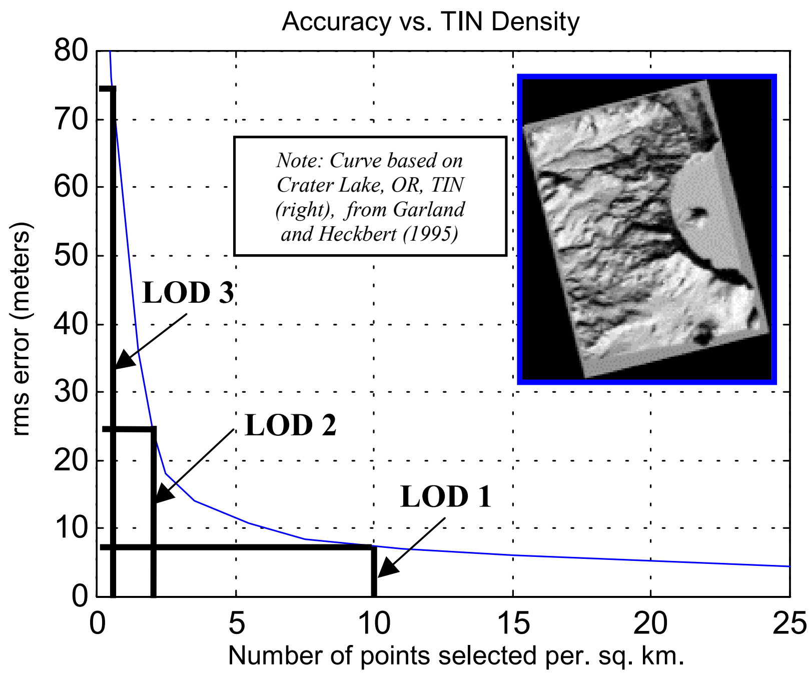


Figure 38. Overall accuracy of terrain TIN vs. number of points used in TIN construction.

4.3.2 Terrain Texturing

Adding digital texture to graphical terrain represented by shaded polygons is valuable for pilot judgement of depth and distance in the visual scene. It has long been recognized that as dots or lines become gradually more densely concentrated, and the spaces between them become increasingly smaller, this pattern of general compression produces a perception of space and distance (Bloomer, 1976). Stevens (1995) provides guidelines for good texturing for graphical perspective terrain. These include:

- *Spatial homogeneity.* To be a valid cue to distance, the physical texture statistics must be invariant across the surface. In particular, a gradual variation in size would, in the absence of other information, erroneously suggest variation in distance.
- *Distinguishable size.* To be a valid cue to distance, a sufficiently narrow range of element sizes must be present in any vicinity, so that projected element sizes at different localities are comparable.
- *Isotropy.* To be a valid cue to slant (the relative angle of the normal of the terrain surface to the viewer), the physical texture must, according to most theories of human perception, be isotropic (look similar from any direction), [or] at least not systematically mimic foreshortening (Figure 39).

The original 3-D display developed for the 1998 Alaskan flight trials had terrain that pilots and observers felt looked realistic from a distance. However, experience with the display yielded the contention that as the aircraft approached terrain depth and distance cues were lost. The textures chosen for the ground and water were considered appropriate from distances of approximately 2000 ft. and above, but lacked definition and became "fuzzy" when the aircraft approached to within a few hundred feet of the surface. Specifically, this texturing did not adhere to Stevens' criterion for distinguishable size, and arguably the criterion for isotropy was violated as well. Since perspective terrain displays become more important to the pilot the closer the aircraft comes to the terrain, an effort was made in later iterations to improve cues for intentional or unintentional operation close to the ground. Specifically, newer versions of the terrain display took better advantage of the texturing guidelines described above to provide good depth cues at low altitudes.

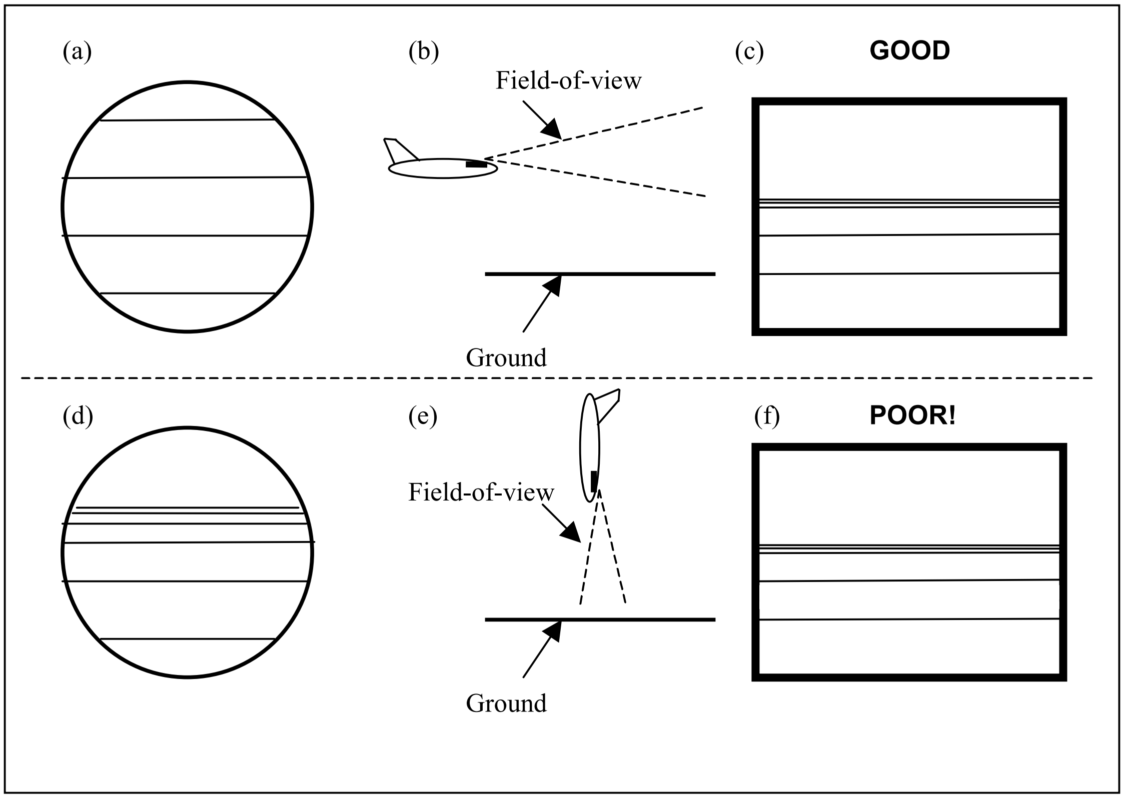


Figure 39. Foreshortening.

An appropriate ground texture has regularly-spaced features, such as lines (a). When this texture is applied to the ground, a observer in an aircraft flying parallel to the ground (b) looking forward will notice features further away look more closely spaced together (c). This is called "foreshortening," and on perspective images this is a cue to relative distance. A poor texture has features that mimic this foreshortening effect (d). In a situation where the observer is flying towards the ground (e), if this poor texture is applied to the ground the associated perspective image provides the incorrect illusion that the aircraft is flying level! (f). Note that (c) and (f) are the same display image.

Newer versions of the terrain display also took advantage of *detail texture*, a feature currently provided on most 3-D graphics acceleration cards. With detail texture, a finer texture emphasizing the details of surfaces is blended in with the regular texture progressively as the distance to the terrain object decreases. Detail texture not only provides additional visual cues as the aircraft approaches terrain, but the onset of the appearance of detail texture warns the pilot that the aircraft is within approximately 1000 ft. of the terrain.

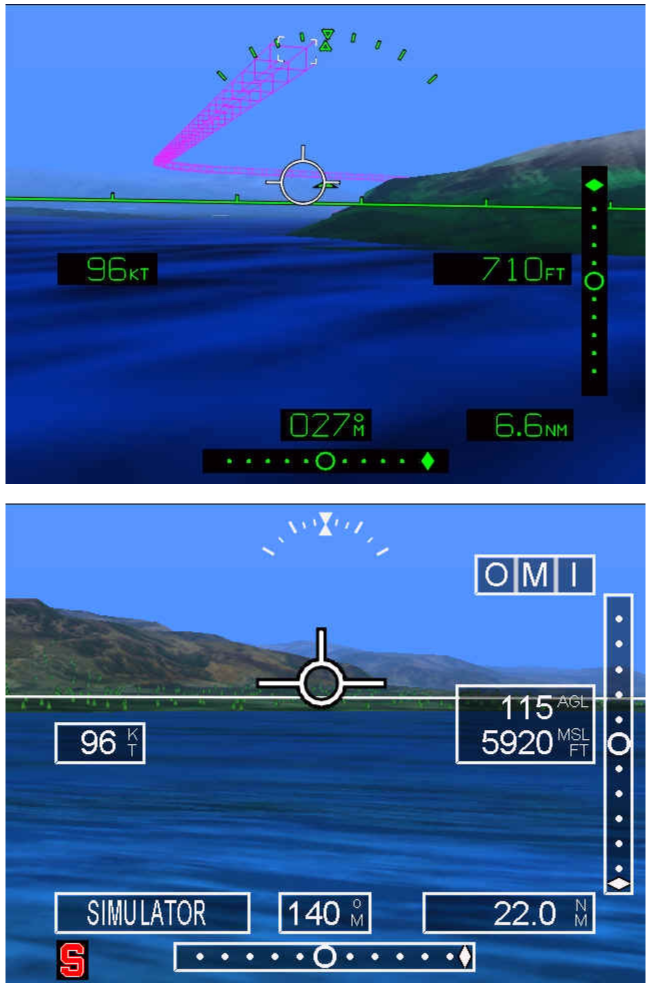


Figure 40. Water without/with detail texture.

Figure 40 shows an older version of the perspective display without detail texture (top) and a newer version with detail texture (bottom). In the older display the aircraft is 710 ft. above the surface. Notice the lack of height cues in the water texture. This lack of definition degrades further as the airplane descends from this altitude. In contrast, with detail texture, the newer display has very good height cues even when the airplane is only 115 ft. above the surface because the movement over the detail texture is so apparent.

4.3.3 Terrain Surface Objects and Display Frame Rate

In addition to digital texturing, adding common-sized objects to a visual scene can improve pilot recognition of relative and absolute distance of features on the terrain. A common precept of perception is that two objects known to be the same size will be seen at relative distances inversely proportional to the visual angles subtended. The one subtending the larger visual angle will appear closer than the one subtending the smaller visual angle (Ittelson, 1960). Kleiss, *et. al.* (1993), through piloted simulation, demonstrated the value of adding trees (or any other common-sized object) to the terrain to improve pilot awareness of altitude change.

Adding 100-ft. tall pine trees scattered randomly across the surface of our terrain models improved pilot awareness of height above terrain, especially when the terrain display was presented on the 6.4" display used in the test aircraft. Trees were chosen over differently shaped objects solely for aesthetic reasons. As indicated above, any common-sized object would have sufficed. The density of the trees on the terrain surface had to be carefully selected so as to provide an adequate number of trees without decreasing the frame rate of the display below acceptable levels. While a frame rate of 10 Hz is considered minimally adequate for flight control (Theunissen, 1997), experience with the perspective display exhibited that smooth animation of the scenery requires a minimum frame rate of approximately 18 Hz. For comparative purposes, theatrical film is shown at 24 frames per second, while standard television updates at 30 frames per second. It should be reiterated here that in order to achieve smoothly animated perspective display motion at 18-24 frames per second, the user position must be updated at a similar rate. Most aviation GPS and WADGPS receivers only output position data at 1 Hz. If not augmented with inertial systems that output position data at higher rates, these low data rate receivers will be ineffective for a perspective display. Receivers that output position and velocity at 5-10 Hz are acceptable without augmentation with inertial units; however, some simple filtering is required (see section 2.2.1).

Figure 41 (top) shows the range of observed frame rates and the average frame rate vs. density of tree objects for our system. Tree object density is a design parameter, as shown. Increasing the tree density significantly will decrease frame rate. It is

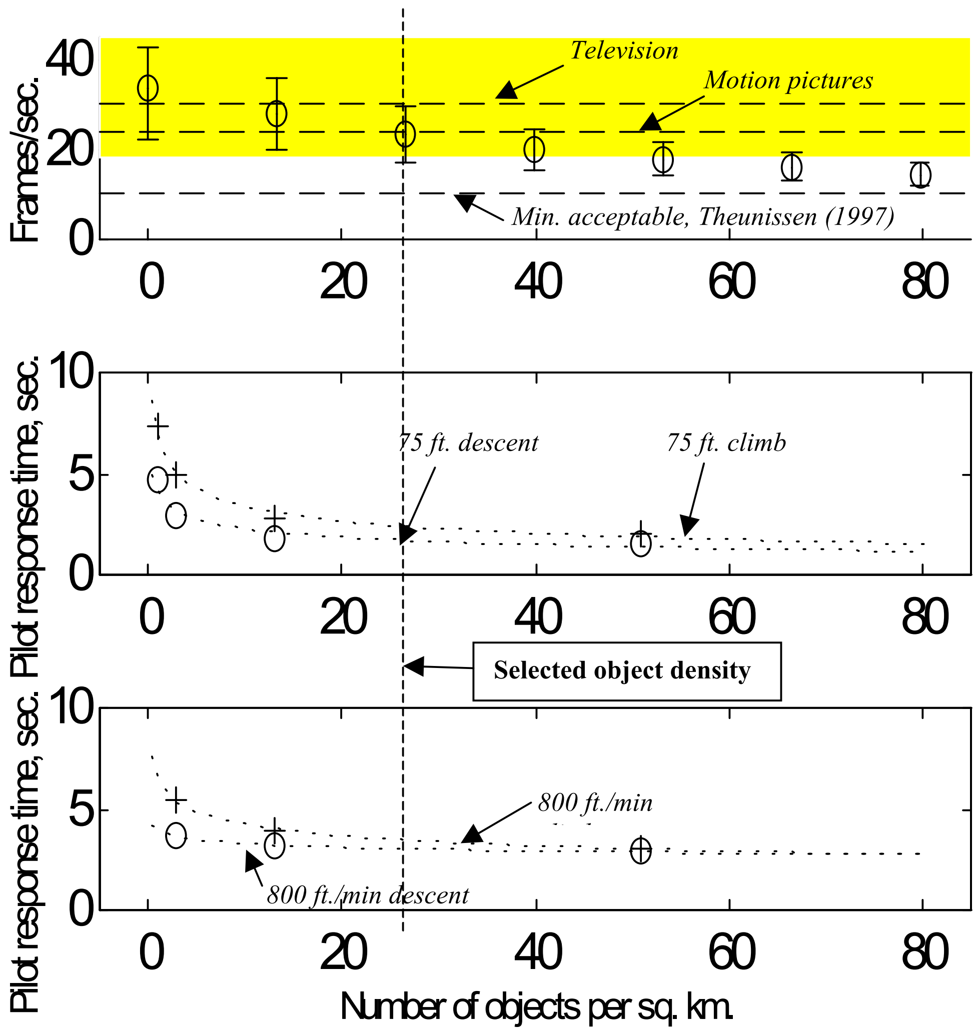


Figure 41. Frame rate and pilot performance vs. ground object (tree) density

(Top) Average frame rates, which are a function of tree density, are plotted as circles. Error bars indicate maximum and minimum observed frame rates for the object density tested. Shaded region represents smooth animation. (Middle) Pilot response to absolute climb or descent. Kleiss (1993) original data shown as symbols, curves are exponential fit. (Bottom) Pilot response to constant climb rate or descent rate. Original data shown as symbols, curves are exponential fit.

possible to increase tree density without decreasing frame rate by lowering the TIN densities used in the terrain generation. Given this, a tree density of 26.6 objects per sq. km. met our requirements for maintaining frame rate without requiring an adjustment of the TIN densities chosen in section 4.3.1.

The acceptability of this value based on pilot performance can be seen when compared with data from the Kleiss study. This study had two experiments of interest. In the first experiment, pilots viewed a visual scene from a simulated aircraft in level flight. The aircraft entered a fog bank (the scene became uniformly gray); when the aircraft exited the fog bank, the aircraft had either climbed or descended a fixed distance. Pilots were tasked with determining the direction of the altitude change as quickly as possible. In the second experiment, the simulated aircraft was initialized with a fixed rate of climb or rate of descent. Again, subjects were tasked with determining whether the aircraft was climbing or descending as quickly as possible. An analysis of Kleiss' data conducted for this thesis work found that exponential models fit pilot performance vs. tree density data very well. Figure 41 (middle) shows pilot recognition time for absolute altitude change. For a climb, the correlation coefficient of the exponential fit was 0.99. For a descent, the correlation coefficient was 0.96. Figure 41 (bottom) shows pilot time to recognize whether the aircraft was climbing or descending. For a positive constant climb rate, the correlation coefficient of the exponential fit was 0.99. For a constant rate descent, the correlation coefficient was 0.99. From this figure, it is evident that for all pilot performance metrics (recognition of positive altitude change; recognition of negative altitude change; recognition of climb; recognition of descent), the most significant improvement in performance occurs with any increase in object density up to approx. 10-20 objects per sq. km. Any increase in tree density above the selected value of 26.6 objects per sq. km. only marginally increases pilot performance.

4.3.4 Additional Depth and Distance Cues

Additional techniques to provided depth and distance cues can be used to further improve pilot spatial awareness. Simulated atmospheric haze can be used to improve pilot recognition of terrain that is closer to the aircraft from terrain further away. With computer-generated haze, as with real-world haze, terrain that is closer to the aircraft looks sharp and clear, while more distant terrain has less contrast or looks more "washed-out". Haze also improves contrast of ridgelines. Colorization of terrain by height can be used to provide cues as to where terrain is higher. This colorization scheme also improves ridgeline detail when ridgelines are at different elevations from terrain behind. Colorization of terrain by height and haze were used in all terrain displays tested.

As perspective terrain displays for aviation are developed, care must be taken to design these displays to match the functional requirements of the flight operation in question. For civil operations, the main purpose of a terrain display is to alert pilots of their proximity to terrain and obstacles. While it might seem most appropriate to design the terrain surface to appear as realistic as possible, making the terrain look more like it does in real life is not necessarily the best way to provide the cues required for terrain separation.

In general, it is difficult to provide visual cues such that the pilot can definitively estimate aircraft height above terrain. Roscoe (1984) explicitly determined that the presentation of a wide field of view image on a small display ("image minification") results in objects on the display to appear farther away than they actually are, and the perceived aircraft height to be greater than reality. Given this, with WAAS altitude and a terrain database it is trivial to compute current height above terrain. The final version of the perspective terrain display developed for this work included a digital indication of altitude above ground level (AGL). This additional indication was generally well received by pilots.

4.3.5 Evaluation of Experimental Concepts

In order to evaluate quantitatively graphical terrain surface options (texture, terrain surface options), pilots who either flew the experimental perspective terrain display concepts or observed them in flight participated in a survey on display capabilities. This survey was issued after the final series of flight tests in 1999. The survey consisted of a series of statements concerning the functional merits and limitations of the experimental display concepts. Pilots were asked to rate only to the statements in the sections relating to the display concepts they flew or observed.

4.3.5.1 Display Concepts

Three experimental display concepts were evaluated (Figure 42). Each was evaluated by multiple pilots and flown over discrete periods of time between 1997 and 1999. The concepts were:

- *Perspective Flight Display, 1997 (PFD '97)*. This version of the HITS primary flight display was developed and flight tested by Barrows (1997). The perspective scene included an orange-brownish-colored ground and blue sky, with green hoops for the approach path and pink five-sided hoops for the missed approach path. The landing runway was shown, as was a control tower on one side of the runway. This display was flown extensively on the Queen Air into Palo Alto, CA and Moffett Field, CA, mostly in traffic patterns, segmented, and straight-in approaches. It was also the display used to fly specific patterns of straight and turning segments to evaluate flight technical error when flying the tunnel. It was flown in Alaska as an overlay of LDA Runway 8 into Juneau and the localizer approach into Petersburg.

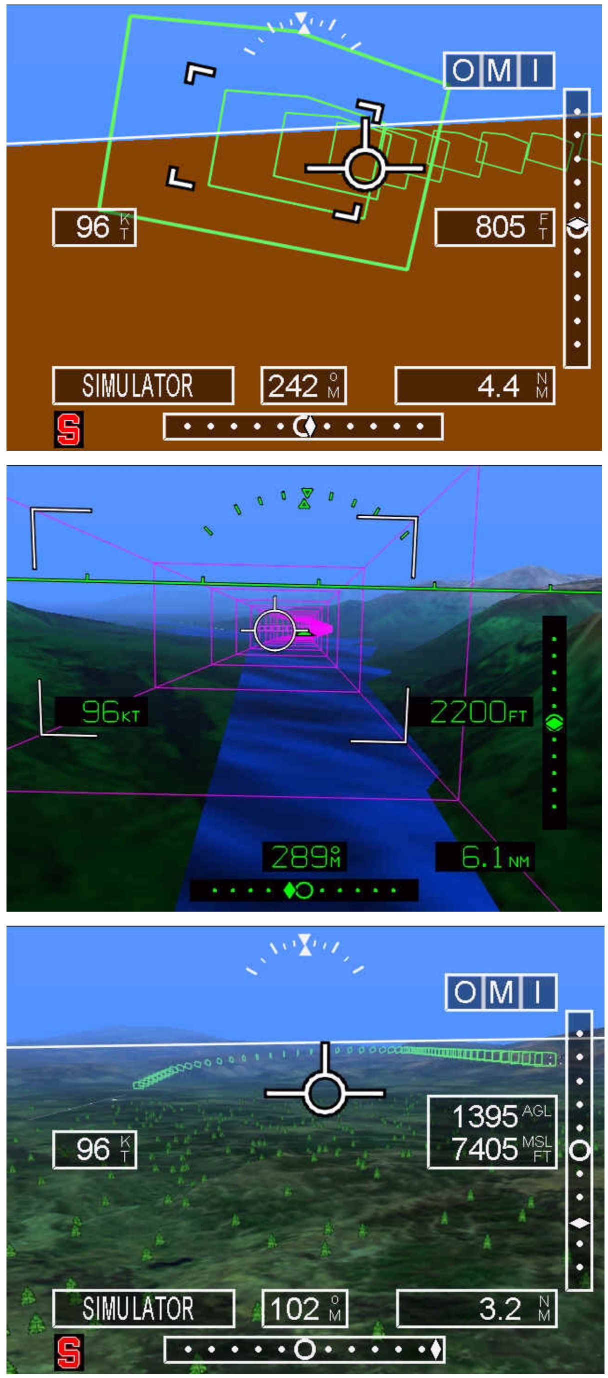


Figure 42. PFD ’97 (top), PFD ’98 (middle), PFD ’99 (bottom).

- *Perspective Flight Display, 1998 (PFD ’98)*. This was the first version of the tunnel display to have perspective terrain and water. It was initially flown around Moffett Field just prior to the 1998 tests in Alaska, and was flown extensively in Alaska around Juneau, Sitka, and Petersburg. The terrain was color coded by altitude, with lower terrain appearing as dark green, intermediate terrain light green, and white peaks. The scene included non-textured runways with runway numbers and touchdown zone markings. The symbology was green alphanumerics and symbols formed with line segments only, or *stroked*. Stroked symbols were chosen for graphics speed, and because stroked symbology is very common on head-up displays, which present a similar "symbology over a perspective scene" presentation. The tunnel had magenta-colored hoops. This version of the display was later flown in several flight tests around Moffett Field.

- *Perspective Flight Display, 1999 (PFD '99)*. The PFD '98 display was updated to include the original bitmapped PFD '97 symbology and five-sided green hoops. The variable-slope missed approach tunnel was first flown using this version of the display. 100-foot tall trees appeared on the ground, and the ground and water textures were different from the PFD '98 display. An altitude above ground level (AGL) digital indicator, based on the difference between WAAS altitude and the altitude of the underlying terrain model, was included on the right side of the display.

In the survey, individual sections were dedicated to each PFD concept. A fourth section asked pilots to respond to statements about terrain awareness when utilizing the airplane windows and primary flight instruments in visual flight conditions. This group of statements served as the control condition.

4.3.5.2 Respondents

10 pilots responded to the survey. The total flight time of the respondents ranged from 80 flight hours to over 16,000 hours, with a median of approximately 1,200 hours. 7 pilots responded to the statements regarding PFD '97; 7 pilots responded to the

statements regarding PFD '98; 7 pilots responded to the statements regarding PFD '99. Four pilots flew or observed all three display concepts, and thus responded to all four sections of the survey.

4.3.5.3 Survey Results

In general, the survey results indicated that detail texture and terrain surface objects improve pilot awareness of distance to and height above hazardous terrain. This result corresponded to pilot statements during test flights, which indicated preference for the newer terrain display concepts.

Results to specific statements are detailed as follows:

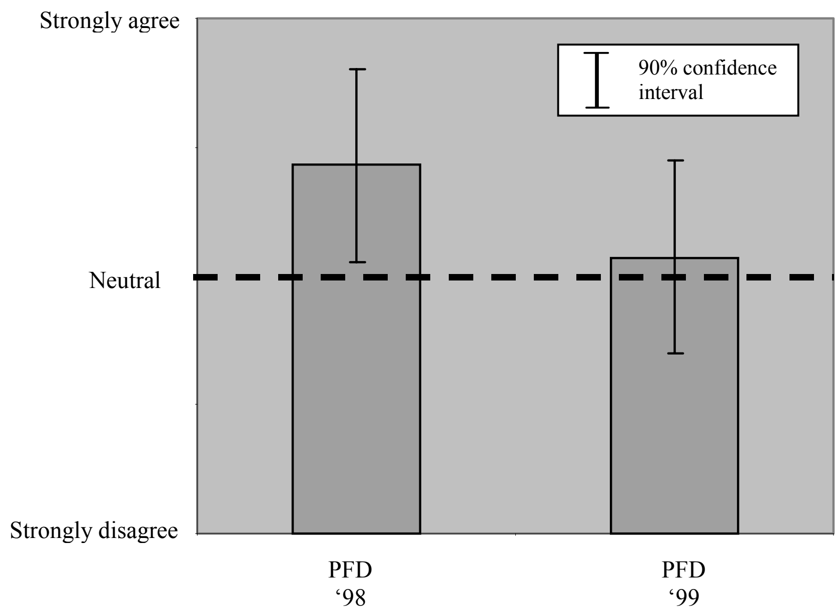


Figure 43. *"When looking out the window of the airplane, the terrain seemed much closer to the airplane in reality than it did on the display."*

- *"When looking out the window of the airplane, the terrain seemed much closer to the airplane in reality than it did on the display."* (Figure 43) Pilot comments during flight testing of the earlier versions of the flight display clearly indicated that the perspective terrain, as depicted on the 6.4" flight display, induced a sense of image minification. This general dissatisfaction is apparent quantitatively as general agreement to the statement above from pilots who flew the PFD ’98 concept. As discussed above, subsequent perspective terrain took advantage of a number of visual cues to improve pilot depth perception. This effort resulted in a quantitative improvement based on pilot responses to the statement above with reference to the PFD ’99 display. In general, pilots neither agreed nor disagreed with the statement. This suggests that the terrain depiction on the PFD ’99 provided representative depth cues as might be seen through an aircraft window. This result is in agreement with the work of Sedgwick (1991), who claims that the image minification perception problem can be overcome with explicit pilot knowledge of the display size and other supporting cues.

- *“At any location when flying approaches below approximately 1500 ft. AGL, it was easy to estimate the absolute altitude of the airplane to within a few hundred feet or better (without using AGL indicator).”* (Figure 44) *Absolute altitude* is defined as the vertical distance of an aircraft above the terrain (Federal Aviation Administration, 1980). This question specifically included the phrase “at any location” to elicit responses with recognition that for approaches over uneven terrain, absolute altitude above local terrain is typically estimated visually. Pilots surveyed responded neutrally when asked about their capability to judge height above terrain to “within a few hundred feet” with external visual cues. As would be expected, strong disagreement to the statement above was found using the PFD ’97 display, which has no terrain depicted. Quantitative responses with respect to the PFD ’98 display were less disagreeable than for the PFD ’97 due to the perspective terrain depiction. However, pilots clearly did not feel that the PFD ’98 terrain depiction was good enough to warrant results on par with those for external

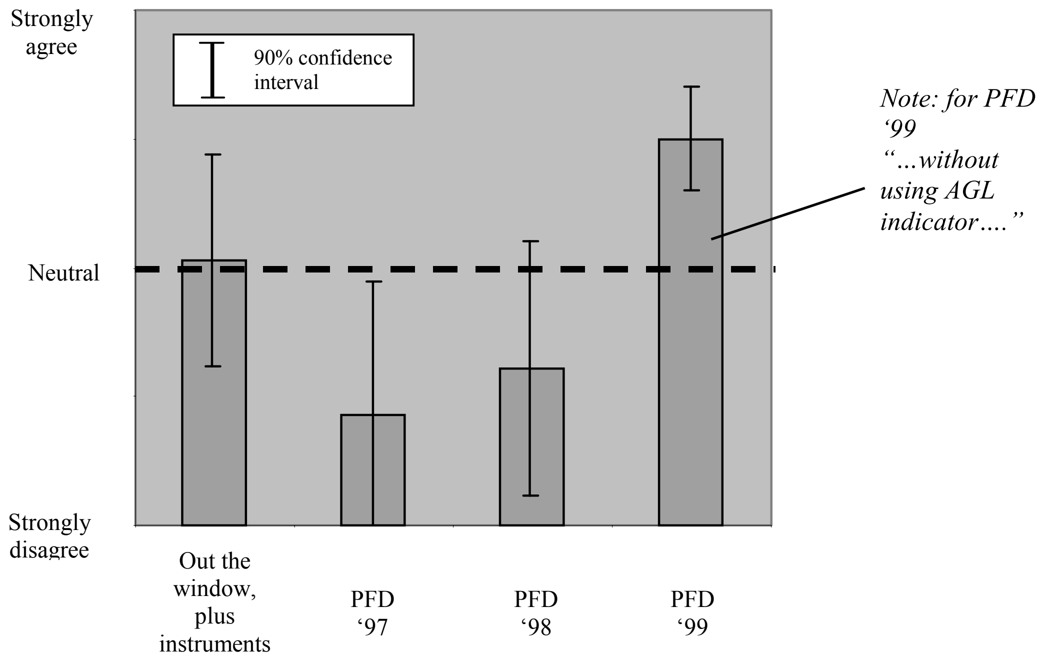


Figure 44. ***"At ANY location when flying approaches below approximately 1500 ft. AGL, it was easy to estimate the absolute altitude of the airplane to within a few hundred feet or better."***

visual cues. In contrast, the PFD '99 ratings were significantly improved over the PFD '98 ratings, suggesting that pilots believed that the additional cues on the PFD '99 display were beneficial for height awareness. Surprisingly, the PFD '99 ratings were better than those for "out the window." This may be due to the pilots' ability to judge height on the PFD '99 display with respect to the 100 ft. tall trees on the perspective display.

- *"In general, it was easy to estimate the relative bearing from the airplane to hazardous terrain within a few miles of the airplane."* (Figure 45) When qualified with the additional statement "…in front of the airplane," this statement yields strong agreement from pilots flying with respect to visual cues as well as pilots who flew either of the PFD '98 or PFD '99 displays.

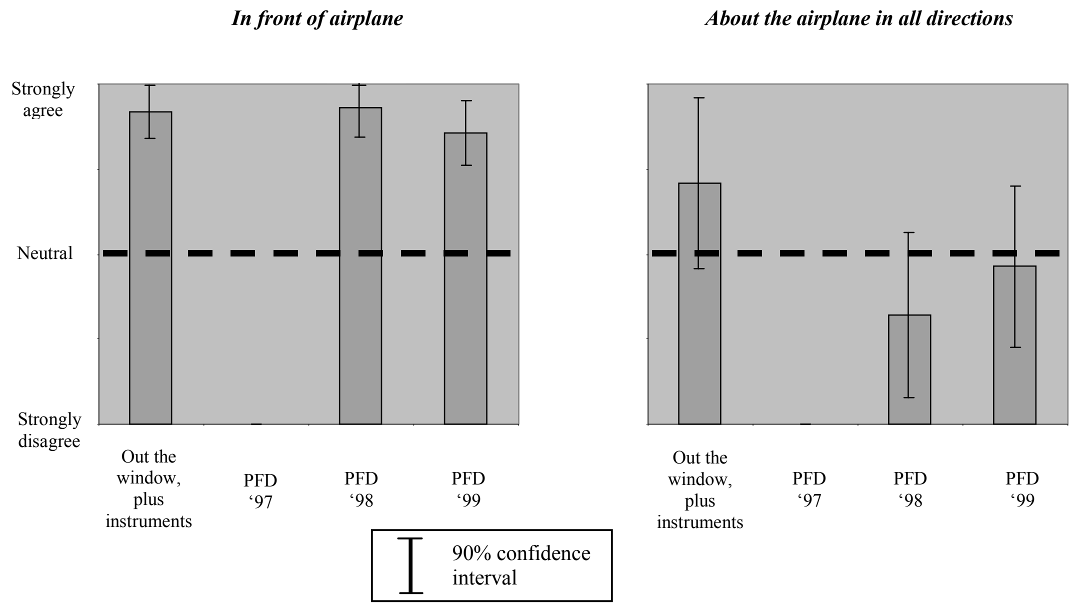


Figure 45. ***"In general, it was easy to estimate the relative bearing from the airplane to hazardous terrain within a few miles of the airplane."***

This is a very positive result for perspective terrain displays, as it strongly suggests that such displays support at least some of the functionality of external windows. However, when qualified with the additional statement "…about the aircraft in all directions," the statement yields agreement with respect to neither the PFD '98 nor the PFD '99 display. This highlights the limitation of perspective displays (as implemented) of only depicting terrain in a somewhat narrow field of view in front of the aircraft, with no terrain depiction to the sides or rear. As expected, universal strong disagreement to this statement existed for the PFD '97 display, which depicted no terrain.

- *"When flying toward terrain, such as a ridgeline or mountain peak, I could estimate to within 15 seconds or better the approximate time remaining before impact"* and *"When flying toward terrain, such as a ridgeline or mountain peak, I could estimate to within 15 seconds the time remaining*

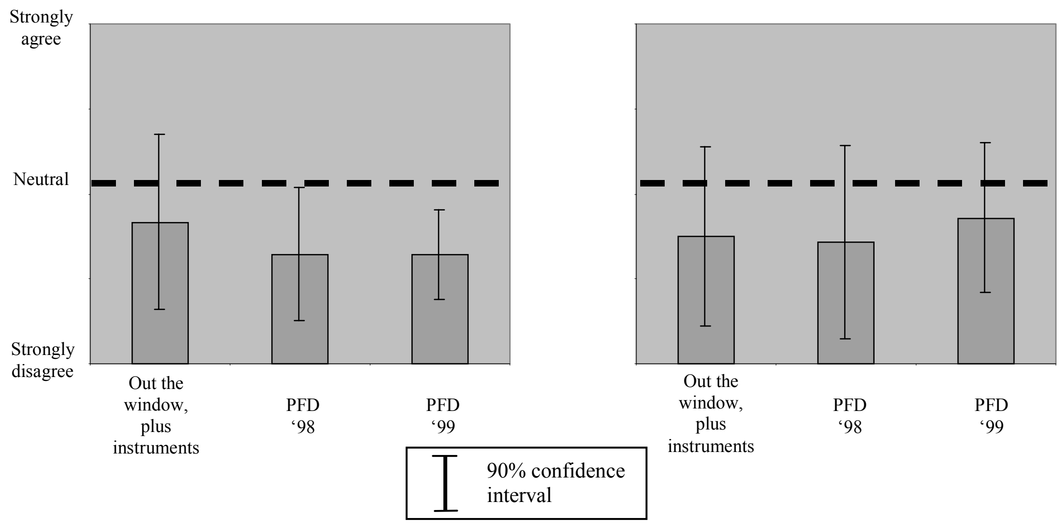


Figure 46. (Left) ***"When flying toward terrain…I could estimate to within 15 seconds or better the approximate time remaining before impact" (Right) "When flying toward terrain…I could estimate to within 15 seconds the time remaining before a climb would no longer result in the airplane clearing terrain."***

before a climb would no longer result in the airplane clearing terrain." (Figure 46) General disagreement existed to both of these statements with respect to both of the perspective terrain display concepts. This result highlights the potential value of terrain alerting systems to augment the deficiencies of perspective terrain depiction.

4.4 Simulator Study: Terrain Alerting

The survey results from the prior section suggest general disagreement with pilots' ability to precisely determine time to terrain impact. This in turn suggests augmentation of the perspective terrain display with 3-D symbology warning pilots of proximate terrain could add value to such a display. This section describes a simulator study to evaluate the benefits of adding 3-D alerting symbology to perspective terrain.

The general concept of alerting pilots to an impending collision with terrain is not novel. The Ground Proximity Warning System (GPWS), which warns pilots of impending terrain incidents based on radar altitude and radar altitude closure rate, has been required on most U.S. aircraft conducting commercial operations and on turbine-powered aircraft since 1974. This system, while generally effective as an alerting system, does not provide pilot information on bearing and relative altitude of terrain in front of and to the sides of the aircraft. In 1991, Allied Signal, Inc. (now Honeywell) developed the Enhanced Ground Proximity Warning System (EGPWS). This augmentation of the basic GPWS concept uses aircraft position information (augmented with stand alone GPS) and a terrain database to provide a 2-D map presentation of terrain in front of and to the sides of the aircraft. EGPWS also provides audio warnings when the predicted aircraft path provides inadequate terrain clearance. This system provides effective prediction of potential terrain conflicts, as opposed to GPWS, which reacts to insufficient terrain clearance. The FAA is in the process of mandating EGPWS on airliners and most turbine powered airplanes. See section 4.3 for a partial listing of other terrain warning systems on the market as of mid-2000.

3-D terrain is not "better" than 2-D representation of terrain; rather, each representation has different benefits and drawbacks. Plan view terrain displays provide good situational awareness of terrain in all directions about the aircraft, while perspective terrain (without lateral terrain indicators, discussed later in this section) only shows terrain in front of the aircraft. However, 2-D displays give limited information as to the precise relative height of terrain peaks in front of the aircraft. More importantly, using a map display in conjunction with a PFD to maneuver to avoid terrain requires the mental fusion of information from two displays, which increases cognitive workload. When a pilot is maneuvering to avoid hazardous terrain, this increase in workload complicates piloting an aircraft during such a critical time. As shown in the prior section, perspective terrain provides very good cues as to bearing to and relative height of hazardous terrain. More importantly, perspective terrain integrated with a PFD puts the most important information on one display in an intuitive format for terrain avoidance. As implemented, the terrain display provides an explicit indication of whether or not the airplane will eventually impact terrain if it proceeds in the direction and flight path angle currently shown by the velocity vector.

Given these benefits of perspective terrain, a perspective terrain display by itself provides limited additional warning information, particularly with regard to how much time a pilot has remaining to maneuver to avoid terrain. In particular, as stated above, the perspective terrain display provides no information about hazardous terrain outside of the field-of-view presented in the perspective display.

The study described in this section was limited to the investigation of alerting for terrain in front of the aircraft, and did not address terrain awareness issues relating to turning flight. While not evaluated through simulator or flight study, an indication system was conceived and developed to provide the pilot information regarding aircraft capability to outclimb terrain not in the field of view of the perspective display. These lateral terrain indicators (LTI) directly show the maximum absolute terrain clearance for maximum performance climbing turns to the left and to the right for all bank angles up to 60 degrees (Figure 47). Terrain clearance is computed based on estimated turning climb performance and estimated winds. The left and right indicators include arrows, each of which are nominally white and point to the top of the adjacent white, yellow, and red vertical scale if a climbing turn in the respective direction will clear terrain by a significant margin. If terrain clearance on either side of the aircraft decreases below 600 ft. (an arbitrary value reflecting marginal terrain clearance, chosen for initial demonstrations of the LTI), the arrow on the appropriate side will start to descend along the scale. The arrow moves down linearly as terrain clearance decreases, and reaches the bottom of the white band if terrain clearance is reduced to 300 ft. If terrain clearance is further decreased, the LTI arrow will turn yellow and continue to descend adjacent to the yellow band. The arrow will turn red and descend into the red band if a climbing turn to the respective side will result in zero terrain clearance, indicating that a course reversal to that side should not be attempted under any circumstances. The LTI concept is intended to situational awareness by continuously updating the pilot as to whether or not the aircraft can or cannot avoid terrain by turning to the left or right prior to such a

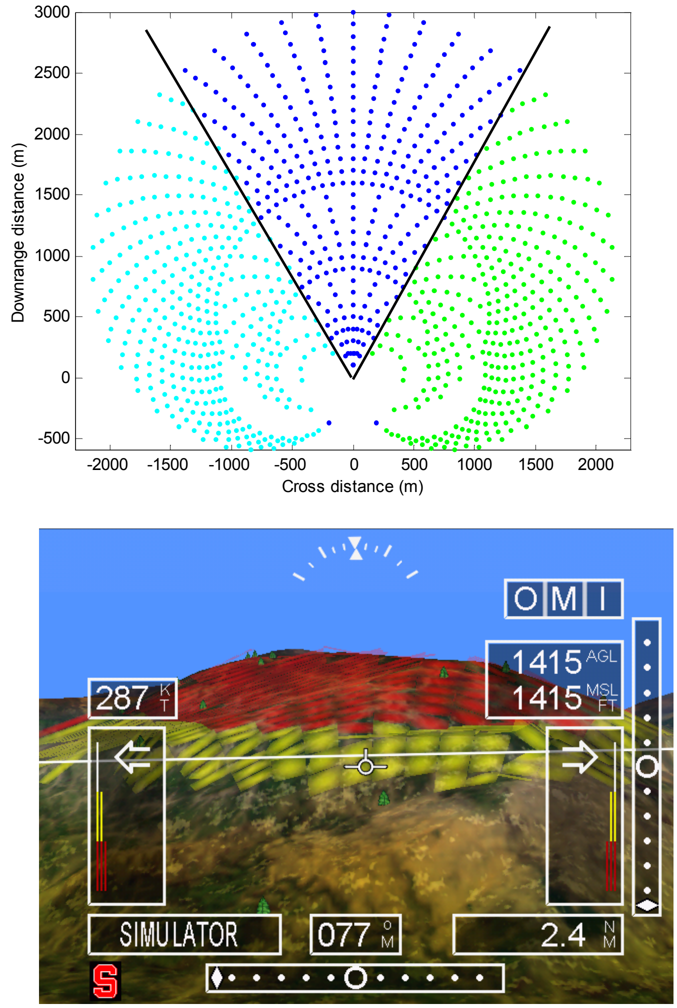


Figure 47. Lateral Terrain Indicator (LTI) concept.

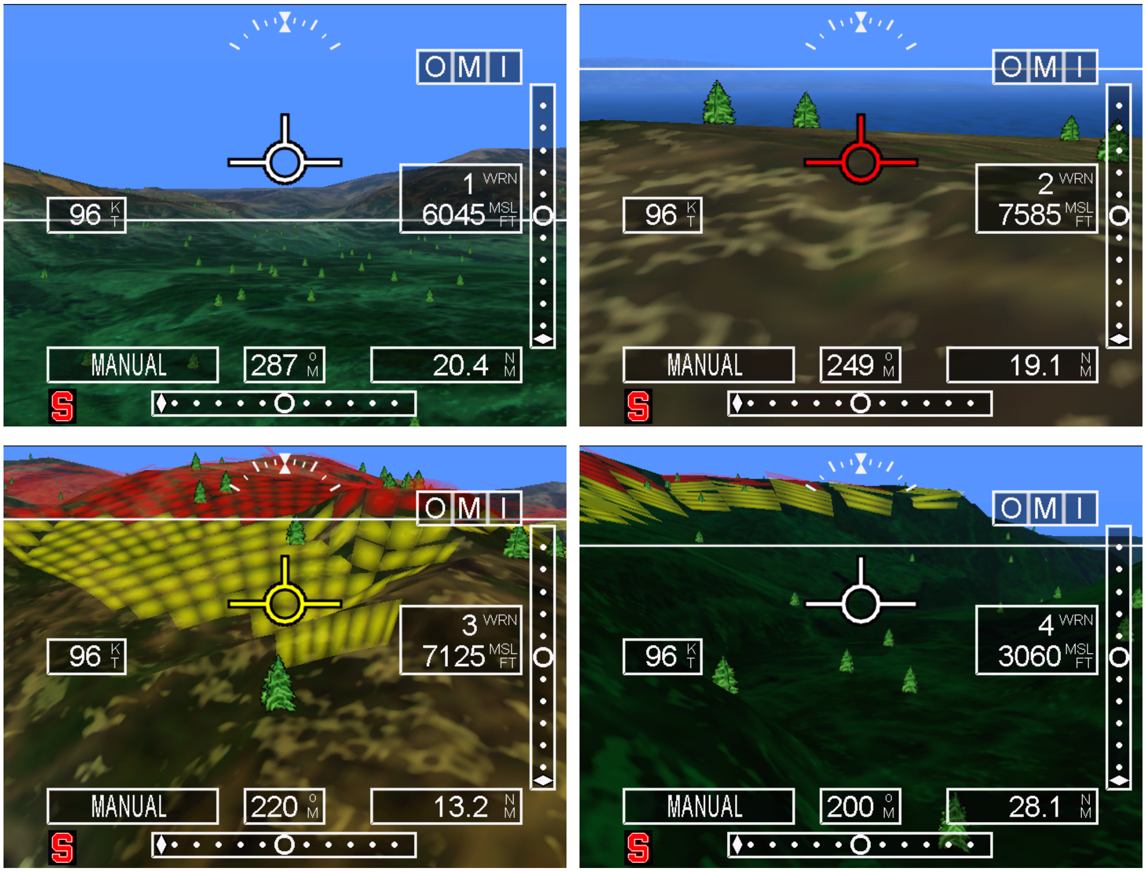
(Top) LTI calculates terrain clearances for locus of possible aircraft positions in the next 60 sec. Dark blue dots indicate points in the forward field-of-view of the perspective display. Clearances at light blue dots are evaluated for left LTI; clearances at green dots are evaluated for right LTI. In this case, there is no wind. (Bottom) LTI symbology consists of arrows that move up and down on the left and right sides of the perspective display.

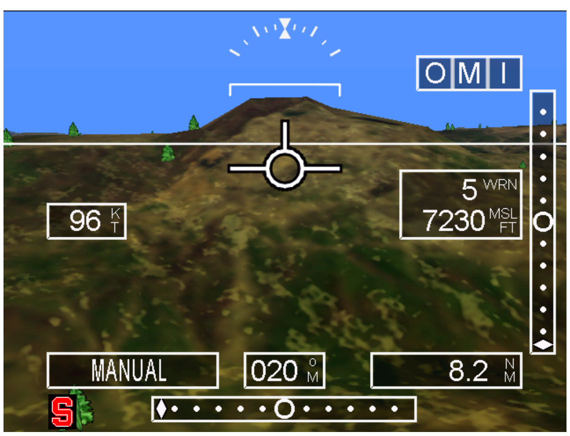
turn being initiated. Given this, the LTI concept may specifically aid perspective display-only implementations. However, in general it is best to show terrain on both the perspective and plan displays, if both are available.

4.4.1 Study Objective

A task analysis of the terrain avoidance function required for all aircraft should include at least the following three tasks. First, the pilot must recognize if the current flight path is clear of terrain for the foreseeable future. In this case, the pilot can fully direct his attention to other functions besides terrain avoidance. Second, the pilot must recognize if the current flight path and profile intersects the terrain in the near future, and, if so, the time remaining before impact based on distance and closure speed. This condition may exist during normal flight operations (e.g., an airplane on base leg with a high ridgeline on the side of the runway opposite the traffic pattern). In this case, the pilot must continually monitor his position relative to terrain so as to take action as necessary prior to a critical situation. Third, in the case of airplanes (as opposed to rotorcraft in most flight regimes), the pilot must continually judge whether the airplane can outclimb terrain ahead of the airplane if necessary. This function requires the pilot to determine whether he can, at any given time, increase power to maximum thrust, climb at the maximum angle of climb airspeed, and still clear high terrain ahead of the airplane. Notice that this task is different from the second task: an airplane may still have significant horizontal clearance from a ridgeline ahead but still lack the ability to outclimb the terrain. These three tasks are not the only tasks required for terrain avoidance, but are the primary tasks associated with avoiding terrain in straight (non-turning) flight.

The objective of the study described here was to investigate four possible alerting symbology augmentations to the basic perspective terrain display (described below). By examining how pilot reaction time to accurately determine the onset of each of the conditions above varies as a function of active augmentation symbology mode, we can measure potential improvement in pilot spatial awareness with the augmented symbologies.





(Top left) Control condition with no alerting symbology. (Top right) First experimental concept (6-sec. alert) (Middle left) Second experimental concept (level shading) (Middle right) Third experimental concept (climb shading) (Bottom left) Fourth experimental concept (climb bar).

Figure 48. Display concepts for simulator study.

4.4.2 Alerting Concepts

The first terrain alerting concept was simply a warning provided when the airplane was 6 seconds from terrain impact. When this warning was active, the velocity vector symbol on the display turned from white to red (Figure 48).

The second concept included shading of terrain based on the current altitude of the airplane. For the purposes of the experiment, terrain at or above the altitude of the airplane was shaded red; terrain between 300 feet below the altitude of the airplane and the current altitude of the airplane was shaded yellow. For the purposes of this experiment, due to limited computer processing power, only a 20 degree horizontal swath ahead of the airplane was shaded as described. A time to impact alert was included. Like the first concept, the velocity vector turned red when the airplane was within 6 seconds of terrain impact. In addition, the velocity vector turned yellow when the airplane was within 6-12 seconds of terrain impact.

The third concept included shading of terrain based on the altitude of terrain above or below the current maximum climb gradient available based on current airplane weight, altitude, etc. In effect, this alerting scheme indicates whether or not the airplane currently has the capability to outclimb terrain ahead of the airplane. For the purposes of this experiment, terrain above this climb gradient was shaded red (indicating that a climb ahead should not be attempted). Terrain between 0-300 feet below the climb was shaded yellow (indicating that caution should be exercised in a climb toward yellow-shaded terrain). No time to impact alert was included with this concept.

The fourth concept was an additional horizontal line added to the head-up symbology that indicated the current maximum climb gradient available (in essence, this mode could be described as a “poor-man’s” version of the third concept). No time to impact alert was included with this concept.

4.4.3 Apparatus

The visual scene and terrain alerting computations were processed on the same Pentium II 333 Mhz. graphics computer used for flight tests (described in section 3.4.1). The scene was depicted on a 21” CRT computer display. The subjects’ only required controls were the two buttons on the PC mouse, as described below.

4.4.4 Subjects

6 subjects participated in the experiment. Each was certified by the FAA as at least a private pilot (one of the subjects was a certified flight instructor). Total subject flight time ranged from 80 hours to 1200 hours, with a mean total flight time of approximately 400 hours. Four of the six subjects had prior inflight experience observing or piloting the perspective terrain display used in the study.

4.4.5 Experiment Design

The basic perspective terrain display was the PFD '99 display as described in section 4.3.5.1. Terrain depicted on the display for the study represented the region about Lake Tahoe, California, USA. As described earlier, the ground was covered with 100-foot tall trees randomly placed on the terrain, and haze was added to the scene to add additional depth cues. The basic perspective scene and head-up symbology was the control display mode. The experimental terrain alerting concepts described above were added individually to the PFD '99 display, respectively, for each experimental condition tested.

The experiment was conducted as a series of independent runs consisting of simulated flight trajectories. For each run, the airplane was repositioned to a new location, altitude, and attitude. When the simulation was unpaused after approximately one second after loading, the airplane flew straight at a constant airspeed, heading, and flight path angle. The subjects' task was to determine whether or not the flight trajectory depicted would impact terrain. If the subject determined the current flight trajectory was not going to intersect terrain in the foreseeable future (Condition A), the subject was instructed to press the RIGHT mouse button as soon as the determination was made. If terrain impact was impending, the pilot was instructed to press the LEFT mouse button to initiate a climb. Subjects were to initiate a climb when *either* the airplane was exactly six seconds from terrain impact (Condition B) or the airplane would just barely outclimb the terrain ahead if the pilot initiated a maximum-performance climb (Condition C), whichever came first.

After interactive instruction through demonstration of the experimental warning systems and the tasks to be conducted, each subject participated in a total of 60 runs. The runs were divided equally by condition, i.e., in 20 of the runs the airplane was not going to impact the terrain, in 20 of the runs the airplane would lose the capability to outclimb terrain ahead prior to six seconds from terrain impact, etc. In each experimental run, none or one of the four experimental terrain alerting symbologies was activated, such that for the control mode and each of the experimental modes 4 runs were Condition A, 4 runs were Condition B, and 4 runs were Condition C. The subject was not told in advance which condition existed for each run.

For Condition A, the dependent measure was the reaction time to recognize the condition and press the RIGHT mouse button. For Condition B and Condition C, the dependent measure was the absolute time deviation between the precomputed optimal time for climb initiation and the actual time that the LEFT mouse button was pressed, compensated for reaction time.

4.4.6 Results and Conclusions

Experiment data was analyzed using the Statistics Toolbox in Matlab™. ANOVA revealed no significant effect on pilot response time to recognize Condition A due to alerting symbology ($F(4,92)=0.1945$, $p>0.1$) (see Appendix B for an explanation of F and p values). ANOVA did not reveal an overall effect on mean absolute deviation (MAD) (in seconds, between pilot response and 6 seconds to impact) for Condition B due to alerting symbology ($F(4,92)=1.522$, $p>0.1$), although MAD did improve somewhat significantly when comparing the 6-second alert to no alerting ($F(1,23)=5.034$, $p<0.05$) (Figure 49). However, there was a significant effect on MAD (in seconds, between pilot response and the point when the climb option is lost) for Condition C due to alerting symbology ($F(4,92)=7.537$, $p<0.001$) (Figure 50). Finally,

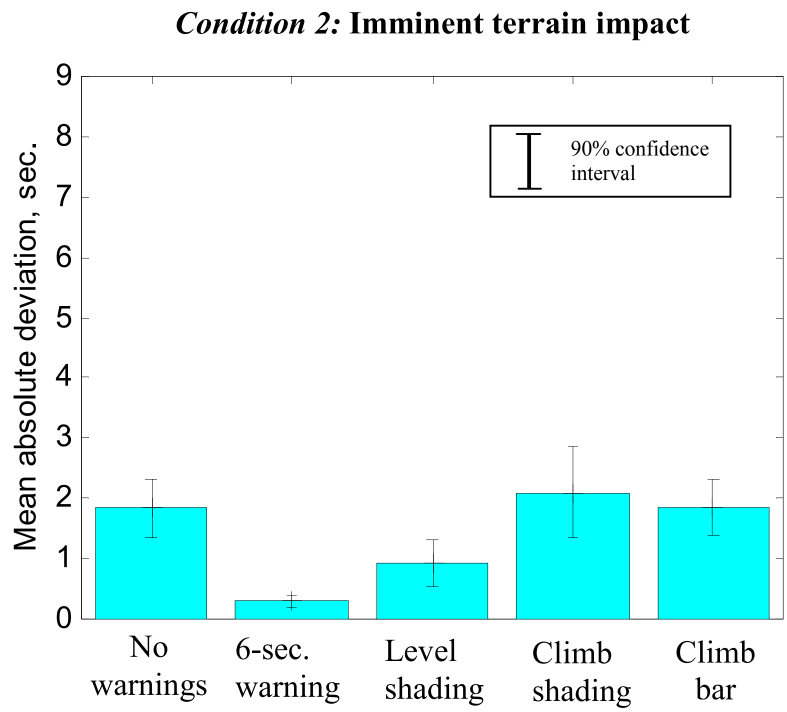


Figure 49. Pilot precision determining imminent terrain impact.

overall MAD for Condition C was significantly higher than overall MAD for Condition B ($F(1,119)=11.05$, $p<0.005$), suggesting pilots find it more difficult to estimate the optimal point for climb initiation than 6-second time to impact.

The results of the experiment suggest that certain terrain alerting symbologies (the 6-sec. warning and the level shading symbology) improve pilot ability to precisely determine their proximity to terrain directly in front of the aircraft, while others (climb shading and climb bar) did not. This result is obvious and expected, as in both of the former alerting schemes the velocity vector turns red at precisely 6 seconds to impact. However, it is surprising to note that MAD for the level-shading concept is higher than

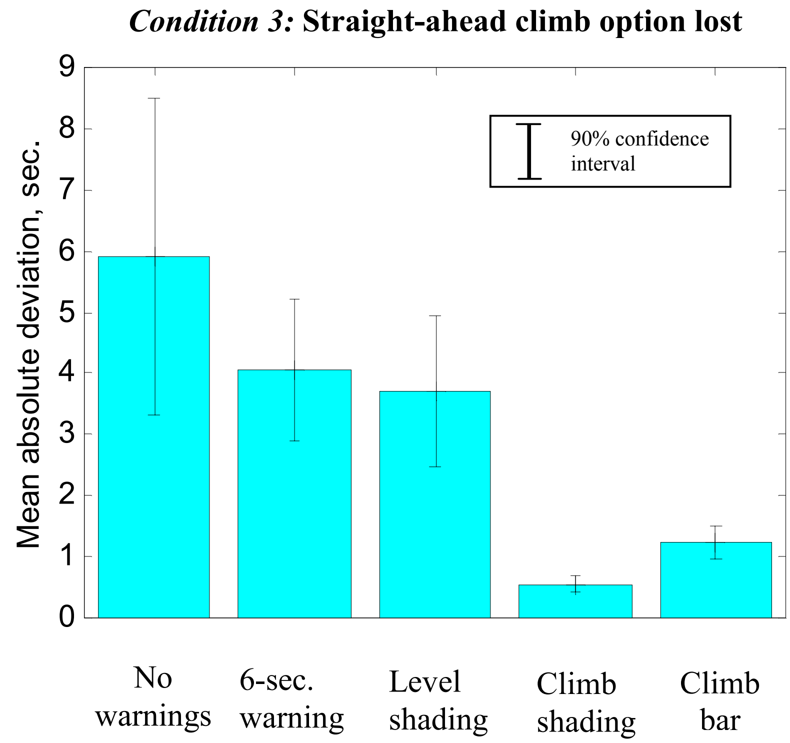


Figure 50. Pilot precision determining climb option lost.

MAD for the 6-sec warning concept, even though both concepts include the exact same 6-second alert. This may suggest that additional red and yellow level shading of terrain distracts attention from the 6-sec. warning cue. Another remarkable result is that absolute deviations from 6-second time to impact were very short (on the order of 2 seconds) for the control display mode, even without any warnings. This result suggests that a quality perspective terrain display without alerting symbology may nevertheless provide good "time to impact" cues, in contrast to a somewhat contrary opinion expressed by pilots in the survey (section 4.3.5.3).

In addition, in the survey, pilots expressed general disagreement as to whether they could estimate "to within 15 seconds" time remaining before the climb option is lost. In contrast, this experiment indicated that pilots were able to use the PFD '99 display (with no augmentation) to determine within 6 seconds, on average, the time at which the climb option is lost (as shown in Figure 50). Note the survey question and the experiment reflect slightly different tasks (determine *time remaining* until climb option lost vs. determine whether aircraft has *no time remaining* and the climb option is lost), and are thus not directly comparable. Nevertheless, the experiment results suggest that, with training, pilots may find their situational awareness with the unaugmented perspective terrain display is better than they might anticipate.

Given this, results from the experiment further show that both the climb shading and the climb bar significantly improve pilot response times over the unaugmented perspective terrain display. Subjects expressed a subjective affinity for the climb bar as a simple yet useful symbol that, in contrast to climb shading, does not add clutter to the display. The inclusion of this symbol could be very beneficial towards improving situational awareness when pilots unintentionally deviate outside of the tunnel. This capability may prove important for the viability of the HITS display as an effective situational awareness tool.

4.5 Conclusion

Pilots who have flown the display report that as long as care is taken to make certain that high contrast is maintained between the tunnel and the scenery behind it on the flight display, the HITS/terrain display is easy to fly and provides valuable information about nearby terrain. As stated previously, the intuitive nature of such a display should minimize pilot training requirements, although care must be taken to inform pilots about limitations of the terrain display (e.g., limited field of view for a perspective display). Until terrain databases reach an extremely high level of guaranteed accuracy, the terrain component of the perspective display must be used only for situation awareness and not for navigation.

As discussed above, flight test experience with the missed approach tunnel demonstrates the value of modification of the tunnel display to match the particular functionality required based on phase of flight. However, our experience dictates that training requirements for variable trajectory tunnels should not be underestimated.

Augmentation of the HITS display, as described above, effectively increases the overall capability of a perspective display. As with the basic HITS concept, these features are, in part, made viable for the general aviation market by a precise, high integrity, low-cost 3-D navigation system such as WADGPS. Continuing work on additional augmentation to the HITS display, such as traffic and wake vortex information, should further improve the potential of the perspective display.

Chapter 5

Conclusion

Air travel and air cargo operations continue to increase as global commerce expands in the information age. The number and density of flight operations in the future will require both optimization of airspace around major airport hubs and all-weather access to and from smaller airports, which may be surrounded by terrain or noise-sensitive areas. A new strategy to the design of arrival and departure procedures may soon be required. Reduction in aircraft TSE increases the practicality of Required Navigation Performance (RNP) IFR approaches and departures. RNP procedures, as described in AC 120-29A (Federal Aviation Administration, 1998), require terrain, obstacle, and traffic clearances based directly on TSE of the navigational and flight guidance systems used. RNP procedures allow curved flight segments as well as straight segments, so long as the TSE requirements can be met in turning flight. If designed correctly, RNP operations are safe, yet the clearance requirements are drastically less conservative than procedures based on traditional Terminal Procedures (TERPS), which were written to accommodate the limitations of older radionavigation and guidance systems.

As shown in this dissertation, technology that exists or will exist in the near future can be used to improve TSE by improving NSE, improving FTE, or both. This new technology not only improves flight precision, but also does so while reducing pilot workload and increasing pilot situational awareness. As emphasized in this work, the low cost of this technology makes it particularly useful to general aviation. Further, this research could be useful for airline operations, particularly with respect to airliners with older instrumentation similar to general aviation instrumentation.

An objective of this research was, in part, to attempt to collect flight simulator and inflight performance data from groups of pilot subjects, not just one or two individual test pilots. Larger groups of subjects are more representative of the pilot population evaluated (in this case, general aviation pilots). While the most thorough pilot performance studies involve dozens of pilots, it is often costly to run such large studies, especially if the studies involve flight testing with aircraft, as opposed to simulator evaluation. Given this, a great deal of human factors research comes from studies with six or more subjects. The results of the two simulator studies described in this work (see sections 3.3 and 4.4) were based on experiments conducted with 8 pilots and 6 pilots, respectively. While it would be valuable to redo these studies with larger pilot groups, both studies yielded statistically significant performance differences between specific guidance symbologies and terrain alerting symbologies. The data from the Alaskan flight trials (section 3.4) was collected from 57 approaches, missed approaches, and holding patterns flown by nine different pilots. The survey results on flight evaluation of perspective terrain (section 4.3.5) were collected from ten individual pilots.

The results of this work yield the following conclusions:

- WADGPS, as a low-cost, high precision position and velocity system, promotes the viability of new and improved display symbology for general aviation aircraft. Further, the high precision of WADGPS may guarantee that errors in the position solution resulting in display jitter will not affect pilot control of the aircraft. Position and velocity data from a WADGPS receiver at 5-10 Hz is sufficient for a smoothly animated (18 frames per second or more) perspective display using appropriate filtering. However, 1 Hz data rates are unacceptable unless the WADGPS receiver is augmented with some kind of inertial navigation system.

- Evaluation of glideslope predictor and pathway-in-the-sky display indicates significant improvements in horizontal FTE, vertical FTE, and pilot workload available with new symbology.

- Flight tests of complex curved approaches and missed approaches in Alaska and Lake Tahoe demonstrate the capability for civil aircraft to fly in and out of airports with restrictive airspace and mountainous terrain.

- Consumer-grade processor and graphics technology is capable of driving real-time, high-quality perspective terrain displays.

- Evaluation of terrain alerting concepts demonstrates significant improvements in pilot recognition of time to terrain impact with 3-D terrain alerting.

5.1 Future Work

This document represents the continuation of prior work in the areas of WADGPS and perspective flight displays. This work will hopefully be extended through future research. Suggested areas for further research include:

- *Kinematic WADGPS.* Significant work remains to validate kinematic WADGPS as a viable navigation system. Further work in characterizing carrier ambiguity and developing algorithms for ambiguity resolution (including methods for on-the-fly ambiguity resolution) is required. User accuracy and continuity issues while utilizing WADGPS-estimated user ionosphere instead of dual-frequency user ionosphere could be further investigated. Additional work in recognition and correction of cycle-slips, or the development of tracking loops that eliminate cycle-slips, would be extremely valuable. This work should ultimately lead to field trials and demonstrations of the kinematic WADGPS concept to reveal issues and operating limitations of such a system.

- *Additional symbology for integrated perspective flight displays.* As with perspective terrain, other objects relevant to civil flight could be added to the perspective HITS display. Further research could address the appropriate presentation of 3-D obstacles on the terrain and the capability of pilots to see and avoid these obstacles. 3-D depiction of traffic could be added to the perspective display. Related issues would include the appropriate symbology for traffic to properly cue the pilot to relative bearing, relative altitude, and closure rate; pilot performance during avoidance maneuvers utilizing this 3-D symbology; and the identification of issues and potential resolution of issues related to the limited field-of-view of perspective displays. Wake vortex information could be added to traffic. How to represent the vortex and determination of pilots' capability to maneuver with respect to the vortex symbology remain outstanding issues.

- *Utilization of WADGPS and perspective displays for closely-spaced parallel approaches.* Currently, parallel runways must be spaced 4,300 ft. (3,400 ft. with Precision Runway Monitor) apart for simultaneous independent instrument approaches to these runways. This requirement places severe limitations during IMC on airports with existing parallel runways spaced as close together as 750 ft. Research into how WADGPS, ADS-B, and novel flight instrumentation could be used to enable closely-spaced parallel approaches in IMC has immediate practical value.

- *Terrain display and terrain alerting.* Further studies into limitations of restricted forward field-of-view on the 3-D display and mitigating symbology would be useful to avionics designers. In particular, appropriate integration using multiple cockpit displays with separate perspective terrain and plan terrain displays should be investigated. More thorough work into the dynamic calculation of aircraft climb capability of airplanes would further augment the 3-D terrain alerting concepts described in this paper. Finally, issues specific to aircraft other than airplanes (e.g., helicopter, airship) should be investigated.

Appendix A

Kalman Filter for Kinematic WADGPS

Let the state vector **x** be defined as

$$\mathbf{x} = \begin{bmatrix} dx \\ dy \\ dz \\ \nabla\Delta N^{(2)}\lambda \\ \nabla\Delta N^{(3)}\lambda \\ \vdots \\ \nabla\Delta N^{n}\lambda \end{bmatrix}$$

where *dx, dy, dz* is the position difference between the unknown static user position and a nearby reference $\mathbf{x}_0$. $\nabla\Delta N^{j}\lambda$ is the unknown difference between the carrier phase ambiguity for the *jth* satellite in view (with a total of *n* satellites in view) and the nominal phase ambiguity $(N^{j}\lambda)_0$ from the ambiguity for the master satellite. The nominal value of $(N^{j}\lambda)_0$ is determined as each satellite comes into view, and is calculated using the known position $\mathbf{x}_0$ and the WAAS estimate of user clock, *b*. The *n x 1* measurement vector **y** of corrected phase ranges is defined as:

$$\mathbf{y} = \begin{bmatrix} res^{(1)} \\ res^{(2)} \\ \vdots \\ res^{n} \end{bmatrix}$$

where

$$res^j = \phi^j - \left\| \mathbf{X}^j + d\mathbf{X}^j - \mathbf{x}_0 \right\| + (B^j + dB^j) + I^j - T^j - (N^j \lambda)_0$$

ϕ^j, I^j are measured phase range and dual-frequency ionosphere. $\mathbf{X}^j, B^j$ are broadcast values for satellite position and clock. $d\mathbf{X}^j, dB^j, T^j$ are WAAS corrections for satellite position and clock, and troposphere, respectively.

For the purpose of satellite-to-satellite single differencing to remove the user clock, the measurement vector is transformed by creating

$$\mathbf{y}' = \mathbf{W}\mathbf{y}$$

where

$$\mathbf{W} = \begin{bmatrix} -1 & 1 & & 0 \\ -1 & & 1 & \\ \vdots & & & \ddots \\ -1 & 0 & & 1 \end{bmatrix}$$

The first satellite in **y** is thus the master satellite. All of the *n-1* measurement differences in **y'** are referenced to the master satellite.

The state error covariance **P** is initialized at

$$\mathbf{P}(0) = \begin{bmatrix} \varepsilon_{x,0} & & & & & & 0 \\ & \varepsilon_{y,0} & & & & & \\ & & \varepsilon_{z,0} & & & & \\ & & & \varepsilon_{N\lambda,0} & & & \\ & & & & \varepsilon_{N\lambda,0} & & \\ & & & & & \ddots & \\ 0 & & & & & & \varepsilon_{N\lambda,0} \end{bmatrix}$$

The process noise covariance is fixed at

$$\mathbf{Q} = \begin{bmatrix} 0 & & & & & 0 \\ & 0 & & & & \\ & & 0 & & & \\ & & & \varepsilon_B & & \\ & & & & \ddots & \\ 0 & & & & & \varepsilon_B \end{bmatrix}$$

and the measurement noise covariance is fixed at

$$\mathbf{R}' = \mathbf{W}^T \begin{bmatrix} \varepsilon_\phi & & 0 \\ & \ddots & \\ 0 & & \varepsilon_\phi \end{bmatrix} \mathbf{W}$$

For the filter implemented here, $\varepsilon_{x,0} = \varepsilon_{y,0} = \varepsilon_{z,0} = 9$, $\varepsilon_{N\lambda} = 4$, $\varepsilon_B = 0.0001^2$, and $\varepsilon_\phi = 0.05^2$.

The measurement transformation matrix **H** is constructed as

$$\mathbf{H} = \begin{bmatrix} \mathbf{WG} & \mathbf{I} \end{bmatrix}$$

where

$$\mathbf{G} = \begin{bmatrix} (los^{(1)})^T \\ (los^{(2)})^T \\ \vdots \\ (los^{n})^T \end{bmatrix}$$

Finally, the Kalman filter is implemented by resolving the following equations at each epoch:

1. $\mathbf{K} = \mathbf{PH}^T(\mathbf{HPH}^T + \mathbf{R'})$
2. $\mathbf{x}_{k+1} = \mathbf{x}_k + \mathbf{K}(\mathbf{dy'} - \mathbf{Hx}_k)$
3. $\mathbf{P}_k = (\mathbf{I} - \mathbf{KH})\mathbf{P}_k^-$
4. $\mathbf{P}_{k+1} = \mathbf{P}_k + \mathbf{Q}$

Appendix B

F Ratio and Statistical Significance

In experimental studies on human performance, results are commonly reported in a format known as the *F ratio* (in honor of the statistician Sir Ronald Fisher, who developed this approach) (Jaccard and Becker, 1990). The value of the F ratio is calculated from experimental data via an Analysis of Variance (ANOVA) algorithm, described thoroughly in Jaccard and Becker's text (and many other statistics textbooks). The F ratio represents how much the data varies systematically between the sample groups as compared to variability due to random sampling error. Higher values of F (depending on the organization and size of the data samples) reflect increased probability that the groups are different.

Publications often report the F ratio in the following format:

F(*m,n)=ratio*, *probability range*

For example, the results of a comparison of ratings of perceived sweetness between different brands of chocolates might be reported as, "Subjects' who ate the chocolates found the Hershey, Nestle, and See's brands varied significantly in terms of perceived sweetness (F(2,10)=15.03, p<0.01)." Note that the F ratio only reveals that the variance between groups is significant, not which group is better. Comparing mean values for the data in each group indicates relative performance.

An explanation of *m, n, ratio,* and *probability* is as follows (for a "one-way" ANOVA, which is a comparison between only two variables; and a "within-subjects" experiment setup, in which each subject is included in the testing of all groups):

- *m:* This term is called the "degrees of freedom treatment," and has the value *k-1*, where *k* is the total number of groups compared. For example, if three groups of chocolates were compared, *m* would be 2. When experimental display symbologies are compared to a control display symbology, *k* includes the total number tested, control and experimental.
- *n:* This term is called the "degrees of freedom error," and is computed as:

$$n = (k-1)(N-1)$$

  where *k* is the total number of groups, as discussed above, and *N* is the total number of data points in each group. For example, if subjects ate, in total, 6 Hershey chocolates, 6 Nestle chocolates, and 6 See's chocolates, *N* would equal 6, *k* would be 3, and thus, *n* would be 10. *n* is an indication of the total number of data points included in the analysis. As *n* gets very large, the amount of variance required between groups to indicate significant differences gets small.
- *ratio:* This is the F ratio, computed from sums and the sums of squares of the data in the different groups, as shown in the Jaccard and Becker text. Again, as F gets large, depending on the values for *m* and *n,* the variation between groups is more likely systematic.

- *probability range:* Once the values for *F, m,* and *n* are given, the probability that the differences are due to chance, *p,* can be computed. Before the advent of computers, calculating the value of *p* was a chore; thus, researchers typically used tables to determine the range in which *p* fell. This was considered acceptable practice, as typically an approximate value of *p* is enough to determine overall level of significance. Tables for looking up values of *p* from the F ratio can be found in most statistics texts. Statistics software, e.g. available as a toolbox for Matlab™, can directly calculate *p* from the appropriate inputs (in Matlab: `p = 1 - fcdf(ratio,m,n)`).

In summary, *m* provides a verification of the number of groups compared (in most cases, this should be apparent in the description of the experiment). *n* reveals the size, and thus the statistical power, of the sample data. The F ratio is printed in case the reader chooses to calculate an exact value for *p* based on *F, m,* and *n*. Finally, *p* indicates how significant the data results are. If $p<0.1$, the results are considered somewhat significant. If $p<0.01$, the results are statistically significant and should be considered meaningful.

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