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FLYING A TUNNEL-IN-THE-SKY DISPLAY WITHIN THE CURRENT AIRSPACE SYSTEM

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ABSTRACT

Enhancing aircrew situational awareness has become recognized as a critical element in reduction of overall aircraft accident rates. Improved display concepts have been investigated for several decades as a means of enhancing 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 depiction of the world with the desired flight path shown as a tunnel or series of hoops. A prototype system was developed to explore the real-world implications of the Tunnel-in-the-Sky display concept. This paper documents flight testing on a Beechcraft Queen Air to investigate real-world operations within the current Air Traffic Control system. A series of tunnel "overlay approaches" was designed on top of existing, published instrument procedures to demonstrate advantages for non-precision approaches, closely spaced parallel approaches, and noise abatement. Results indicated an order of magnitude reduction in cumulative flight technical error on approach. The flight tests also showed that Tunnel-in-the-Sky displays could improve aircrew situational awareness and operational flexibility during these flight operations.

INTRODUCTION

Loss of aircrew situational awareness is a contributing factor in accidents across many segments of aviation. In light aircraft, pilots must contend with inadequate currency and confusing, antiquated cockpit instrumentation. Instrument flight in these aircraft is a challenging process of integrating separate information sources to comprehend where the aircraft is and where it is going. Even highly trained crews of well-equipped transport aircraft occasionally lose awareness of the aircraft's position relative to terrain or the desired flight path. Synthesis of this "big picture" is sometimes referred to as "situational awareness" - an understanding of where the aircraft is relative to important features such as desired flight path, terrain, and traffic.

Improved display concepts have been investigated for several decades as a means of enhancing aircrew 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 depiction of the world with the desired flight path shown as a tunnel or series of hoops[1-6]. Most of the work done in this area has focused on large aircraft and laboratory simulation. The attendant high cost of integrated sensors, displays, and computing power has hampered effective commercialization of the technology. However, the emerging technologies of GPS, active matrix liquid crystal displays (AMLCDs), and embeddable computers are changing this situation rapidly.

Stanford University has developed a prototype system to explore real-world implications of flying with a Tunnel-in-the-Sky display. The display is shown in Figure 1 and described in the next section. Iterative refinement through flight testing on light aircraft has ensured that the cost, size, and power factors of larger aircraft are addressed realistically. Several years of research under this *low-cost* and *operationally oriented* paradigm have enabled better

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understanding of many real-world implementation issues. This paper describes recent flight test campaigns in a Beechcraft Queen Air to investigate approach operations within the current Air Traffic Control (ATC) system. A series of tunnel "overlay approaches" was designed on top of existing, published instrument approaches. Each experiment was designed to demonstrate a specific potential benefit of Tunnel-in-the-Sky displays.

DISPLAY DESIGN

Design of the display was a compromise between including enough information for the pilot to perform the flying task and preventing excess clutter. The Tunnel-in-the-Sky display, shown in Figure 1, was designed to aid aircrews by providing an "out the window" view of the world, allowing the horizon, runway, and desired flight path to be seen even in instrument flying conditions. The display presented an artificial horizon along with numerical readouts of groundspeed, heading, and altitude. Raw horizontal and vertical deviation information was displayed on scales similar to the familiar localizer and glideslope needles. The perspective field of view was 40 deg horizontal by 50 deg vertical, with the approach and missed approach paths depicted as a series of 100-m wide by 60-m tall "hoops" spaced at 200-m intervals. Trajectories were stored as sequences of segments with constant turn radius (including straight segments) and constant climb gradient (including constant-altitude flight or descents).

Predictor symbology similar to that used by Grunwald in Reference 7 provided pilot guidance through the tunnel. A "predictor symbol" shaped like a circle with wings displayed the aircraft's predicted position (based on current position, velocity, and lateral acceleration estimated from bank angle) 3.5 sec in the future. Another symbol, the "nominal path symbol," consisted of four tick marks representing the aircraft's desired position in 3.5 sec as if it were flying exactly down the center of the tunnel. The predictor time of 3.5 sec was chosen to suit aircraft dynamics; larger aircraft with slower dynamics would benefit from longer prediction times[7]. From the pilot's point of view, the guidance task was simply to fly the predictor symbol into the center of the four tick marks. This task is very similar to flying with a flight director since the higher derivatives used to drive the predictor symbol

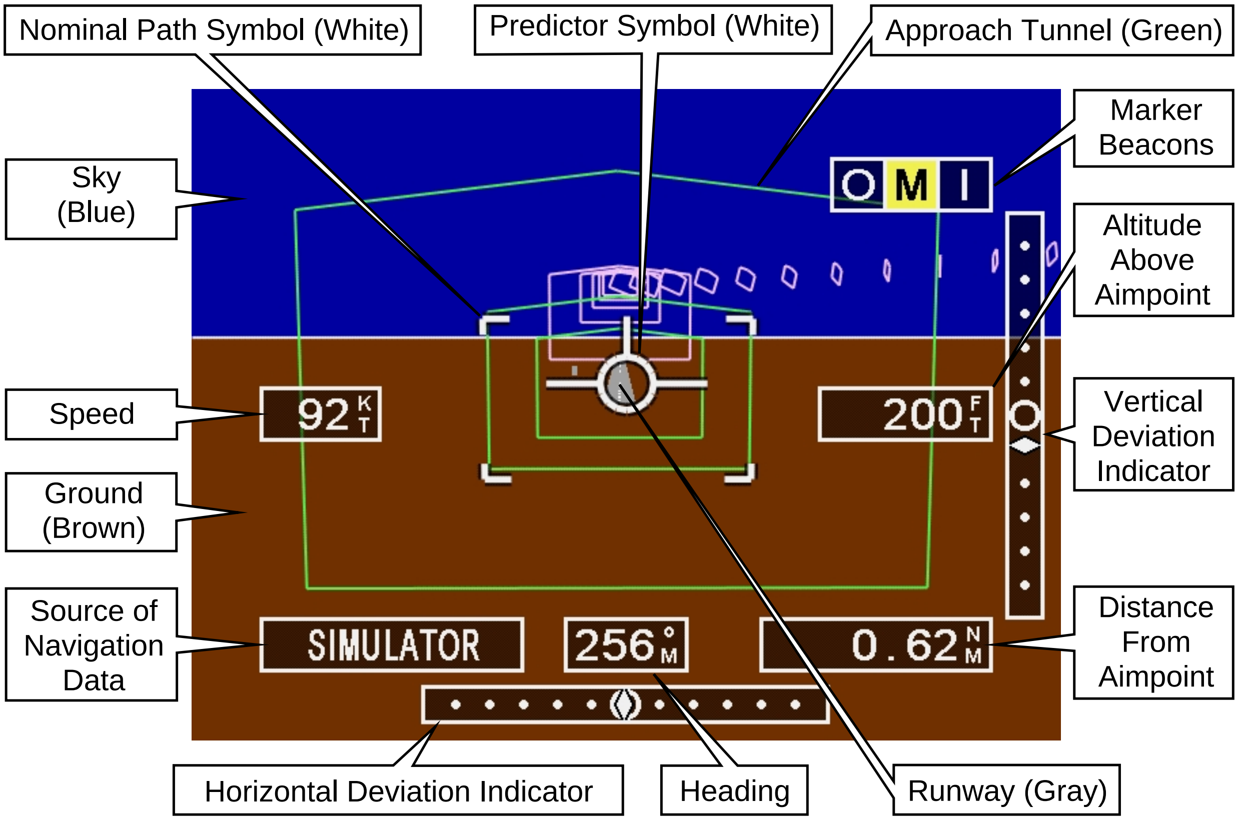

Figure 1 Tunnel-in-the-Sky Display

provide lead compensation. This scheme provided intuitive guidance with the added advantages of trajectory preview and enhanced spatial awareness.

EXPERIMENTAL SETUP

Three-dimensional differential GPS position and velocity data were provided by a Wide Area Augmentation System (WAAS) prototype developed at Stanford University and by a commercial system based on DGPS corrections supplied by United States Coast Guard reference stations. These typically gave claimed 95% vertical accuracy on the order of 2 m[8]. Roll, pitch, and heading information was supplied by a hybrid system combining short-baseline GPS attitude with low-cost inertial sensors[9]. The symbol generator system was based on commodity PC hardware to address the price, form, and power factors associated with small aircraft. All equipment was mounted in a rack onboard the test aircraft. The Tunnel-in-the-Sky was displayed on a sunlight-readable 6.4-inch diagonal AMLCD mounted in the instrument panel to the left of the heading indicator - central enough in the pilot's scan to serve as the primary flight display.

The test aircraft was a 1965 Beechcraft Queen Air, a twin piston engine aircraft capable of carrying two pilots and six passengers. A cruise speed of 160 kts and approach speeds ranging from 120 to 140 kts were typical of flight test operations. Although several pilots have been involved with this continuing research program, one pilot performed all flying presented in this paper. This Commercial Pilot had approximately 3000 hours of flight time. The pilot typically wore view-limiting glasses to simulate instrument flight conditions. All developmental flight testing was flown in visual meteorological conditions with a properly qualified safety pilot in the non-flying pilot's seat. The approaches were hand flown; in fact, the aircraft did not have an autopilot installed. Throughout the process, the display design methodology relied on iterative refinement with pilot feedback from real-world testing. Clearly, the limited number of flight hours and single-pilot nature of these tests indicate that the results presented here are qualitative. It is hoped that resources will be available in the future to conduct a statistically significant, multiple-pilot study.

A staged development program led up to the flight tests described here. Initially, piloted simulation was employed for early pilot input into the display design methodology[10]. Developmental flight testing was performed on a four-seat, single piston engine Piper Dakota and demonstrated capabilities for straight-in and simple curved and segmented approaches. Further testing on the Beechcraft Queen Air expanded the system's capabilities with closed patterns including curved and segmented approaches. Standard visual traffic patterns were also flown by instrument reference to demonstrate the flexibility of the system. The ability of pilots to maintain situational awareness on extremely complex curved paths was verified through GPS-guided skywriting[11].

FLIGHT TEST CAMPAIGN

This paper documents three flight experiments - each intended to demonstrate one aspect in which a perspective display can simplify or improve real-world operations within the current Air Traffic Control (ATC) system. A series of tunnel "overlay approaches" was designed on top of existing, published instrument approaches. Simply flying through the hoops on the Tunnel-in-the-Sky display resulted in approaches that satisfied the horizontal and vertical limitations designated on the published approach plate. From ATC's point of view, the procedures looked like the ones they see every day, although they may have noticed that the pilots flew them more accurately than usual.

An important metric for path-following accuracy on approach is total system error (TSE), the difference between the aircraft's actual position and its desired position at a given time. TSE is a combination of navigation sensor error and flight technical error. Navigation Sensor Error (NSE) is simply the difference between the aircraft's actual position and the position measured by the navigation sensor, and is a function of the navigation equipment both onboard and external to the aircraft. Flight Technical Error (FTE) is the difference between the position measured by the navigation sensor and the desired position. Since the actual "truth" position is not available onboard the aircraft, the best a pilot or autopilot can do is drive FTE to zero. Even in this case, sensor error will likely result in a nonzero TSE. For example, the horizontal and vertical deviation signals generated by a DGPS approach receiver represent FTE. These FTE quantities drive the deviation "needles" seen by the pilot. The NSE (and therefore TSE) is not observable in this case.

Since a "truth" receiver was not available on the flight test aircraft, the quantity measured during flight tests was FTE, not the TSE ultimately desired. However, the DGPS receivers used had specified accuracies on the order of 2 m - smaller than the FTE trends typically observed. Since NSE was presumably smaller than FTE for these DGPS experiments, the observed trends in FTE are a good approximation of total system error behavior.

PRECISION APPROACHES FOR A NON-PRECISION AIRPORT

Controlled Flight into Terrain (CFIT) continues as a major category of air carrier accidents. A well-known CFIT cause is loss of vertical situational awareness on non-precision approaches. The increased (and unnecessary) workload associated with pitch and power changes on non-precision approaches has led to a poor safety record relative to precision approaches. The term “non-precision” typically refers to an instrument approach that lacks positive vertical flightpath guidance. These include localizer (LOC), VHF Omnidirectional Range (VOR), and Non-Directional Beacon (NDB) approaches along with their counterparts aided by Distance Measuring Equipment (DME). A barometric altimeter is used to remain at or above “minimum descent altitude” (MDA) at various points along the approach for terrain and obstruction clearance. Progress along the approach - and also the relevant MDA at each point - is monitored using DME, VOR cross radials, marker beacons, or stopwatch timing. This requires a skilled instrument scan and integration of various information sources to establish vertical situational awareness. In the worst case of pilot failure to integrate this information correctly, the pilot descends below the MDA and strikes terrain. Even highly trained flight crews of transport aircraft have fallen into this CFIT trap. For this experiment, the Tunnel-in-the-Sky display added positive vertical guidance to a non-precision approach to enable long, stabilized descents to the runway or missed approach point.

Existing Published Approach Procedure

The nominal profile for the (non-precision) VOR/DME approach to runway 30 at Palo Alto, California is shown as a dashed trace on Figure 2. The published approach begins with the aircraft outside the San Jose VOR at 3000 feet above mean sea level (ft MSL). As soon as the aircraft passes over the VOR inbound, the pilot can legally descend to the “stepdown altitude” of 1700 ft MSL. Starting this descent requires an aircraft configuration change in power and pitch accompanied by pilot workload (configuration change #1). During the descent, there is no electronic vertical guidance; the altimeter provides the only indication of whether the aircraft is above the relevant MDA. The actual path followed through space depends on descent rate, speed, winds, and aircraft weight. On reaching the MDA of 1700, the pilot must level off (configuration change #2). The aircraft flies inbound level at 1700 ft MSL until 4.5 NM from touchdown (5 NM DME from the San Jose VOR). At this stepdown fix the pilot begins another descent (configuration change #3). The pilot descends to the final MDA of 460 ft MSL and levels out (configuration change #4). Pilots of light aircraft are trained to make a relatively rapid descent to MDA, allowing more time there to visually acquire the runway. Unfortunately, this also increases the chance of descending below the MDA. When the aircraft is finally in a position to make a normal approach to landing, the pilot may descend (configuration change #5) to land on the runway. The timing and altitudes associated with the configuration changes are critical - misinterpreting the correct MDA for the current approach segment can result in flying below the MDA and impacting terrain.

Tunnel Overlay Procedure

To create positive vertical guidance for this approach, a glidepath was extended from the runway touchdown point to the stepdown fix 4.5 NM from touchdown (5 NM DME from the San Jose VOR). This resulted in a glidepath angle of 3.552 deg, close to the standard angle of 3 deg. The glidepath was then extended further back along the approach until reaching 3000 ft MSL, the published initial altitude for the approach. This occurred approximately 8 NM from touchdown. Finally, an initial approach segment was added that crossed San Jose VOR at 3000 ft MSL. The result was a constant precision glidepath that satisfied the minimum altitude requirement at the stepdown fix while avoiding the many configuration changes of the VOR/DME approach.

Results

Figure 2 shows a profile view of the approach flight data. The thick trace shows an approach flown using conventional horizontal deviation needle and altimeter techniques. This conventional approach exhibits transients near the configuration changes while the pilot trimmed the airplane. The apparent descents below MDA are most likely due to altimeter error. (The aircraft never descended below MDA according to the barometric altimeter in the cockpit). By fitting a straight line to the measured ground

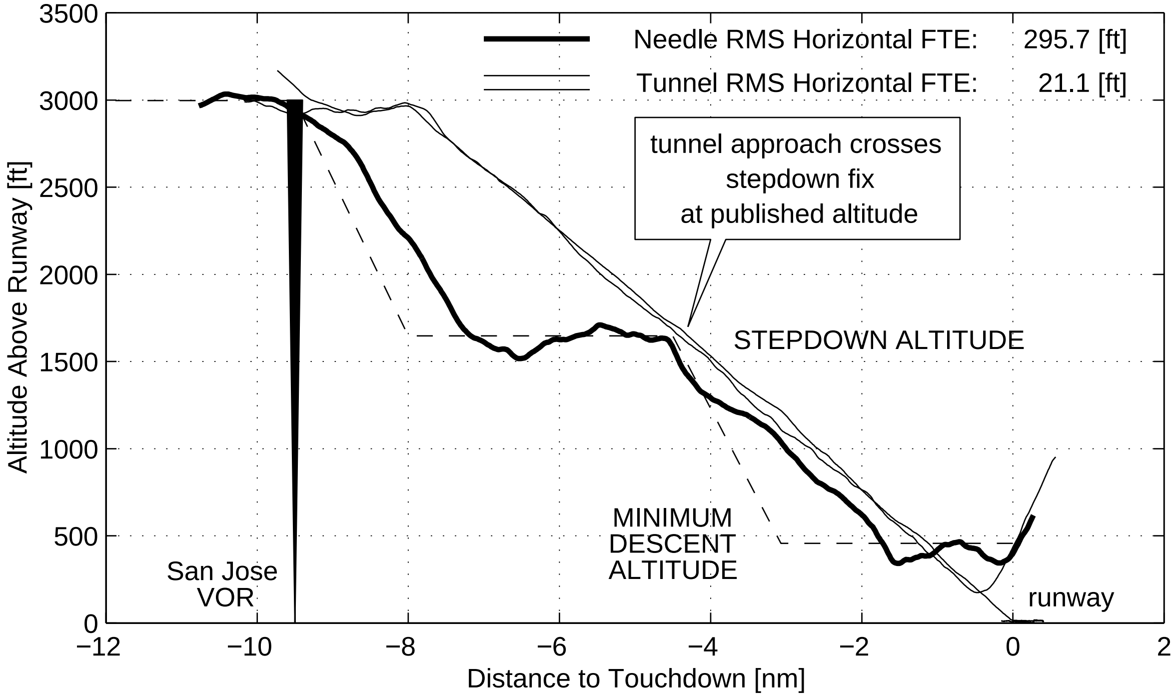

Figure 2 Profile View of Flight Data on Palo Alto VOR/DME Approach

track, approximate horizontal FTE was determined to be 90.1 m root mean square (RMS) (295.7 ft RMS) for the conventionally flown approach.

The two thin traces represent approaches using the Tunnel-in-the-Sky display. These were performed with average horizontal FTE of 6.4 m RMS (21.1 ft RMS) and average vertical FTE of 8.3 m RMS (27.3 ft RMS). Maximum deviations from the tunnel centerline were 16.3 m (53.4 ft) horizontally and 17.4 m (57.1 ft) vertically. Both tunnel approaches clearly followed a long, stabilized descent profile that arrived at the stepdown fix with the desired 1700 ft MSL altitude. The pilot stated (subjectively) that the tunnel approaches were easier to fly than the approaches using VOR needle, DME, and altimeter.

Discussion

A high level of path-following accuracy was achieved with the Tunnel-in-the-Sky display compared to conventional instrumentation. Eliminating unnecessary aircraft configuration changes reduced the inherent workload. This suggests that by using tunnel overlays, the requirements of certified non-precision approaches can be satisfied while providing the safety of precision approaches.

APPROACHES FOR CLOSELY-SPACED PARALLEL RUNWAYS

Simultaneous instrument operations on closely spaced parallel runways are limited by existing communication, navigation, and surveillance systems. The lower limit for runway separation ranges from 2500 to 4300 ft depending on installed equipment and type of operation. This leaves airports with less than 2500 ft of runway separation with no alternative but to revert to inefficient single-runway operations during non-ideal weather conditions. The improved navigation and surveillance capabilities of GPS - combined with improved flight displays that keep aircrews aware of other traffic - may allow for closely spaced parallel approaches (CSPA) even in bad weather. This experiment was intended to demonstrate very accurate lateral approach tracking and situational awareness, two of several capabilities necessary for future instrument CSPA operations.

Existing Published Approach Procedure

The localizer/DME approach to runway 32R at Moffett Federal Airfield, CA uses a radio signal for horizontal guidance and the altimeter to ensure terrain and obstacle clearance. This non-precision approach has three intermediate stepdown altitudes and a final MDA, resulting in *nine* pitch and power configuration changes on a typical approach. (Although a full precision approach existed, only the localizer portion was used.)

Tunnel Overlay Procedure

A tunnel approach was overlaid on the existing approach, with the ground track matching the localizer beam. Although the experiment's emphasis was on lateral tracking, a vertical glidepath angle of 3 deg was added, allowing the pilot to make a single configuration change at 5500 ft to establish a stabilized descent to the runway.

Results

Figure 3 shows an overhead view of the approach flight data. The thick trace portrays an approach made using the conventional localizer needle display. Cumulative FTE was calculated over the approach from 20 NM until approximately 0.7 NM before touchdown. For the conventional approach, large absolute FTE (estimated using the display's DGPS sensor) resulted far from the runway due to the angular nature of the localizer beam. For this approach, cumulative horizontal FTE was 157.6m RMS (517.0 ft RMS).

The thin traces depict three tunnel overlay approaches. The average horizontal FTE using the Tunnel-in-the-Sky display was 7.3 m RMS (23.8 ft RMS), far smaller than that for the conventional approach. The pilot stated that these approaches were very easy to fly.

Discussion

Despite the dramatic difference in FTE using the two displays, the conventional approach was actually flown quite well by the test pilot. The ground track remained almost entirely within a one-dot range of the course deviation indicator (CDI) needle, and thus met the highest standards for certification as an Airline Transport Pilot. The resulting ground track accuracy is well within specifications for certified approaches. Highlighting the disparity in FTE for the two methods could, on one hand, be considered unfair. After all, the pilot did an excellent job flying the approach given the navigation system used. At large distances from the runway, NSE in the localizer beam itself dominates total system error. However, the performance criterion demanded by instrument operations to runways only several hundred feet apart is *total system error*. The very tight horizontal accuracy demonstrated suggests that such a system may have promise in CSPA situations. A perspective display that includes other aircraft via datalink would allow for a presently unavailable degree of traffic awareness during instrument operations. Even on parallel DGPS approaches flown using autopilot, the situational awareness afforded aircrews by a

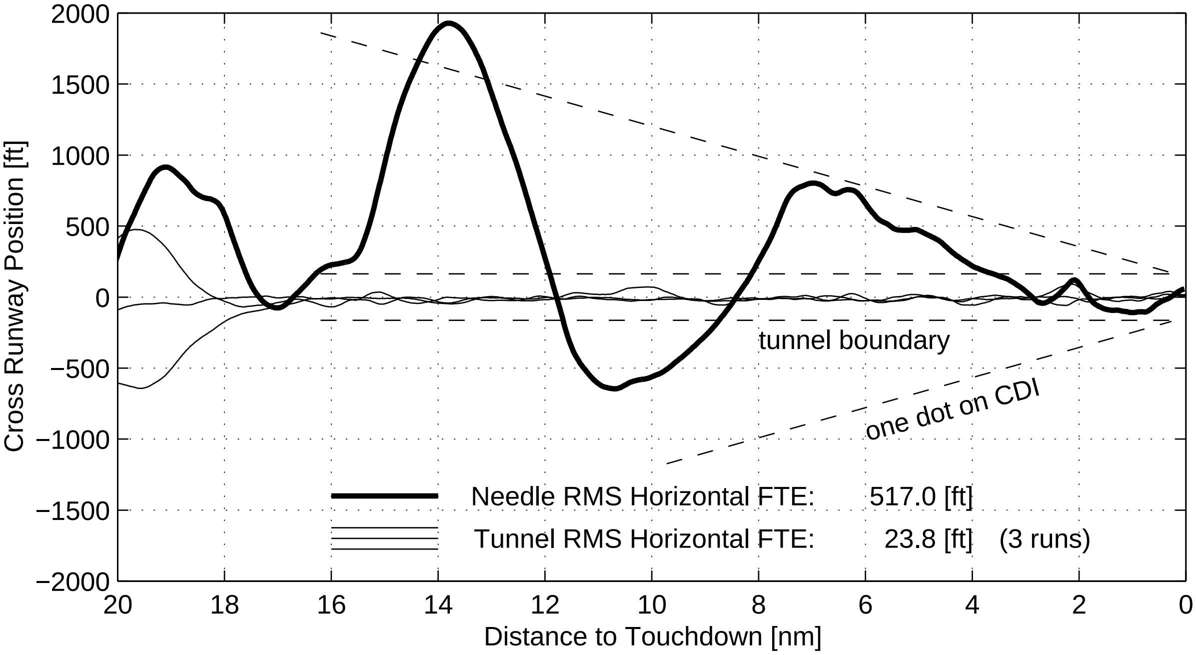

Figure 3 Overhead View of Flight Data on Moffett Field LOC/DME Approach (note exaggerated cross-track scale)

perspective display could be very beneficial. Modeling and display of the other aircraft's probable wake vortex location would address one of the major operational concerns in this area.

NOISE ABATEMENT APPROACHES

Aircraft noise is of continuing concern outside of - and therefore within - the aviation community. The environmental and human impact of aircraft noise will only increase with growth in urban sprawl and air travel. This expensive problem reduces the utility of the world's airports through restrictions on airport development and nighttime operations. Better engine and nacelle design has reduced noise footprints considerably over the last several decades. The ability to fly complex flight paths with precision, both laterally and vertically, can also reduce cumulative noise exposure on the ground. Laterally, the noise footprint can be moved to reduce overflight of the most crowded areas. Flight paths can also be shifted throughout the day to avoid repetitive overflights of the same area. In the vertical dimension, initial approach glidepath angles and power settings can be made more favorable to reducing noise on the ground. Obviously, operational limitations, traffic mix, local conditions, and - above all - safety must be considered before implementing any new capabilities.

One method for reducing noise (and in some cases maintaining terrain clearance) is to fly approaches at glidepath angles steeper than the standard 3 deg. Since the Instrument Landing System (ILS) glideslope is fixed in space, an aircraft equipped only with ILS cannot arbitrarily use an off-nominal glidepath. Some flight management systems found in modern turbine aircraft allow for enhanced vertical flight profiles, but most of these rely on standard displays to establish vertical situational awareness. Unless the system includes a profile display, trajectory preview to allow the pilot to plan ahead is absent. This test was performed to demonstrate the enhanced spatial awareness on steeper-than-normal glidepaths that can be gained using a 3-D perspective display.

Existing Published Approach Procedure

The ILS approach to runway 32R at Moffett Federal Airfield was used as a baseline. This typical approach had a decision height of 250 ft and a 3 deg glideslope.

Tunnel Overlay Procedure

Steep approaches were created that joined a standard 3 deg ILS glideslope close to the runway. Beyond 8 NM from touchdown, each approach descended on a normal 3 deg glideslope as seen on Figure 4. At approximately 7.5 NM from

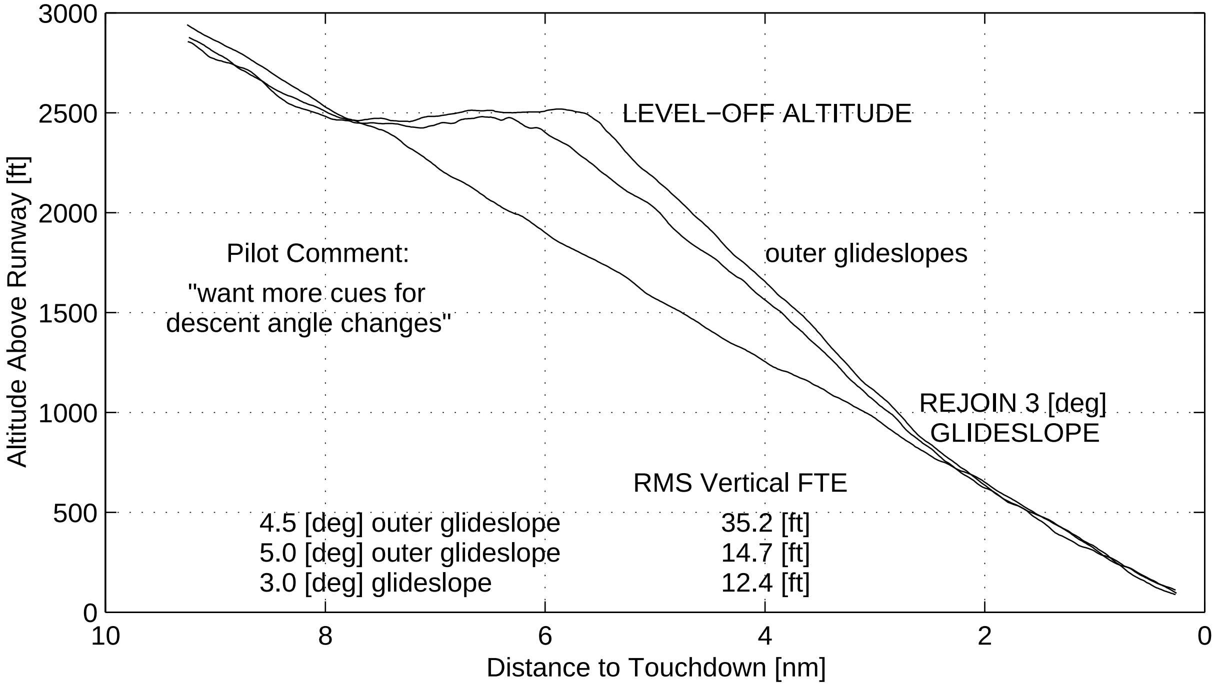

Figure 4 Profile View of Flight Data on Moffett Field Noise-Reducing Approaches

touchdown, the overlaid approach tunnel leveled off at 2500 ft MSL. The approach continued until intersecting a 4.5 deg or 5 deg “outer glideslope.” When this steeper-than-normal glideslope intersected the normal glideslope approximately 2.5 NM from touchdown, the approach tunnel rejoined the 3 deg “inner glideslope.” This enabled the aircraft to remain high and at low power for reduced noise, but permitted a standard stabilized descent during the final 2 NM of the approach. The maximum glideslope for the test aircraft was limited to 5 deg by engine shock cooling considerations.

Results

Figure 4 depicts flight data on these approaches, with an approach flown using the normal 3 deg glideslope displayed for reference. The pilot was able to follow the Tunnel-in-the-Sky display’s vertical guidance with no observed difficulty. The vertical FTE was 10.7 m RMS (35.2 ft RMS) for the 4.5 deg glideslope, 4.5 m RMS (14.7 ft RMS) for the 5.0 deg glideslope, and 3.8 m RMS (12.4 ft RMS) for the normal 3.0 deg glideslope. FTE for the 4.5 deg glideslope may have been highest because it was performed first. (A more complete set of approaches would be needed to compensate for learning effects.) The pilot stated that although it was not difficult to interpret the changes in tunnel slope as they appeared on the display, a stronger cue to these changes would have been useful. For example, a cue 15 sec in advance of the flight path angle changing from level to a 5 deg descent would have helped him plan for changes to flaps, landing gear, and power.

Discussion

The test pilot’s request for stronger vertical cues alludes to one of the accepted advantages of the perspective display - trajectory preview. This is simple to interpret in the case of turns, where the tunnel ahead can be seen turning out the side of the display. But changes in vertical glidepath are evidently not as easily recognized. The design of augmented cues for glidepath angle changes remains a subject of future study. With such cues, enhanced situational awareness on complex noise-abatement approach and departure procedures could prove significant for the air transport industry.

CONCLUSIONS

The flight experiments described here provided qualitative confirmation that *tunnel overlay approaches* can be used to realize benefits within today’s ATC system. Key observations included:

1. The Tunnel-in-the-Sky display allowed for greater path-following accuracy than conventional instruments while reducing subjective pilot workload and increasing perceived situational awareness.
2. Non-precision approaches can be overlaid with precision tunnel approaches to enable long, stabilized descents to the runway. A VOR/DME approach overlaid in this fashion resulted in an order of magnitude decrease in FTE while eliminating unnecessary aircraft configuration changes.
3. Approaches can be flown with a degree of accuracy that could enable bad-weather closely spaced parallel approaches. Cumulative FTE over a long 20 NM final approach was reduced by more than an order of magnitude relative to a conventional needle display. Perspective display of traffic approaching the parallel runway could enhance CSPA situational awareness.
4. Perspective displays may enable situational awareness and accuracy on complex noise-abatement procedures. Vertical guidance on steeper-than-normal approaches allowed the pilot to transition to a standard glideslope on short final approach. Stronger vertical preview cues would aid in aircraft configuration planning during the approach.

This flight test campaign - and those leading up to it - suggest some broader conclusions. To date, the system has been flown by 8 pilots, on 4 different aircraft types, at 7 airports in California and Alaska[12]. 121 instrument approaches (5 of them in instrument meteorological conditions with the ILS being monitored by a safety pilot) have been flown along with 130 complex curved patterns at altitude. Implementation using low-cost technologies and small aircraft suggest that Tunnel-in-the-Sky displays may soon become commercially viable. Pilots learned to fly the system with a minimum of instruction, implying benefits for aircrew training and usability. Flight testing showed that the Tunnel-in-the-Sky display enhanced situational awareness, operational flexibility, and path-following accuracy while reducing subjective workload. Future ATC concepts such as Free Flight can derive safety and operational gains from these aircrew-centered improvements. These advantages will be applicable across a wide spectrum of aviation and can benefit specialized operations such as medivac, search and rescue, military operations, remote sensing, flight inspection, and fire fighting.

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