# Flight Testing WAAS for Use in Closely Spaced Parallel Approaches

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## ABSTRACT

In good weather, San Francisco International Airport can support approximately 60 landings per hour on its two parallel runways which are 750 ft apart; however, current navigation and surveillance systems lack the accuracy required for two aircraft to fly through clouds in such close proximity. During even fairly benign instrument meteorological conditions, the airport degrades to a one-runway operation, the landing rate drops to 30 per hour, an airborne traffic jam ensues, and many passengers become restless.

The inadequacy of today's Instrument Landing System (ILS) for this task is due to the angular nature of its radio beam, typically 3 to 6 deg wide. Farther away from the runway, the resolution of the aircraft's absolute position accuracy degrades; for landings on parallel runways, the two ILS approach beams will eventually overlap somewhere on the approach. Special equipment and procedures can allow parallel instrument approaches to runways as little as 3400 ft apart; however, these solutions are expensive and are not applicable to airports such as San Francisco with 750 ft runway spacing.

GPS positioning from the Wide Area Augmentation System (WAAS) can be used to create straight instrument approach corridors that are free of the angular dependence of ILS. These high-accuracy parallel approaches do not overlap and navigational separation is possible, even far from touchdown. A prototype WAAS-based avionics suite was built at Stanford University and flight tested at Moffett Federal Airfield in the fall of 1998 onboard a Beechcraft Queen Air. Pilots flew 27 approaches using the needle-based Course Deviation Indicator (CDI) as well as a 3-D "tunnel-in-the-sky" display. Data was gathered on flight technical error (FTE), the pilot's guidance-following accuracy and navigation sensor error (NSE), the accuracy of the WAAS-derived guidance. Pilots flew the WAAS-based corridor approaches with less deviation from centerline than that of the ILS approaches. Additional data shows that using a tunnel-in-the-sky display dramatically reduced FTE both horizontally and vertically. Finally, statistical models were generated for both horizontal and vertical FTE that may be used in computational models of aircraft approach trajectories.

## INTRODUCTION

Flying into San Francisco (SFO) on a sunny day, one can look out the aircraft window and see another airline's jet a short distance away, flying a parallel approach into either runway 28L or 28R. Since the pilots can see each other as well as the airport, this procedure is perfectly safe and enables SFO to land approximately 60 airplanes an hour. Bring in a layer of clouds at 3000 feet, though, and SFO reverts to single runway operations and the landing rate halves. This illustrates one of the major problems facing airports today: the inability to maintain high aircraft landing rates during cloudy weather. At airports such as Newark, NJ and Chicago's O'Hare International, slowdowns in landing rates affect the entire country. While myriad reasons exist for the variation in landing rates at different airports, one of the primary reasons for reduced landing rates at airports such as San Francisco, Seattle, Atlanta, Boston, and Memphis during instrument meteorological conditions (IMC) is the changeover from independent, dual runway operations to dependent, dual or single runway operations.

## DUAL RUNWAY OPERATIONS

During visual meteorological conditions (VMC), the Federal Aviation Administration (FAA) permits approaches to be conducted under a "see and avoid" criteria. Separation responsibility in the landing pattern shifts from the controllers to the pilots and simultaneous landings on parallel runways may be conducted at airports with runway separations as small as 700 ft; however, during IMC, the controllers are responsible to ensure safe separation between aircraft that may not be able to visually acquire each other. Currently, runways must be 4300 ft apart in order to conduct independent parallel approaches under IMC. At airports with runways between 4300 and 3000 ft apart, dependent parallel approaches may be conducted with a diagonal spacing of 2 and 3 nm, respectively, between aircraft landing on different runways. Airports with runways separated by less than 2500 are driven by the wake vortex hazard and limited to essentially single runway operations during IMC (ref 1).

The separation criteria are driven primarily by the accuracy of the Airport Surveillance Radar (ASR-7/ASR-9) and its 4.8 sec update rate. Based on data gathered at SFO in 1990 with the ASR-7 monitoring approaches, at 10 nm from the runway threshold an aircraft's position may be determined within a box 360 ft along track and 374 ft crosstrack. These numbers are heavily dependent on radar location with respect to the runway (ref 2). An even larger concern, though, is the 1000 ft an airplane travels between radar updates and the 2000 ft it would travel if an update was missed. This delay in the system means that an aircraft could blunder toward the flight path of a neighboring aircraft and controllers might not realize it until almost 10 sec later. With the close spacing of parallel approaches, it is not difficult to envision a scenario where the midair collision is a real possibility.

The FAA realized the shortcoming of the ASR-9 in providing coverage for closely spaced parallel runways and initiated the Precision Runway Monitor program. The result of this effort was the PRM electronically scanned radar with an update rate of 1.0 sec and azimuth errors of one mrad, one-third that of the ASR-9. In addition to more precise sensing, a new final monitor controller position was created with the sole responsibility of monitoring the two airplanes on approach and broadcasting a warning and instructions to off-course aircraft. Based on Lincoln Laboratory analyses and testing of this new radar and the new procedures at Memphis (ref 3), simultaneous independent approaches in IMC may be performed on runways with a 3400 ft separation. The PRM is now installed at two airports, Minneapolis-St. Paul and St. Louis Lambert Field, and is scheduled to be installed at three more, New York's JFK, Atlanta, and Philadelphia airports (ref 4). San Francisco is also scheduled to have a PRM installed in order to reduce the ceilings at which visual approaches may continue to be conducted. Ref. 5 contains a more detailed comparison of Air Traffic Control radar characteristics.

With FAA support, NASA is exploring ways to increase airport capacity through its Terminal Area Productivity program (ref 6). Two subprograms of TAP are the Airborne Information for Lateral Spacing (ref 7) and the Closely Spaced Parallel Approach (ref 8) programs. Together with RTCA SC-186, working group 1, these programs are investigating technical issues and air traffic control procedures that would enable simultaneous parallel approaches to runways with spacing less than 4300 ft. One particular area of ongoing research is the alerting algorithms and aircraft procedures for the case of aircraft blundering while executing a parallel approach (refs 9, 10)

## THE INSTRUMENT LANDING SYSTEM (ILS)

In addition to the errors associated with the surveillance sensor, today's precision navigation system itself does not support closely spaced parallel approaches. The inadequacy of the Instrument Landing System (ILS) for this task is due to the angular nature of its radio beam, typically 3 to 6 deg wide horizontally and 1.4 deg wide vertically. These maximum angular deviations are what results in a full-scale needle deflection on the CDI. During an approach, if the pilot exceeds a full scale needle deflection, he or she must abort the procedure and execute a missed approach. The ILS consists of two components: the localizer beam for horizontal guidance and the glideslope beam for vertical guidance. The localizer transmits in the 108.10 to 111.95 MHz range while the glideslope transmits in the 329.15 to 335 MHz range. (refs 11 and 12). As a result of the angular guidance, the further the aircraft is from the runway, the lower the position resolution for a given aircraft's Course Deviation Indicator (CDI) needle deflection. As illustrated in figure (1) for landings on parallel runways, the localizer beams of each runway will eventually overlap somewhere on the approach. For instance, if the runways were separated by 750 ft, the overlap at full CDI needle deflection would occur 1.2 nm from the threshold. If the pilot was flying a “good” one-dot approach, the overlap would occur approximately 6 nm from the threshold.


Figure 1: Angular Approaches

## GLOBAL POSITIONING SYSTEM (GPS) BASED GUIDANCE FOR PARALLEL APPROACHES

Given the need for completely separate, non-overlapping approaches to parallel runways, the ideal approach path would be a constant width corridor extending five or more miles from the runway threshold, as illustrated in figure (2). Augmented GPS position from the future Wide Area Augmentation System (WAAS) can be used to create these straight instrument approach corridors that are free of the angular dependence of ILS. These high-accuracy parallel approaches do not overlap and navigational separation is possible, even far from touchdown. Current non-precision approach certified TSO C129 GPS receivers can also generate constant width approaches, such as the Apollo GX60 (ref 13). While these receivers do not provide the precision approach capability that WAAS will, they are excellent examples of the flexibility that GPS offers in creating instrument approach paths.

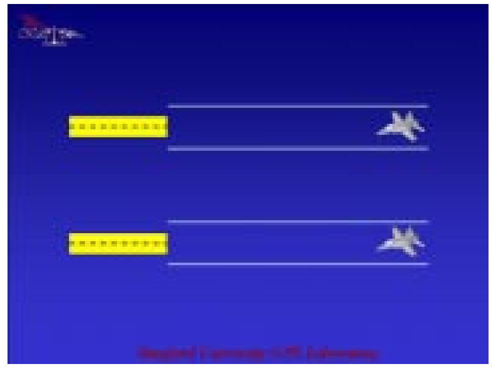

Figure 2: Corridor Approach

## PLANNED FAA WAAS PRECISION APPROACH PROFILE

The WAAS Minimum Operational Performance Specification (MOPS) contains a normal WAAS precision approach and a Vector To Final (VTF) approach. The inbound approach for each begins with a corridor +/- 1 nm wide horizontally for glideslope intercept. The normal approach then angles down from +/- 1 nm to +/- 0.3 nm at the Final Approach Waypoint (FAWP) over the course of 2 nm and then proceeds at a 2 deg half angle to the runway. The VTF approach does not have the intermediate step from 1 nm to 0.3 nm, but transitions directly from +/- 1 nm to a 2 deg angular approach just prior to the FAWP. Figure (3) illustrates each of these approaches (ref 14). Note that these approaches were designed to emulate existing ILS approaches.

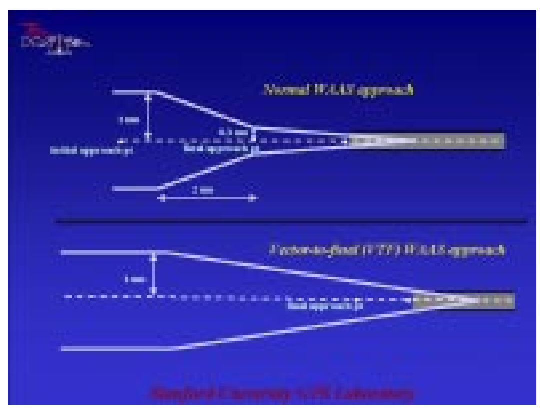


Figure 3: WAAS MOPS Approaches

## TRANSITIONING FROM ANGULAR TO CORRIDOR APPROACHES

In determining the viability of WAAS for precision approaches to parallel runways, one must understand and quantify the errors associated with flying both an ILS and WAAS approaches. Given this data, one may then model a "typical" ILS approach, compare it with a "typical" WAAS approach, and determine if using the corridor type of approach will enable parallel approaches and, if so, how closely the runways may be spaced. The primary errors to be quantified are navigation sensor error (NSE) and flight technical error (FTE) which combine to make total system error (TSE). Navigation sensor error is the difference between the actual and measured aircraft position in space. Flight technical error is a measure of how well the pilot or autopilot follows the indicated path through space. NSE is solely a function of one's navigation system while FTE is primarily a function of the pilot or autopilot. Figure (4) is a pictorial representation of these errors.

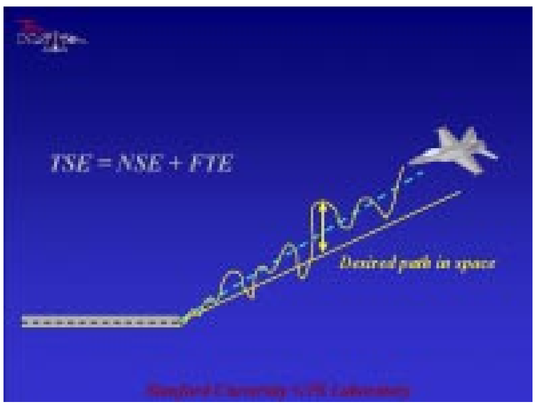


Figure 4: Total System Error

In order to gather actual FTE for differential GPS-based, constant width approaches, Stanford University created a WAAS-based precision approach to Moffett Field in the fall of 1998 and flew multiple approaches aboard a Beechcraft Queen Air.

**WAAS ACCURACY**

The goal of these flight tests was to gather enough data on various kinds of approaches to model the characteristics of each with respect to FTE. Unfortunately, it is very difficult to gather a statistically significant number of approaches to account for all variables; however, the data gathered does give useful insight into the basic trends of FTE for various types of approaches. Using a carrier-smoothed, double difference, GPS code phase technique with the Stanford reference station as "truth", NSE was determined to be approximately three meters for the approaches, effectively making FTE the primary error source of TSE. The two-dimensional histogram in figure (5) shows the results of 1.3 hours of WAAS flight test positioning. The accuracy of the position solution is given along the horizontal axis and the vertical axis reports the Horizontal Protection Level (HPL) which is the confidence bound on the position accuracy.

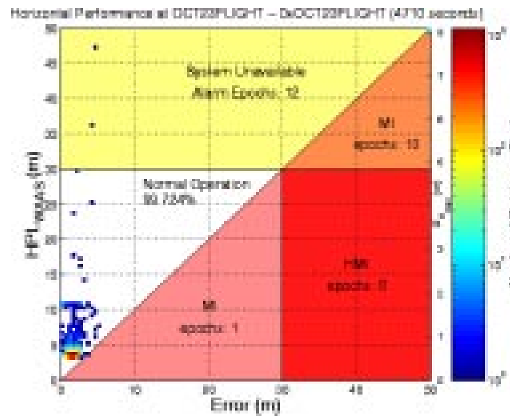


Figure 5: Horizontal WAAS Accuracy During First Flight Test, 10-23-98. Horizontal axis is actual WAAS error measured by code phase DGPS from the Stanford reference station.

**TYPE OF APPROACHES AND DISPLAYS**

Novel display concepts have been investigated for several decades as a means of enhancing piloting accuracy and situational awareness of position, flight path, and terrain in three dimensions. One of the most promising is the Tunnel-in-the-Sky primary flight display, which presents a three-dimensional "out the window" depiction of the world with the desired flight path shown as a tunnel or series of hoops. The high cost of integrated sensors, displays, and computing power has hampered development of the technology. However, the emerging technologies of GPS, active matrix liquid crystal displays, and embedded computers are changing this situation rapidly. Stanford University has developed a prototype system to explore the real-world implications of the Tunnel-in-the-Sky display concept. With this display, shown below in figure (7), the pilot uses simplified guidance symbology to fly the aircraft through the displayed tunnel. Iterative refinement and several years of flight testing on light aircraft have yielded compelling results for accuracy, situational awareness, and operational flexibility (ref 15).

The flight test experiments were designed to test two primary variables: (1) whether the approach was angular or constant width and (2) whether a traditional CDI with needles or a tunnel in the sky was presented to the pilot for guidance symbology. Four types of approaches were conducted: 1) angular ILS with the CDI, 2) angular WAAS that closely approximated the Moffett Field ILS parameters with the CDI, 3) constant width corridor with WAAS and the CDI, and 4) constant width corridor WAAS with a tunnel in the sky display. The displays are presented in figures (6) and (7). The location of the display in the cockpit is presented in figure (8)..

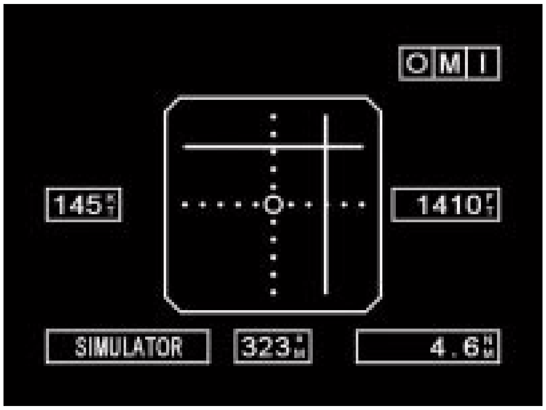


Figure 6: CDI Needles Display, Used in WAAS Corridor and WAAS Angular Approaches


Figure 7: Tunnel in the Sky Display

Figure 8: Queen Air cockpit - note LCD on left side

Four flight tests occurred on Oct. 23, 26, Nov. 28, and Dec. 13, 1998 at Moffett Field, California. A total of 27 approaches were flown with a detailed summary of the flights presented at the conclusion of the paper in Table 23. Pilot #1 was a commercial pilot with 3500 hours total flight time while pilot #2 was a former military pilot with an ATP rating and 1600 hours total flight time.

**APPROACH SPECIFICATIONS**

The ILS approach at Moffett has been decommissioned since the flight tests, but had a 3 deg glideslope and 3 deg localizer half angle. Width of the localizer at runway threshold was 700 ft. The glideslope antenna was located at the aimpoint and had a 0.7 deg half angle.

The WAAS angular approach imitated the ILS approach with a 3 deg glideslope and a 3 deg half angle localizer. Width of the localizer at runway threshold was 700 ft.

The WAAS corridor approach with the tunnel-in-the-sky display had a glideslope of 3 deg and tunnel dimensions 100 m wide by 60 m high for the entire approach.

The WAAS corridor approach with CDI needles imitated the tunnel-in-the-sky dimensions so that direct comparison might be made with the tunnel. For the entire approach, the corridor was 100m (328 ft) wide by 60m (197 ft) high at full needle deflection. Note that the 328 ft width is half that of the ILS width at the runway threshold. Thus, the sensitivity of the CDI needles was twice that of an ordinary ILS at decision height, requiring the pilots to fly very precise approaches. This is also true of the WAAS tunnel-in-the-sky approaches.

For the majority of the flights, in order to capture the glideslope, the tunnel was displayed to the pilot until the approach was established at approximately 10nm. At that point, if the ILS was being flown, the display was covered and the GPS-driven horizontal situation indicator (HSI) was turned off. If a WAAS approach was being flown, the ILS and HSI were not used. The pilot flew from the left seat and wore foggles until decision height, at which point he removed the foggles and executed either a touch and go or low approach. A safety pilot occupied the right seat. All of the approaches were performed in VFR conditions, with varying wind and turbulence levels. The airplane was flown with gear down and at 100 to 130 kts ground speed. Roll, pitch and yaw were provided to the WAAS display from a Trimble TANS-based short-baseline, GPS attitude system (ref 16). There is no autopilot on the Queen Air.

## RESULTS OF ANGULAR VERSUS CORRIDOR APPROACHES

Data from the ILS and WAAS angular approaches were combined to form one data set while the WAAS corridor approaches flown with reference to the CDI needles and WAAS corridor approaches flown with reference to the tunnel in the sky display formed comparison data sets. Figures (9) to (11) present the time histories of horizontal FTE for ILS and WAAS angular, WAAS corridor with CDI needles, and tunnel in the sky approaches, beginning 10 nm from the runway. Note that the vertical scales are identical for all three plots. Plots of vertical FTE about the glideslope are presented at the end of the paper.

The time histories were converted into histogram form in order to look at the distribution of FTE and its standard deviations. Figures (12) to (14) present histograms corresponding to the time histories in figures (9) to (11), which show nine, ten, and four approaches, respectively. Also shown is the best-fit Gaussian distribution. The data begins at 10 nm from the runway and is truncated at 0.5 nm from the threshold, which corresponds to when the pilot transitioned from simulated instrument to visual flight.

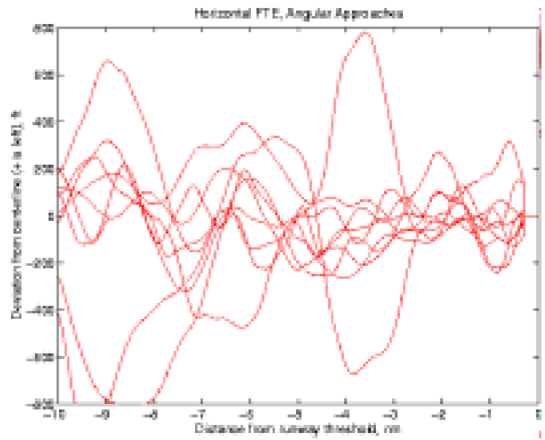

Figure 9: Horizontal FTE, ILS and WAAS Angular Approaches. Runway is at zero on horizontal axis.

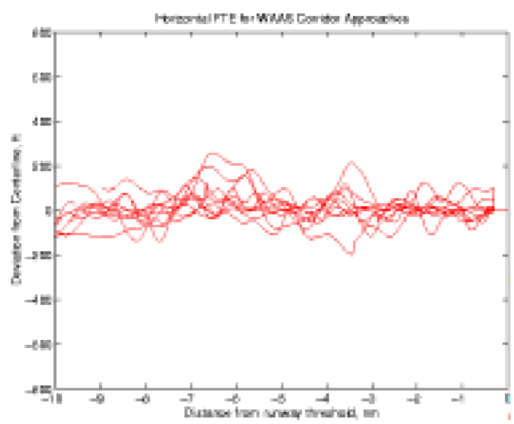

Figure 10: Horizontal FTE for WAAS Corridor Approaches

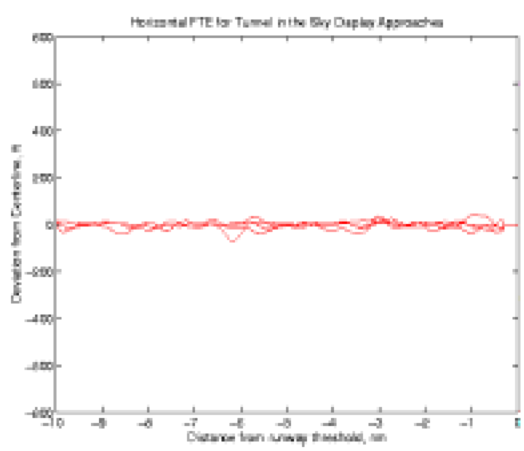

Figure 11: Horizontal FTE for the Tunnel in the Sky Display Approaches

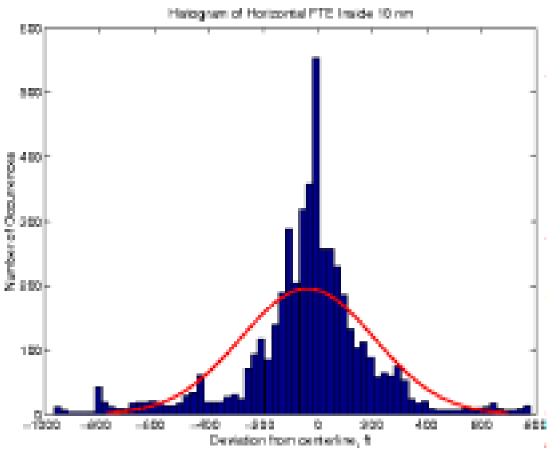

Figure 12: Histogram for Horizontal FTE, ILS and WAAS Angular Approaches from 10 nm

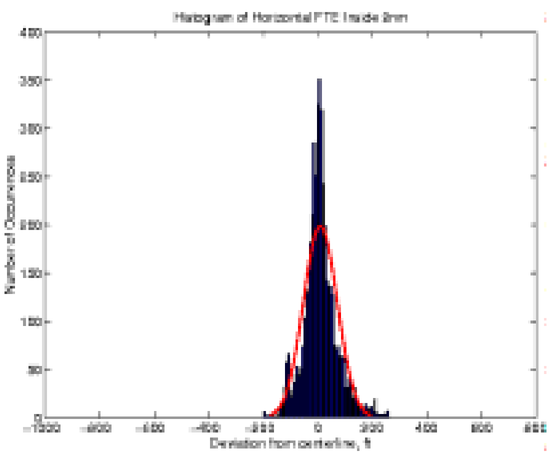

Figure 13: Histogram for Horizontal FTE, WAAS Corridor

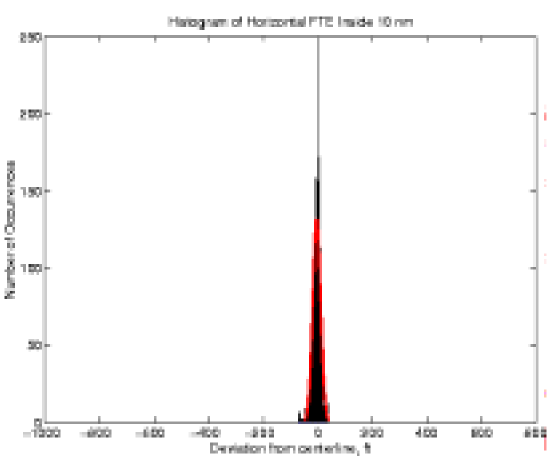

Figure 14: Histogram for Horizontal FTE, WAAS Tunnel in the Sky

Since the data is not truly gaussian, pseudo standard deviations were generated for each data set by a counting technique. Each data point was assigned to a particular bin. After all data points were binned, the FTE was taken from the bins, counting out from zero on the histogram, that contained the 68$^{th}$ and 95$^{th}$ percentile data points. The FTEs in these bins bound 68 and 95 percent, respectively, of the other data points. Since the WAAS corridor and tunnel approach path widths are not a function of distance from the runway, composite statistics may be formed starting 10 nm from the threshold. The width of an angular approach is indeed a function of distance, so pseudo standard deviations were calculated for one nm increments. Tables 15 and 16 present the 68th and 95th percentile horizontal and vertical FTEs as well as the first standard deviation and mean from the best fit gaussian distribution for the WAAS corridor, tunnel and angular approaches.

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**Table 15:** . Composite FTE standard deviations for WAAS Approaches, 10nm to 0.5nm from threshold (ft)

| NM from runway | 68th/ 95th horz | Gauss 1 σ, horz | mean horz | 68th/ 95th vert | Gauss 1 σ, vert | mean, vert |
|---|---|---|---|---|---|---|
| Corridor | 49/ 129 | 62 | 10 | 28/ 94 | 46 | -6 |
| Tunnel | 10/ 32 | 15 | 3 | 13/ 33 | 14 | -10 |

**Table 16:** . Incremental FTE standard deviations for Angular Approaches, 10nm to 0.5nm from threshold (ft)

| NM from runway | 68th/ 95th horz | Gauss 1 σ, horz | mean horz | 68th/ 95th vert | Gauss 1 σ, vert | mean, vert |
|---|---|---|---|---|---|---|
| 10-9 | 269/ 875 | 375 | 38 | 94/ 284 | 106 | 68 |
| 9-8 | 314/ 802 | 374 | 25 | 141/ 321 | 129 | 57 |
| 8-7 | 267/ 569 | 224 | 159 | 136/ 276 | 126 | 36 |
| 7-6 | 195/ 447 | 221 | 6 | 89/ 229 | 109 | 19 |
| 6-5 | 186/ 344 | 183 | 8 | 73/ 223 | 108 | 8 |
| 5-4 | 191/ 499 | 198 | 70 | 57/ 279 | 111 | 22 |
| 4-3 | 191/ 719 | 323 | 45 | 50/ 200 | 91 | 19 |

**Table 16:** . Incremental FTE standard deviations for Angular Approaches, 10nm to 0.5nm from threshold (ft)

| NM from run-way | 68th/ 95th horz | Gauss 1 σ, horz | mean horz | 68th/ 95th vert | Gauss 1 σ, vert | mean, vert |
|---|---|---|---|---|---|---|
| 3-2 | 88/ 264 | 114 | 13 | 50/ 138 | 55 | 16 |
| 2-0.5 | 79/ 217 | 100 | 8 | 37/ 69 | 30 | 17 |

## DISCUSSION OF ANGULAR VS. CORRIDOR APPROACH RESULTS

In order to determine the error associated with modeling the FTE of angular approaches as a gaussian distribution, figure (17) presents plots of the 68th percentile FTE and the best fit gaussian one sigma value. The gaussian is generally more conservative than the actual data, so modeling FTE in this way will result in more conservative separation distances between airplanes.

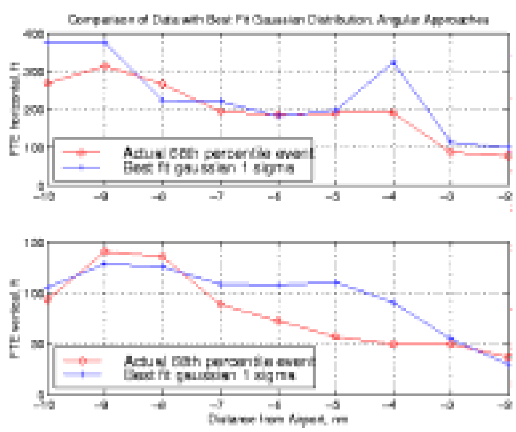


Figure 17: Actual vs. best fit Gaussian 1-sigma standard deviations of FTE

It should also be noted that the resolution of an ILS increases as the airplane nears the runway, so one would expect a decrease in standard deviation. Figure 18 plots Table 16, the pseudo standard deviations. As expected, the FTE on the ILS decreases markedly with proximity to the airport; however, one notices a spike at 4 nm. Given that only nine data sets were used to generate the distribution, even one larger than average FTE can heavily influence the standard deviations. This curve should smooth with a larger data set.

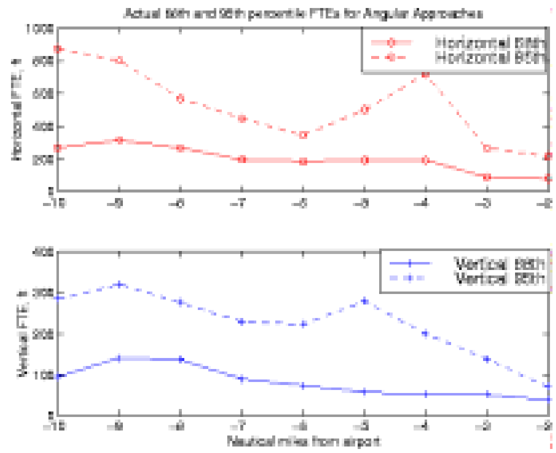


Figure 18: Standard Deviation as a Function of Distance to the Runway, Angular Approaches

For corridor approaches, one would expect integrated standard deviation over time to be constant. Figure (19) shows that while this is true for the tunnel in the sky display, there is a trend, albeit slight, toward decreased FTE as the distance to the runway decreases when flying with reference to the CDI. It is speculated that this trend is related to a settling time undergone by the pilot after establishing on the approach. It appears to take a finite amount of time for the pilot to adjust himself to the control inputs necessary to maintain a tight track. This may be related to wind compensation or may be solely a function of transitioning from en-route to approach flight techniques.

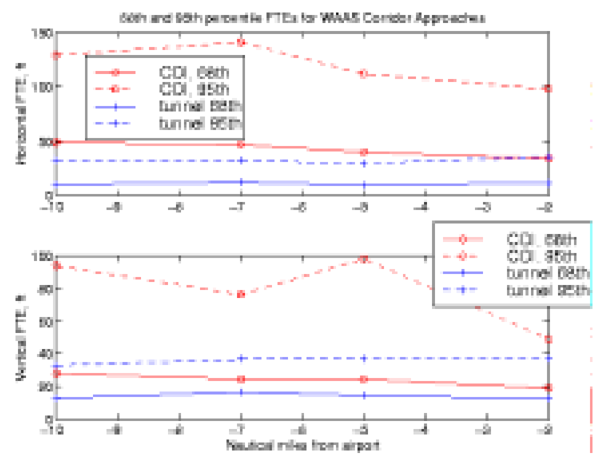


Figure 19: 68th and 95th Percentile Events of Corridor Approaches Using CDI Needles or Tunnel in the Sky

The dimensions of the defined path through space were identical for the tunnel-in-the-sky and the CDI needles. The only difference was the pilot display. As can be noted from figures (11), (14) and (19), the tunnel in the sky enables the pilot to fly a more precise glideslope and localizer throughout the entire approach. The flight observer also noted that the tunnel greatly reduced the input frequency of corrections, thus reducing pilot workload. The human/machine interface of the tunnel appears to be much more intuitive than the CDI and the FTE bears out this result (ref 17).

## ANALYSIS OF RUNWAY SPACING CRITERIA

Based on (ref 1), the 4300 ft of required runway separation for independent parallel approaches in IMC is made up of the following components:

| | |
|---|---|
| Normal Operating Zone: | 1150 ft |
| Detection Zone: | 900 ft |
| Delay Time: | 1000 ft |
| Correction Zone: | 600 ft |
| Miss Distance: | 200 ft |
| Navigation Buffer: | 450 ft |
| **Total:** | **4300 ft** |

The components of interest for this flight test are the Normal Operating Zone (NOZ) and the Navigation Buffer (NB). The NOZ is composed of TSE and radar surveillance resolution while the NB accounts for TSE of the second aircraft on the adjacent approach. The airspeed of the blundering aircraft was assumed to be 150 kts with an intrusion angle of 30 deg.

Based on the results of these flight tests (Table 15) and analyses performed in (ref 18), using WAAS and the tunnel in the sky display, the following revisions are possible:

| | |
|---|---|
| Normal Operating Zone: | 300 ft |
| Detection Zone: | 900 ft |
| Delay Time: | 1000 ft |
| Correction Zone: | 600 ft |
| Miss Distance: | 200 ft |
| Navigation Buffer: | 100 ft |
| **Total:** | **3100 ft** |

Further reductions may be anticipated in the Correction Zone, Detection Zone and Delay Time, depending on the implementation of ADS-B and the development of alerting algorithms. Additional issues regarding Air Traffic Control and pilot responsibilities would also have to be addressed.

## CONCLUSIONS

Flight Technical Error data were gathered for 27 hand-flown approaches in a Beechcraft Queen Air during the fall of 1998. Approach paths included the standard ILS, a WAAS approach emulating the ILS, and straight, WAAS-guided corridor approaches. Pilot interface included the standard CDI needles and a tunnel in the sky display. Overall, pilots flew the corridor approaches more precisely than the ILS. Since the WAAS corridor approaches do not have an angular dependence, this type of approach path would be suitable for closely spaced parallel approaches. Using the presented FTE and the NSE specified for WAAS, simulation studies may be performed that will determine the efficacy of using WAAS-based corridor approaches for parallel runways. Using WAAS with the tunnel-in-the-sky display, the required distance between runways for independent parallel approaches during IMC may be significantly decreased without decreasing safety.

## ACKNOWLEDGEMENTS

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(11) FAA’s Airman’s Information Manual web site: www.faa.gov/ATPubs/AIM/P0101009.HTM

(12) SC-153, “Minimum Operational Performance Standards for Airborne ILS Localizer Receiving Equipment Operating Within the Radio Frequency Range of 108-112 MHz,” RTCA/DO-195,November 1986.

(13) UPS Aviaton Technologies web site: www.upsat.com/dwnlds/gxdoc/gx60op.pdf, pg 50

(14) SC-159, “Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System Airborne Equipment,” DO-229A, June 1998.

(15) Barrows, A., Alter, K., Enge, P., Parkinson, B., and Powell, J.D., “Operational Experience with and Improvements to a Tunnel-in-the-Sky Display for Light Aircraft,” Proceedings of the ION GPS-97, Sept. 1997, Kansas City, MO. pp. 791-799.

(16) Hayward, R., Gebre-Egziabher, D., and Powell, J.D., “GPS-Based Attitude for Aircraft,” International Conference on Integrated Navigation Systems, St. Petersburg, Russia, May 1998.

(17) Barrows, A. K., Enge, P., Parkinson, B., and Powell, J.D., “Flying Curved Approaches and Missed Approaches: 3-D Display Trials Onboard a Light Aircraft,” Institute of Navigation GPS Conference, Kansas City, MO, September 1996.

(18) Gazet, R., “Aircraft Surveillance and Collision Avoidance Using GPS,” Ph.D. Dissertation, Stanford University, 1996.

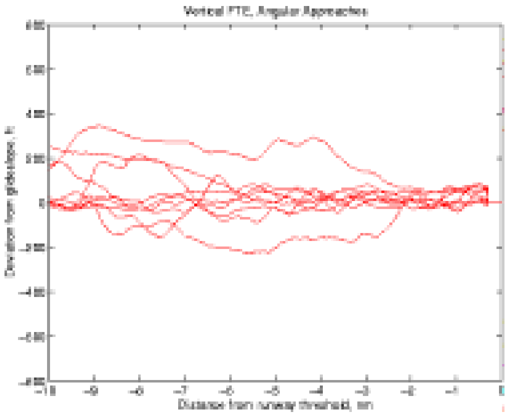


Figure 20: Vertical FTE, Angular Approaches

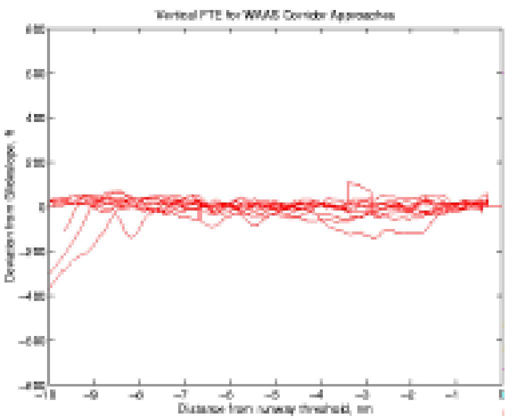


Figure 21: Vertical FTE, WAAS Corridor Approaches with CDI Display

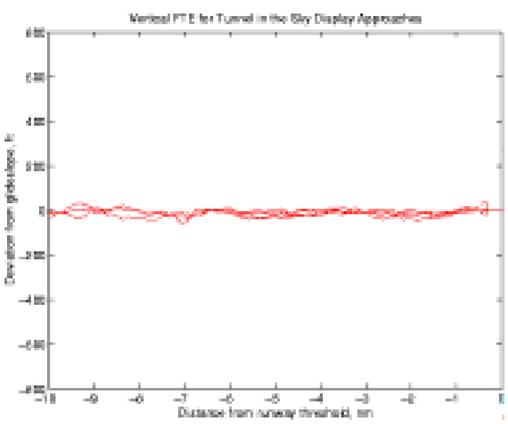


Figure 22: Vertical FTE, WAAS Corridor Approaches with Tunnel in the Sky Display

**Table 23: Summary of Flight Tests**

| Appr No. | Flight No. | Angular | Corridor | ILS | WAAS | CDI | Tunnel | Touch & go | Low approach | Pilot #1 | Pilot #2 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | X | | X | | X | | X | | X | |
| 2 | 1 | X | | X | | X | | X | | X | |
| 3 | 1 | X | | X | | X | | X | | X | |
| 4 | 1 | X | | | X | X | | X | | X | |
| 5 | 1 | X | | | X | X | | X | | X | |
| 6 | 1 | | X | | X | | X | X | | X | |
| 7 | 1 | | X | | X | | X | X | | X | |
| 8 | 2 | X | | X | | X | | X | | X | |
| 9 | 2 | X | | X | | X | | X | | | X |
| 10 | 2 | | X | | X | | X | X | | X | |
| 11 | 2 | | X | | X | | X | X | | | X |
| 12 | 2 | X | | | X | X | | X | | X | |
| 13 | 2 | X | | | X | X | | X | | X | |
| 14 | 2 | X | | | X | X | | X | | | X |
| 15 | 3 | | X | | X | X | | X | | X | |
| 16 | 3 | | X | | X | X | | X | | X | |
| 17 | 3 | | X | | X | X | | X | | X | |
| 18 | 3 | | X | | X | X | | X | | X | |
| 19 | 3 | | X | | X | X | | X | | X | |
| 20 | 3 | | X | | X* | X | | X | | X | |
| 21 | 3 | | X | | X* | X | | X | | X | |
| 22 | 3 | | X | | X* | X | | X | | X | |
| 23 | 4 | | X | | X | X | | X | | X | |
| 24 | 4 | | X | | X | X | | | X | | X |
| 25 | 4 | | X | | X | X | | | X | | X |
| 26 | 4 | | X | | X | X | | | X | | X |
| 27 | 4 | | X | | X | X | | | X | | X |

*Note: Approach used corridor width dimension of 700 ft rather than 328 ft. These data sets were not used in the analysis.