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Evaluation of Trajectory Errors in an Automated Terminal-Area Environment

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Summary

A piloted simulation experiment was conducted to document the trajectory errors associated with use of an airplane's Flight Management System (FMS) in conjunction with a ground-based Air Traffic Control (ATC) automation system, called CTAS (Center-TRACON (Terminal Radar Approach Control) Automation System) in the terminal area. Integrating the trajectory prediction capabilities of the two automation systems in the terminal area could enable airplanes to fly accurate FMS trajectories that are matched by CTAS-predicted trajectories, resulting in better arrival-time predictions over current-day procedures. This more accurate match could help to implement reduced spacing operations at some of the nation's busiest terminal areas, thereby contributing to capacity increase.

Three different arrival procedures into Dallas Fort Worth International airport (DFW) were compared, beginning at the metering fix and ending at the final approach fix. The three procedures used were current-day (vectors from ATC), modified arrival (using current-day procedures with minor procedure updates), and data link with FMS lateral navigation. All represent current or near-term capabilities, with the data link procedure requiring the most changes to current-day operations. Six active airline pilots flew the simulated arrivals in a fixed-base simulator, and provided subjective comments (in addition to the simulator data collected).

The FMS-datalink procedure resulted in the smallest time and path distance errors, indicating that use of this procedure could reduce the CTAS arrival-time prediction error by approximately half over the current-day procedure. The modified procedure did not result in a substantial improvement in arrival-time accuracy or path distance errors over current-day procedures, but had smaller crosstrack errors. Significant sources of error which contributed to the arrival-time error were crosstrack errors (in particular through the turns to base and final), and early speed reduction in the 2-4 miles prior to the final approach fix. Pilot comments were all very positive, indicating the FMS-datalink procedure was easy to understand and use, and the increased head-down time and workload did not detract from the benefit. Significant issues need to be resolved before this method of operation would be ready for commercial use. These issues include development of procedures acceptable to controllers, changes to procedures to account for speed differences, and certification of FMS database procedures to support the FMS approach transitions.

1. Introduction

1.1 Background

This work was part of the NASA Terminal Area Productivity (TAP) program, which was aimed at increasing capacity in the nation's busiest terminal areas during Instrument Meteorological Conditions (IMC) to levels comparable to those obtained in Visual Meteorological Conditions (VMC). This capacity increase is necessary because of the rapidly expanding volume of air traffic, which is projected to continue to grow. The scope of the TAP program was primarily near-term, thus requiring solutions with current-day technologies. One of the elements within the program is the Reduced Spacing Operations (RSO) element, which seeks to develop technologies and procedures to safely reduce inter-arrival spacing of aircraft. Part of the RSO program involves removing some of the variability in aircraft trajectories by taking advantage of the accurate trajectory following that is possible by using an airplane's Flight Management System (FMS), and interfacing with a ground-based air traffic management automation system called the Center-TRACON Automation System (CTAS). The resulting combination of systems would enable aircraft to fly more accurate, predictable trajectories in terminal area airspace while maintaining required separation and improving throughput.

CTAS is an air traffic management automation system developed at NASA Ames that includes tools to provide sequencing, separation, flow control, and scheduling of airplanes, as well as for computing descent trajectories similar to the FMS-computed trajectories [1]. Atmospheric and airplane performance models are used to obtain better agreement with the FMS trajectories. However, the FMS trajectory is computed with fuel-efficiency in mind, where the CTAS trajectory is computed to reduce system delays while maintaining safe separation standards. To maximize the level at which both of these goals can be achieved, it is necessary for the FMS and CTAS to arrive at a mutually agreeable aircraft trajectory, to best satisfy the constraints. This requires exchanging trajectory, performance, and constraint information between CTAS and the FMS, and developing procedures for the pilot and controller to interface with the FMS and CTAS. It is also necessary to develop supporting charted instrument procedures that can be loaded into the FMS database to allow the aircraft to remain coupled with lateral navigation throughout the arrival.

1.2 CTAS concept

The CTAS program was originally developed as a suite of three main tool sets called Traffic Management Advisor (TMA), Descent Advisor (DA), and Final Approach Spacing Tool (FAST). Each of the tool sets is made up of a series of software process modules. Interfacing with the software processes is done by means of the graphical user interfaces (GUIs), to configure the display, toggle on and off functions or options, and display aircraft properties [2]. In addition to the software processes, a database of procedures and airspace is required for the facility in which CTAS is to be used. This "site adaptation" requires extensive details of operations at the facility, and is used to develop the video map of the facility and operational procedures for routes. The CTAS program was designed to operate in the current vectoring environment, but uses algorithms for computing airplane trajectories similar to those computed by an FMS.

FAST is a decision support tool for the terminal area, which in its full implementation can provide aircraft sequencing, runway assignment, and controller advisories for vectoring (speed and heading). However, the advisories require different equipment (color graphical user interface) not currently available at most TRACON facilities. The FAST tool was deployed to Dallas Fort Worth International airport (DFW) TRACON for operational test and evaluation in a form with partial functionality, involving only sequencing and runway assignment. This configuration of FAST is called passive-FAST (p-FAST), while the full configuration is referred to as active-FAST (a-FAST). The p-FAST evaluation at DFW demonstrated the potential benefits in a multiple-runway environment, resulting in a 10-15% increase in arrival rate, and a reduction in excess in-trail separation [3].

Since the environment for the current experiment was the TRACON, only the FAST portion of CTAS was used. The program was configured as a-FAST, with some modifications added to enable data link communications, trajectory dump (for data analysis), and the addition of custom waypoints to the database.

1.3 Related Studies

Previous to this effort, other experiments have focused on interfacing FMS and CTAS functions. In 1991, a joint NASA Langley/Ames simulation experiment was conducted to investigate a profile negotiation process between CTAS and an advanced FMS during the final cruise and enroute descent phase of flight [4]. The results of this study showed that airplane preferences could be successfully incorporated in the CTAS automation system and flight trajectories could be synchronized between airborne and ground automation via data link. The data link procedures and clearances developed for this experiment, however, were found to be cumbersome and would require refinement in order to be operationally acceptable.

Following this study, two flight tests were conducted to evaluate the trajectory prediction accuracy of the Descent Advisor tool [5]. The flight tests involved flying the Langley Transport Systems Research Vehicle (TSRV), a modified jet transport aircraft used for research purposes, in Denver Air Route Traffic Control Center's airspace with the DA tools in operation. Trajectory data were obtained from the FMS and CTAS, state and weather data from the airplane, and weather data from ground sources. The trajectories were compared to determine errors in CTAS arrival time prediction compared to the actual aircraft arrival time at the meter fix, a point at the entry into the TRACON airspace. Results indicated that the trajectories predicted by DA were similar enough to the FMS trajectories to achieve arrival time errors within 15 seconds (standard deviation). Errors in weather data were identified as being the major contributor to arrival time prediction errors.

1.4 Experiment Overview

The focus of this particular study in the FMS-CTAS Integration effort is the TRACON airspace, where it was believed that gains in capacity could be achieved by use of FMS trajectories that match the CTAS predictions. In typical current-day operations, an airplane may remain on its FMS route until reaching the end of the Standard Terminal Arrival Route (STAR), (typically about 10-20 miles before the approach). At this point ATC provides vectors for the aircraft to intercept the localizer for the final approach segment. A great deal of variation in ground track (and subsequently arrival time) can be introduced during this segment, due to differences in vectoring, pilot compliance with clearances, and winds, among other things. Remaining on an FMS path throughout the arrival and approach can significantly reduce the uncertainty regarding the aircraft's position at any particular point in time.

The goal of this experiment was to investigate the additional accuracy in arrival time prediction that could be achieved by using CTAS and the FMS during the transition from arrival to approach, compared to what is possible with current techniques. The approach taken was to simulate a series of arrivals into DFW airport, varying the level of FMS lateral guidance used during this segment from none (vectors throughout the transition) to full (remaining in FMS lateral navigation, LNAV, throughout). For the complete LNAV cases, the CTAS trajectory was data linked to the FMS for the pilots to quickly load, review, and execute the route.

An important part of the technology being tested in this experiment was the data link communication between CTAS and the FMS. Current data link technology was used to enable exchange of trajectory information between the aircraft and ground. A set of messages based on the ARINC 702a format was implemented to allow the aircraft to send position and trajectory information to CTAS, and for CTAS to send trajectory, winds, and clearance information to the aircraft. The lateral route clearance uplink was of primary importance in this experiment. This message was formatted to include a text portion to appear on the FMS Control and Display Unit (CDU) to advise the crew of the content of the uplinked message, and a portion with route data that could be loaded into the Flight Management Computer (FMC) with a single button push. The loaded data was used by the FMC to compute a modified route, which could then be reviewed by the crew and executed, becoming the new active route to be flown in LNAV guidance.

In order to be able to easily modify the existing FMS route with a trajectory uplink to become the complete LNAV route, some changes had to be made to the existing charted arrival procedure. The lateral path for the modified arrival procedure was the same as for the existing arrival, with an extension to include the downwind leg and constraints specific to aircraft landing to the South. Section 3.2 describes the charts used in this study. The new procedure was coded into the database that was loaded into the FMC, with a unique identifier that would appear on the CDU "Arrivals" page when accessed by the crew. When selected, this arrival could be easily connected to the approach with the route modification uplink from CTAS.

2. Experiment Facilities and Test Procedure

This section includes descriptions of the test procedures for the piloted simulation.

2.1 Simulator Configuration

For the simulator test, the CTAS program was run on a workstation, with a socket connection between the workstation and the Research Flight Deck (RFD) simulator, which was situated in a different building. The RFD simulator (figure 1) is a fixed-base full-mission research simulator running a modern twin-engine jet simulation model (performance and subsystems) and electronic flight displays. Voice communications were enabled through phone lines between the controller's CTAS workstation location and the simulator cab.

Figure 1. – Research Flight Deck simulator.

The flight management system in the RFD consisted of standard commercial equipment. Flight guidance mode selection is handled using a conventional Mode Control Panel (MCP).

Because this experiment was the first research study conducted in this simulator, some of the baseline simulator functionality was not available due to time constraints. In particular, glideslope guidance was not fully functional. Although the raw data indication on the Primary Flight Display (PFD) was correct, the guidance was not yet coupled, which meant that the pilots had to follow the glideslope indication manually, or by use of one of the vertical modes, such as Vertical Speed. Since glideslope capture occurred very close to the end of the data collection, this was not considered a problem.

CTAS configuration

The CTAS FAST modules enabled the controller to display the CTAS routes for the Southwest arrival, choose a profile, and display advisory points for altitude and speed. Additional functionality was added to the Planview Graphical User Interface (PGUI) to allow the controller to use the interface to execute the actions required for this study.

Software modifications to the basic functions that were made specifically for this study are summarized below:

- Ability to freeze routes – In its normal operation, FAST continually updates the routes at each "radar sweep." In order to interface with the FMS, this trajectory update was stopped at the waypoint CREEK, which was located on the downwind leg. The frozen route that was computed at the final update, was then data linked to the FMS.

- Trajectory dump – In order to compare the airplane and CTAS trajectory, it was necessary to obtain trajectory data from the CTAS program at the instant that the route was frozen. The full trajectory data was not available directly from this CTAS version as desired, however a process was developed to generate the route in post-processing of the run data.

- Data link socket connection – this connection between the CTAS workstation and the simulator's FMC enabled the simulator to receive data linked messages and trajectories from CTAS.

- Data link message generation – The messages data linked from CTAS were required to have a certain format to enable the FMC to receive, process and load the data. This functionality was added to the CTAS version used for this experiment.

2.2 Instrument Procedures and Charts

Two Standard Terminal Arrivals Routes (STARs) were used for this experiment. One was an actual current-day procedure, which was called Glen Rose 3 (JEN3). The JEN3 arrival is a commonly used arrival for the southwest quadrant at DFW. The second charted procedure was a version of the JEN3 arrival modified for this experiment and named the Glen Rose South (JENS) arrival (see Appendix). The main difference between the JEN3 and JENS arrivals is the addition of the downwind leg on the JENS arrival, with three additional waypoints, ROSEL, GOKKA, and WILAM. Also on the JENS arrival the downwind turn waypoint, which is called DELMO in the JEN3 arrival, was changed to DELTR and moved slightly so that the nominal ground track with the airplane on LNAV guidance would be the same as the nominal vectored path. The JEN3 chart had crossing conditions for landing on several different runways, but only the conditions for jets landing to the South applied in this experiment and are discussed here. The runs were initiated at the waypoint FEVER, (located approximately 40 nmi from the airport) on a 039˚ track to the downwind leg.

On the JEN3 STAR, the crossing conditions at FEVER are an altitude of 11000 ft and an indicated airspeed of 280 kts. The airplane was initialized with these crossing conditions so that no immediate changes needed to be made at the beginning of each run. The next constrained waypoint on this route is HIRST, which requires a speed reduction to cross the waypoint at 250 kts. This is followed by DELMO with another speed reduction to cross the waypoint at 210 kts. The aircraft is to depart DELMO on a heading of 350°, which is the approximate downwind heading. However, the controller will usually issue a heading to generate a better track, especially in the presence of winds. At this point, the standard arrival terminates with vectors from ATC to transition onto the final approach course.

All the JEN3 STAR constraints from FEVER to DELMO were kept the same for the JENS STAR. In addition, as mentioned previously the waypoint DELMO was replaced in the JENS STAR by DELTR (same crossing conditions applied), and the turn to downwind was part of the procedure, so no heading change was required to depart this waypoint. Instead, the procedure continued on to include the downwind leg past the point where the nominal base turn would be initiated out to the custom waypoint WILAM, which was the farthest point at which the base turn could be initiated due to airspace restrictions. The other two custom waypoints were there to accommodate a speed reduction (ROSEL) and the nominal turn to base for a visual approach (GOKKA) in the CTAS route. Since this chart was also used for the data link procedure, two inset figures on the chart showed the geometry of the FMS transitions. Although two transitions were shown (for runways 18R and 17C), only the one for runway 18R was used. As outlined on the chart, the FMS transition, began at the waypoint ROSEL and ended at the waypoint GOKKA. Two additional unnamed waypoints are also shown at the corners of the turns to base and final. These waypoints are unnamed because they are "floating" waypoints, rather than pre-defined fixes. Because CTAS continues to update the route until it is frozen, the exact location of these points is unknown until the freeze point. Once the route is frozen, the waypoints are labeled by their latitude/longitude, and included in the route modification message uplinked to the FMS.

All three procedures transitioned onto the same approach (ILS18R), which is an Instrument Landing System (ILS) precision approach. No changes were made to this procedure, and all charted restrictions applied as appropriate.

2.3 CTAS route

The three sets of procedures tested used either the JEN3 or JENS arrival with the ILS18R approach to generate a track similar to what was computed by CTAS, which is described below.

Lateral

The lateral route computed by CTAS is based on the nominal vectored route. Since the route is based on the route used in visual conditions, when used in conjunction with an instrument approach, the final (and downwind) leg must be extended by approximately 2 nmi to accommodate the required distance and angle to intercept the localizer course for a precision approach.

Speed

Once CTAS is tracking an aircraft, its route is continuously re-computed, and updated on the display at every simulated radar sweep. All constraints are used according to the charted procedures. The final two speed reductions are based on what controllers would generally do when vectoring an airplane in a landing pattern. The waypoint ROSEL, which is approximately abeam the final approach fix, is where the speed reduction to 190 kts occurs, and the final speed reduction to 170 kts occurs at the final approach fix, FF18R. These speed reductions are implemented in the CTAS system as “cross at”, such that the deceleration begins approximately 2 nmi prior to reaching the waypoint.

Altitude profile

The altitude profile used for this experiment was similar to that used in actual operations at DFW TRACON. For the initial segment from FEVER until the turn to downwind, the altitude was kept level at 11000 ft (MSL). The final descent within the TRACON began at about the turn to downwind, where the aircraft was cleared to an altitude of 3000 ft (this is an acceptable procedure in real-world operations if traffic permits). A constraint to be at 3000 ft prior to completing the turn to base was imposed, as would be done if parallel independent approaches were being conducted.

2.4 Pilot / Controller Procedures

Three different sets of charted arrival procedures were used: current-day, modified, and LNAV data link. This section summarizes the different procedures. The simulated ATC communications for all three procedures were representative of a relatively low traffic level. Specific pilot and controller tasks for each of the different cases are described below. In all the runs, the aircraft was advised by ATC to “maintain 170 kts until the final approach fix”, and given normal clearances for the approach and landing as in current-day operations.

Current-day

This baseline procedure for the experiment is similar to procedures currently in use at many major terminal facilities. With this procedure, the STAR terminates with a turn to the downwind heading, followed by ATC vectors to the final approach course. For these runs, the JEN3 STAR and ILS18R approach were loaded in the FMS, and the discontinuity between the end of the STAR and beginning of the approach was left unresolved. The autopilot was engaged with LNAV at the beginning of the run, and remained engaged until the end of the STAR.

After the First Officer (FO) made an initial check-in with ATC at the beginning of the run, the Captain complied with crossing conditions (speed reductions) via the MCP. At the end of the charted arrival, the pilot disengaged LNAV and complied with instructions from ATC by using the MCP "heading" mode. Either Flight Level Change (FLCH) or Vertical Speed (V/S) mode on the MCP was used to comply with the descent to 3000 ft.

Modified

With the modified procedure, the JENS arrival was used, but the pilots were still issued vectors for the turns to base and final. The FMS route discontinuity between the end of the JENS STAR and beginning of the approach was left unresolved. The autopilot was engaged with LNAV at the beginning of the run and remained so until the end of the STAR.

The remainder of this procedure was similar to the Current-day procedure, except that the downwind leg was part of the charted arrival, and ATC did not issue vectors until the turn to base leg. At this point, the crew engaged the MCP heading mode to comply with ATC instructions.

FMS-datalink

The runs that used the FMS-datalink procedure started out the same as the ones using the modified procedure, i.e., with the JENS arrival and ILS18R approach loaded, and a route discontinuity between the end of the STAR and beginning of the approach. The autopilot was engaged with LNAV at the beginning of the run and remained active throughout the approach, until localizer capture.

Shortly after the aircraft turned downwind, the controller froze the CTAS route, which triggered an automatic uplink of the clearance for the FMS transition. A chime unique to the ATC uplink sounded in the simulator cab after the uplink was received, to prompt the crew to access the ATC CDU page for the uplinked message. The uplinked FMS transition consisted of a route modification that began at the waypoint ROSEL and ended at FF18R. The uplinked route contained no discontinuities, and could be reviewed as a modified route on the Navigation Display (ND) and the CDU "LEGS" page before being executed as the active route.

When the route was executed (by pushing the EXECUTE function button on the CDU), an automatic downlink of the FMS trajectory was sent to CTAS, and the crew could then return to the ATC Uplink page, where an acknowledgement reply was sent to ATC. Thus, the entire downwind-base-final transition could be sent and acknowledged completely by data link.

2.5 Test Matrix, Pilot Subject Profiles, and Schedule of Events

Test Matrix and Wind Models

The test matrix for each pilot in this experiment consisted of nine scenarios: three procedures and three wind conditions. The scenarios were randomized for each pilot, and each pilot completed all nine. The scenario numbers shown in Table 1 below were associated with the indicated combination of procedure and wind condition, and are used for reference throughout the data analysis.

Table 1. Scenario Numbers with associated procedure and wind condition.

Scenario Number	Procedure	Wind Condition
1	Current-day	No wind
2	Modified	No wind
3	FMS-datalink	No wind
4	Current-day	Crosswind, constant 20 kts
5	Modified	Crosswind, constant 20 kts
6	FMS-datalink	Crosswind, constant 20 kts
7	Current-day	Headwind, decreasing from 22 kts
8	Modified	Headwind, decreasing from 22 kts
9	FMS-datalink	Headwind, decreasing from 22 kts

The wind conditions (shown in Table 2) represented a baseline case (no wind) and two cases from different directions with speed and direction profiles that had a significant effect on the lateral path and arrival time estimates, without overshadowing other factors. The wind reference (crosswind or headwind) is relative to what would be experienced when the airplane was on final approach (the crosswind was from the West and the headwind was from the South). The speed and direction profile of the crosswind case was modeled after wind conditions actually recorded at DFW. The headwind case represented a generic profile similar to conditions typically encountered in this phase of flight.

Table 2. Wind Profiles Used in Simulator Study

Condition	Wind Speed at start (kts)	Wind Direction (deg)	Vertical Profile (speed)	Vertical profile (direction)
No wind	0	0	---	---
Crosswind	20	270	Constant above 2000 ft, decrease to 0 kts at ground	Constant above 2000ft, rotate to 090 at ground
Headwind	22	180	Decrease at 2kts/1000 ft to 0 kts at ground	Constant

Pilot Subject Profiles

Three different airlines were represented: one pilot each from US Airways and American Airlines, and four from United Airlines (three active and one recently retired). The pilots' experience ranged from 17-37 years total, including military flying time (commercial flying time ranged from four to fourteen years). In terms of hours, the range was from 3500 hrs to 16000 hrs. A single subject pilot was used, with a confederate pilot in the right seat acting as First Officer. This configuration was used because the purpose of the test was not to investigate any crew resource management issues, and allowed a form of experimental control by always having one crewmember that was well rehearsed in the procedures.

Schedule of Events

Each pilot was mailed a briefing package for review, which included background and details on the FMS-CTAS integration work being done, a description of the experiment and pilot tasks, and copies of the procedure charts to be used for the experiment. Upon arrival at Langley and before going to the simulator, each pilot was given a verbal briefing covering material from the briefing package in more detail, plus step-by-step instructions on the data link CDU procedures.

Before the start of each run, the subject pilot was told which procedure and wind condition would be used for that run. The wind condition was not really of major consequence to the pilot, since he would not be responsible for determining corrections to compensate for it, but it was information that he would normally be aware of in real-world operations. The pilots had copies of all the necessary charts to which they could refer if needed.

Each run took approximately 20 minutes to complete, and were normally completed in groups of no more than three in a row followed by a break. The runs were completed in one day for each pilot except the first one (due to a hardware problem). Each pilot was initially given the opportunity to hand-fly the simulator for familiarization purposes. He was then asked to fly three training runs, each with one of the three procedures (all with the no-wind condition) before beginning the data runs, to ensure that he was exposed to all three procedures. The nine data runs followed a break after the practice runs.

Following completion of all the data runs, the subject pilots were asked to complete a questionnaire and had a short debrief session before departing. The subject pilots were also free to make comments at any time during the simulation.

3. Results and Discussion

The primary factors used for evaluation of these procedures were errors in the predicted arrival time at the final approach fix and errors in predicted path distance (path length). For this experiment, the CTAS-computed trajectory was used as the prediction, and all errors were computed relative to the CTAS trajectory, unless otherwise noted. The segment of interest for the evaluation was from the waypoint ROSEL to the final approach fix, and both time and distance were computed between these points for the analysis. It was assumed that time was synchronized at the waypoint ROSEL. Since path distance was computed as distance-to-go, the path distance is zero at the final approach fix for both CTAS and FMS trajectories. After the data analysis was started, two additional factors, crosstrack error and airspeed, were identified as having a strong influence on the distance and time errors, and are also discussed. After all seven pilots had completed their runs it was discovered that, for one of the pilots, one run was unusable due to an error in the CTAS-computed trajectory. In order to keep the same number of data points for the analysis for all the runs, this pilot's data was not used; thus the data presented in this paper is for only six pilots. Since the sample of pilots was relatively small, an exhaustive statistical analysis was not used, and it is recognized that any large deviations by one or two pilots could have a significant effect on the resulting numbers.

This section is divided into three subsections. The arrival time and path distance error data from the simulator runs is summarized and discussed in the first subsection. Following that is a summary and discussion of contributing errors (crosstrack and airspeed). The last subsection contains a discussion of the subjective data from the pilot questionnaire.

3.1 Time and Path Distance Errors

Arrival time errors

Table 3 below summarizes the mean and standard deviations of arrival time error at the Final Approach Fix (FAF) for each run, for the six pilots.

Table 3. Summary of arrival time errors.

Run Number	Mean Time Error (sec)	Std. Deviation
1	3.52	13.27
2	9.67	9.60
3	12.02	3.94
4	-3.03	10.29
5	8.92	11.90
6	8.85	4.96
7	7.40	14.75
8	17.55	13.05
9	13.93	8.08

Procedure differences

The time error results are grouped according to procedure in Table 4 below.

Table 4. Time error according to procedure used.

Procedure	Mean Time Error (sec)	Std. Deviation Time Error
Current-day	2.63	12.90
Modified	12.04	11.62
FMS-datalink	11.60	5.97

When comparing the procedures, it can be seen that the mean time errors for the modified and FMS-datalink procedures are much higher than for the current-day procedure. As will be seen later, these values contained a speed-induced time error that shifted all the values higher in the positive direction, and gave the appearance of a higher time error when using the modified and FMS-datalink procedures than with the current-day procedures. This effect will be discussed in later sections. The standard deviation is a key factor when comparing the arrival time errors for the procedures. The data in the table shows that use of the FMS-datalink procedure resulted in being able to meet the CTAS arrival-time predictions with about half the standard deviation error encountered with the other two procedures, which means this procedure gave more consistent arrival times.

To further illustrate these points, the time error data is shown plotted for each wind condition in figure 2. It can be seen that of the three procedures (within each wind condition) the current-day procedure had the lowest mean time error, but usually also the highest standard deviation.

Also, the mean time errors for the modified and FMS-datalink cases were similar for each of the wind conditions, but the FMS-datalink procedure had the lowest standard deviation (40-70 percent lower than the other two procedures). The trajectories computed by the CTAS and FMS systems were very similar, so it was expected that the mean time errors would be quite small when using the FMS-datalink procedure. As seen in the graph, this was not the case. Since these data appeared to have a bias, and it was observed during the simulation runs that most pilots did not closely follow the exact speed schedule that was assumed by CTAS in computing the arrival time for the final approach segment, the issue of speed conformance was further investigated, and is addressed in a later section.

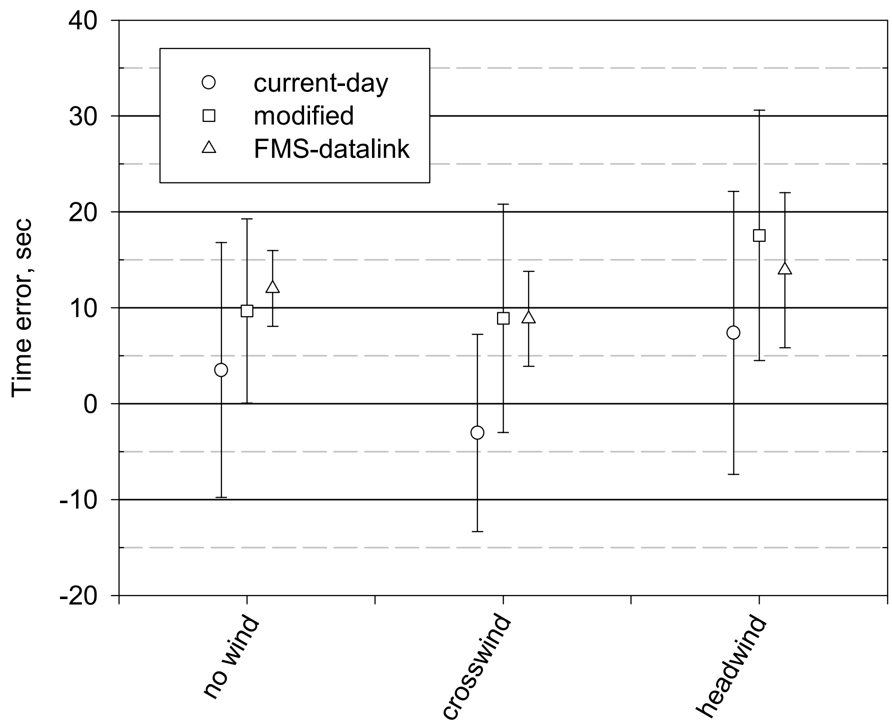

Figure 2. - Arrival time errors at Final Approach Fix.

Wind effects

In Table 5 below the data are grouped by wind condition to identify any wind-related differences.

Table 5. Arrival time error by wind condition.

Wind Condition	Mean Time Error (sec)	Std. Deviation Time Error
No wind	8.40	9.85
Crosswind	4.91	10.65
Headwind	12.96	12.33

It can be seen from the table that the mean arrival time for the headwind case is greater than in the no-wind or crosswind cases. The standard deviations for the three wind conditions were similar.

Referring back to figure 2, it can be seen that, for the current-day procedure the standard deviation is quite high for all wind conditions, but the mean arrival time error is higher (later aircraft arrival time) for the headwind case than the others. Similarly, with the modified and FMS-datalink procedures the headwind cases have higher mean arrival time errors than the no-wind and crosswind cases. This would indicate that, for a particular procedure, the arrival time was affected by the headwind on final, causing a slower groundspeed and later arrival time (although the amount of added delay caused by the wind was not quantified).

Path Distance Errors

Table 6 summarizes the mean and standard deviations of path distance error for each run, for the six pilots.

Table 6. – Path distance error summary for each run.

Run Number	Mean Distance Error (nmi)	Std. Deviation
1	-0.12	0.66
2	-0.01	0.34
3	0.03	0.03
4	-0.46	0.55
5	0.00	0.63
6	0.00	0.09
7	-0.04	0.63
8	0.40	0.59
9	0.06	0.06

Procedure differences

When grouped according to procedure type, as in Table 7, it can be seen that the mean and standard deviation of the path distance errors was much smaller for the FMS-datalink procedure than for the other two. The magnitude of these numbers (less than 1/10 nmi), indicated that CTAS and the FMS computed paths that matched well (this was also evident from plots of the lateral paths). It also indicated that most of the arrival-time errors in the FMS-datalink cases were not due to path errors. The standard deviations of the path distance errors for the other two procedures were closer than expected, although the mean distance error for the modified procedure was about halfway (in magnitude) between the current and FMS-datalink procedures, as expected.

Table 7. Path distance errors by procedure.

Procedure	Mean Distance Error (nmi)	Std. Deviation Distance Error
Current	-0.21	0.61
Modified	0.13	0.54
FMS-datalink	0.03	0.07

The distance errors for the current and modified procedures contained an effect that was evident from plots of the lateral paths, but not necessarily obvious from looking at the data. Intuitively, the modified case should have produced smaller errors and deviations than the current procedure, falling somewhere between that and the FMS-datalink procedure, but this is not evident from looking at the overall summary of path distance errors. When separated out by wind condition also (figure 3), the expected relationship appears only in the no-wind case, while the standard deviations remain high in both the current and modified scenario for the other two wind cases.

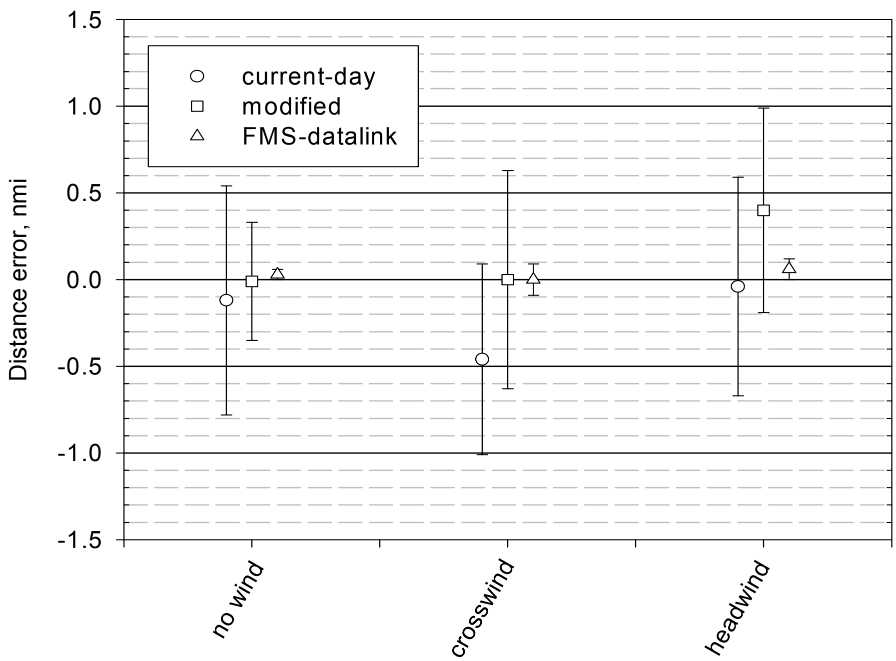

Figure 3. - Path distance errors.

Looking at the lateral paths flown by one pilot for each of the nine runs (figure 4) helps to explain what occurred. The scale on the plot is in nautical miles (both x and y). The black lines show the runs flown with current-day procedures, the gray show the runs flown with the modified procedure, and the white lines show the FMS data link procedure runs. Waypoint locations from CTAS data are also shown for comparison (the CTAS path is a point-to-point connection of these waypoints). It can be seen that with the current procedure the paths can be considerably different than the CTAS prediction, based on factors such as the controller's vectoring technique, piloting technique, or winds. Also, a trajectory that started well outside the nominal CTAS path could end up with a mean path distance error of close to zero if the airplane was later turned inside the CTAS path. With the modified procedure, that variability was removed on the downwind leg, but there were still distance errors produced by late turns to base, or a shortened path on the intercept leg to final. The plots from the current procedure showed much more variation than was evident from simply looking at the mean and standard deviation data. From the path distance and arrival time data, it would appear that the modified procedure was not much of an improvement over the current-day procedure. The difference comes from looking at not only path distance errors, but also crosstrack error, which is a better indication of how well the airplane was able to conform to the CTAS lateral path. This is explored further in a later section.

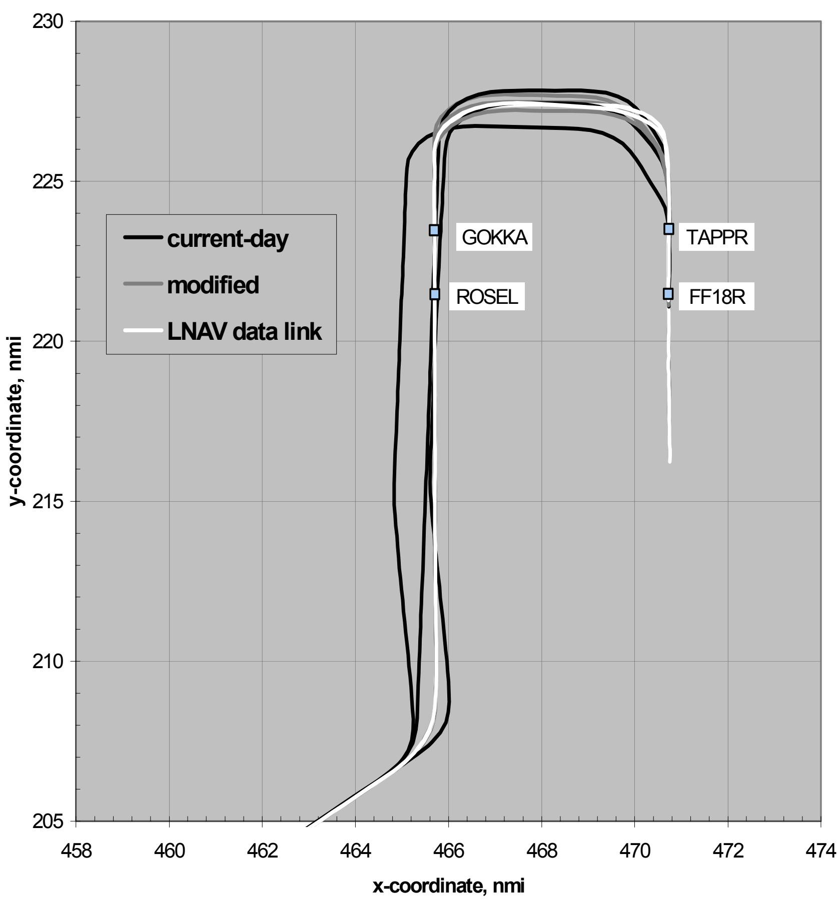

Figure 4. – Ground tracks for a single pilot subject.

Wind effects

Table 8 summarizes the path distance error data for all the runs, grouped by wind condition.

Table 8. Path distance errors by wind condition.

Wind Condition	Mean Distance Error (nmi)	Std. Deviation Distance Error
No wind	-0.03	0.41
Crosswind	-0.15	0.51
Headwind	0.14	0.51

As expected, the no-wind case had the smallest mean error in path distance and standard deviation. The mean distance errors and standard deviations in both crosswind and headwind cases were very similar, and comparable in magnitude to those seen with the modified procedure (when the data was separated by procedure, rather than by wind condition). However, the standard deviations were very similar in all three cases (slightly lower with no wind). This seemed to indicate that, for this case with relatively normal conditions, the wind was not as significant a factor in determining path distance accuracy as was the procedure used. Controller technique also factors into this. Errors generated while using the current procedure might not be significantly affected by wind condition, if the controller is able to compensate well, such as by issuing corrections along the downwind leg.

With the data further separated into individual runs as in figure 3, it can be seen that, in the presence of winds, the distance errors are larger for both the modified and FMS-datalink scenario, but not for the current-day procedure. As with the scenario differences, it is necessary to look at crosstrack errors to better describe wind effects on path conformance.

3.2 Contributing errors

As mentioned in preceding sections, it was observed that path distance was not the only factor that had a primary effect on the arrival time error. In the FMS-datalink runs, the path distance errors were very small, yet there was usually a time error of 9-14 seconds (with standard deviation of 4-8 seconds). In conducting the simulation, it had also been noted that most of the pilots slowed to final approach speed earlier than was anticipated, and it was known that maintaining the CTAS-defined speed schedule was necessary in order to maintain the prediction accuracy. Also, in examining the path distance data it was observed that path distance errors alone were not always the best indication of trajectory accuracy. To develop a better overall picture of the path and time errors, two additional parameters, airspeed and crosstrack errors, were also included in the analysis, and are discussed here.

Speed Error data

In the verbal briefing before starting data runs, the pilots were asked to execute the arrival and approach the way they would normally do it in the real world, under similar conditions. Most of the pilots ended up crossing the final approach fix at less than 170 kias, even though they had been instructed by the controller to “maintain 170 kts until [the final approach fix]” (the controller did not issue corrections to those pilots who slowed too soon).

Figure 5 shows the crossing speed for each of the nine runs, summarized for the six pilots. There does not appear to be any pattern to the crossing speed errors at the final approach fix that might depend on procedure or wind condition. Although the no-wind cases appear to have a more consistent mean crossing speeds across the three procedures, the standard deviations for all nine runs are similar, ranging from about 12 to 19, with most around 15. The overall mean crossing speed for all runs, for all pilots was 155.3 (std. Dev. of 14.4), or about 15 kts slower than the speed used by CTAS for trajectory prediction.

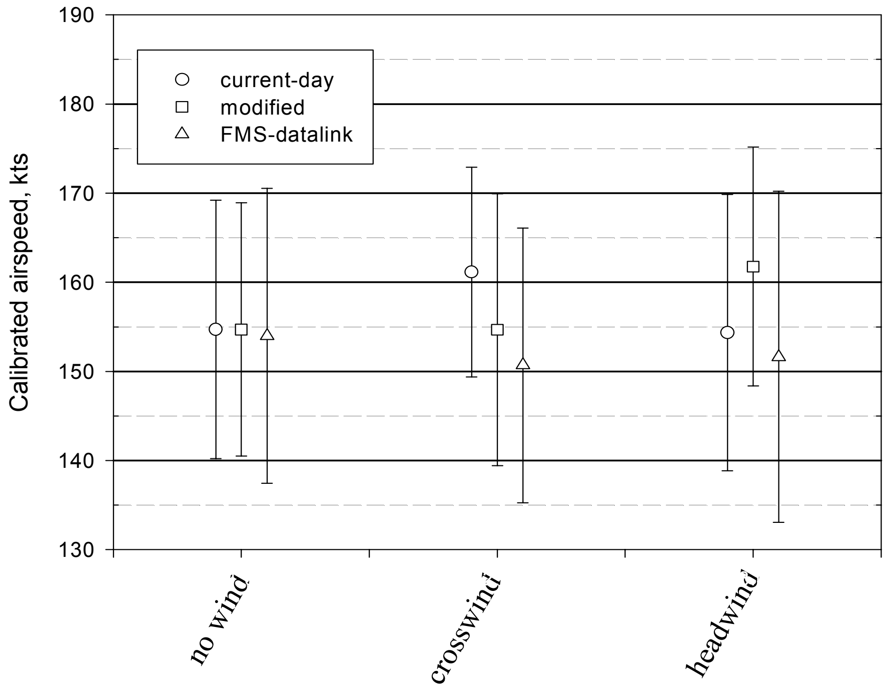

Figure 5. - Crossing speeds at Final Approach Fix.

Of the six pilots included in the data analysis, only one (Pilot F in figure 6) maintained 170 kts until the final approach fix, most of the time actually crossing the marker before slowing to final approach speed. One of the pilots (Pilot A) began slowing down just prior to the final approach fix, such that he crossed within 5 kts on all but two runs. On those two remaining runs, however, he crossed about 30 kts slow, which caused the high standard deviation. The rest of the pilots crossed 10-20 kts below the assigned crossing speed on most of their runs.

In figure 6 it can be seen that the error in crossing speed at the final approach fix varied a great deal by pilot, even though they were all given the same briefing, and also within each pilot's set of runs (except for Pilot F). Much of the variation within each pilot's runs was most likely due to the effects of learning and experimentation with the approach (the approach procedure was identical for all the runs, regardless of what arrival procedure was used). Looking at individual runs does not produce any observable trends based on procedure, wind condition, or order of runs. The only effect noticed was a tendency to cross the waypoint ROSEL at higher than the assigned crossing speed of 190 kts on the vectored runs. This is due to the pilot's knowledge of the crossing speed from the charted procedure, and having that waypoint displayed on the

Navigation Display during the modified and FMS-datalink runs, which prompted them to slow earlier to cross at that speed. In the vectored cases they did not have the waypoint depicted on the ND, and thus did not know the exact location of the speed reduction until it was issued by ATC, and often ended up crossing 10-15 kts higher.

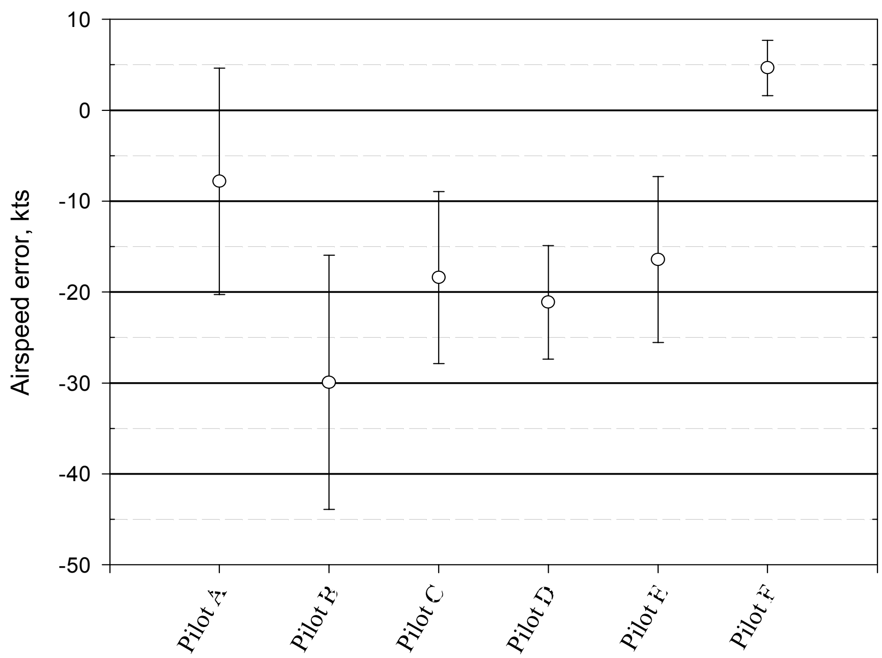

Figure 6. - Mean FAF crossing speed error for all pilots.

To better assess what effect the low outer-marker crossing speeds had on the arrival time errors it is useful to look at the crossing speeds at the waypoint just prior to the final approach fix (figure 7). This waypoint, named TAPPR, is located 2 nmi north of FF18R. By the time the airplane crossed TAPPR, it was established on the approach path and guided by the autopilot (in localizer mode) regardless of which arrival procedure was used, so crosstrack and path distance errors were virtually non-existent. This waypoint is prior to where CTAS assumes the speed reduction to 170 kts will begin, so the CTAS trajectory still shows 190 kts at TAPPR. Most pilots began to slow to 170 kts before TAPPR and had already reached that speed by the time they crossed the waypoint. Figure 8 shows the crossing speeds at TAPPR. (Note: The large deviation in the speed for the FMS-datalink runs with a headwind is due to one pilot for whom things seemed to fall apart a bit when he was cleared for the approach, and subsequently crossed TAPPR at 132 kts. Eliminating his run would bring the mean up by 5 kts and standard deviation down to less than 5 kts).

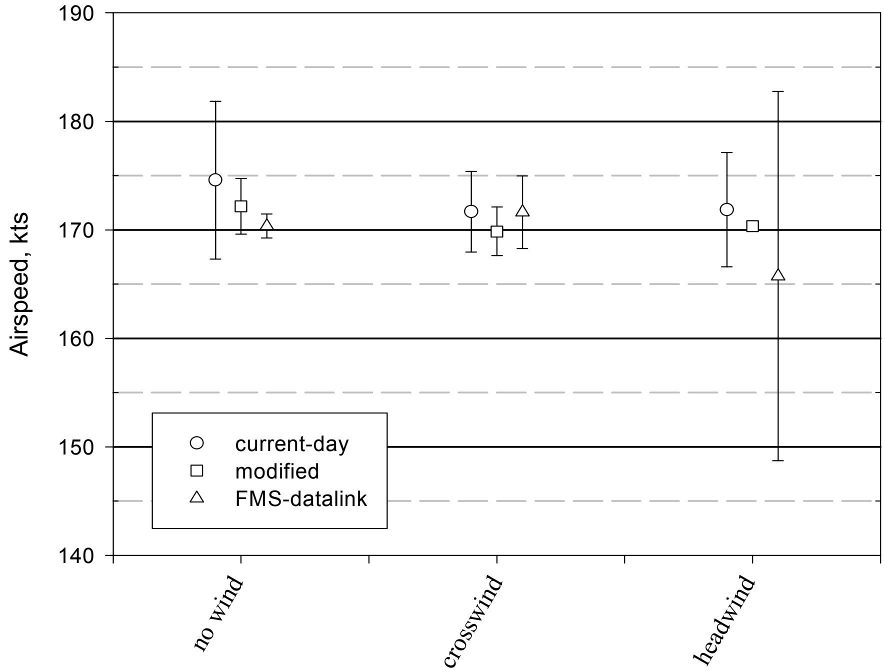

Figure 7. – Crossing speed at waypoint TAPPR.

The net effect is that the 2 nmi segment between TAPPR and the final approach fix were flown, on average, 15-20 kts slower than predicted by CTAS. This could account for approximately 4-6 seconds longer flying time for this segment alone. A quick analysis of the data corroborated this finding, by using the average of actual speeds for this segment from simulator data and an average speed of 185 kts for CTAS (the CTAS speed reduction begins about halfway between the waypoints, and a linear decrease was assumed). As seen in Table 9, for all cases there is an increase in overall arrival time error of about the same magnitude (5 seconds) during this short segment between the two waypoints.

Table 9. Time errors at TAPPR and FF18R, by procedure.

Procedure	Mean Time Error (sec)		Std. Deviation Time Error	
(Waypoint →)	*TAPPR*	*FF18R*	*TAPPR*	*FF18R*
Current-day	-1.88	2.63	11.67	12.90
Modified	7.73	12.04	11.15	11.62
FMS-datalink	5.93	11.60	3.97	5.97

The accumulation of time errors can be seen in figure 8, where data were analyzed at the waypoints on the route (between ROSEL and the FAF) and at several points between the named waypoints to better identify the locations where errors were building up. With the current-day and modified procedures, the additional time error accumulated between TAPPR and FF18R is about 4.5 seconds, and with the FMS-datalink procedure the additional error is 5.7 seconds. The crosstrack and path distance errors in this segment are very small (on the order of 0.05 nmi or less), and can account for only about 1 second of delay. Most of the additional time error built up between TAPPR and FF18R is due to the difference in speed used by CTAS and the speed actually flown.

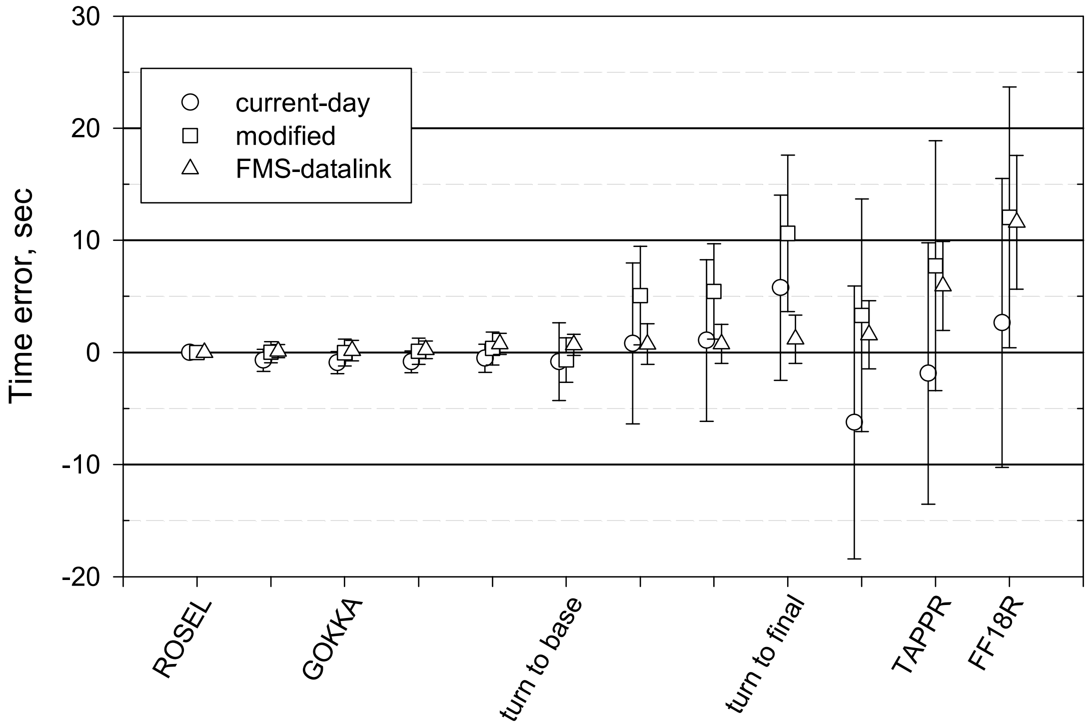

Figure 8. - Time error at waypoints and various intermediate points.

If this is further carried on to a point 2 nmi prior to TAPPR (approximately the end of the turn to final), an additional 4 seconds of error accumulation can be seen across all the procedures. It seems reasonable to conclude that if the speed were maintained according to the CTAS prediction, the mean time errors would be shifted by 9-10 seconds (in the negative direction), and the final approach fix crossing times would more closely match with theoretical expectations.

Crosstrack Error data

In evaluating path distance errors, it was found that these errors do not always show which procedures resulted in the best lateral tracking. A second parameter, crosstrack, is needed to determine this, and is discussed in this section. Figure 9 shows a summary of the distribution of crosstrack errors in the path segment from ROSEL to the final approach fix. As expected, there are no crosstrack errors on the downwind leg for the modified and FMS-datalink procedures, since the airplane was still on LNAV guidance in that region. However with the current-day procedure, the crosstrack errors in this segment are of magnitude up to one-half nautical mile. During the turn to base, errors for the current procedure continue at about the same magnitude until the turn to final, when the localizer mode has captured and the localizer guidance keeps the airplane on the final approach course. For the modified procedure, during the turns to base and final the errors build up from previous values, but remain smaller than with the current-day procedure. The FMS-datalink case shows some slight crosstrack errors during this same segment as well, most likely caused by differences between predicted and actual winds, or between the turn radius computed by the FMS and the CTAS prediction. Although there are slight crosstrack errors when using the FMS-datalink procedure, they are relatively small, remaining below one-tenth nautical mile throughout the segment.

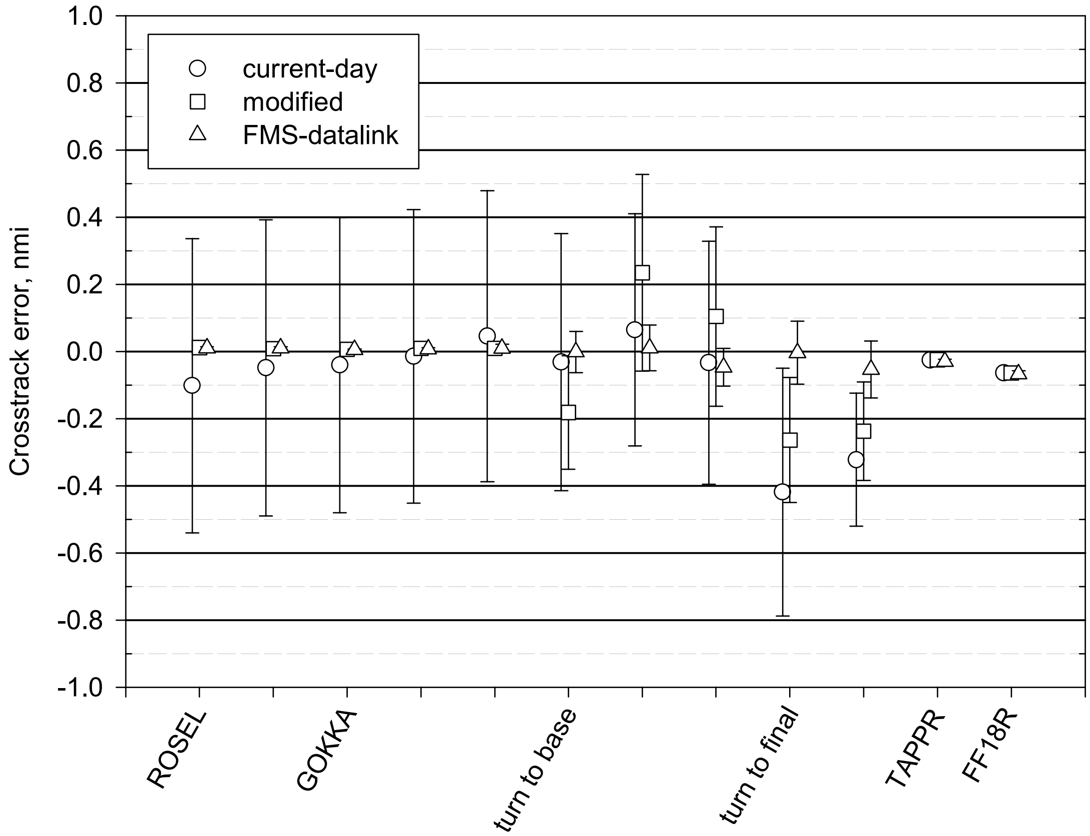

Figure 9. - Crosstrack error at waypoints and various intermediate points.

One final note needs to be made regarding the appearance of crosstrack error at the final two waypoints. During the data analysis it was discovered that the value for latitude in the CTAS waypoint database was incorrect for the final approach fix, FF18R. The value that was entered into the CTAS database file was off by 3 seconds of latitude, or approximately 300 ft. This did not create a significant problem for the analysis, since the airplane used its own (FMS) database. The only effect is that it appears as if there is a crosstrack error for all cases at the final approach fix, when there is none. The error in the position of the previous waypoint, TAPPR is due to a difference in significant digits used to define the location of the waypoint. This and related issues are discussed in the concluding remarks.

3.3 Pilot Comments

Following completion of all the runs, each pilot was given a questionnaire to obtain their evaluation of the FMS Arrival chart, procedure acceptability, and FMS-CTAS data link acceptability. The major points from their responses and comments are summarized in this section.

Overall, the pilots indicated that they found the charted procedure and data link procedure acceptable, but had recommendations for improvements to the CDU procedures. Generally, the pilots felt that there was no other information that needed to be included on the charts, and the charts were clear, organized, adequate, and acceptable for the task.

The pilots were comfortable with the use of LNAV during the arrival and transition portions of the procedure, and rated the procedure, itself as very acceptable. No part of the procedure was considered unclear or confusing. None of the pilots felt that their workload was increased when flying the custom arrival and transition procedure compared to current-day procedures, answering that their workload was unaffected or somewhat decreased. Most of the pilots said that flying the custom procedure was very easy, and compared to current-day descent procedures, was "very desirable" and "very acceptable".

The pilots indicated that the use of data link to execute the FMS-CTAS procedure and the associated tasks were acceptable, and they did not feel rushed to complete the tasks. Only one pilot objected to the amount of head-down time required for loading, reviewing, and executing the route, and suggested a simpler procedure.

When asked to comment on the adequacy of the briefing and training, the pilots indicated that the arrival and FMS transition procedure briefing and the CDU data link procedure briefing prepared them sufficiently. Their opinions were divided on whether or not simulator training was needed for introduction of the FMS arrival procedure, but all felt that only one or two descents were needed to become comfortable with the overall procedure.

Other general comments of interest from the questionnaire are excerpted below:

"The procedure was very easy to fly and if anything, decreased the pilots workload. …I think that VNAV should also be incorporated whether or not each aircraft descends differently in VNAV..."

"New procedure has the potential to decrease pilot workload and decrease radio congestion/interface at terminal facility. Problem will be ATC – acceptance and implementation"

"It is easy to see why this method… will increase arrival capacity. It seems very efficient. Even with a relatively late uplink I felt completely comfortable with the loading, executing, and flying of this procedure…I think this will be a great asset for the terminal phase of flight."

"Idea is excellent. Just need to reduce the head down time and make it simple…"

"…CBT training session should be conducted so the PNF knows the sequence of data entry and has an idea of any pitfalls he might encounter."

"Exposure to how it is loaded and how the map display can enhance your situational awareness…"

The general feeling from these and other comments made by the pilots was that there was no problem with using the charts and procedures as presented, but that the interface (CDU interaction) could be streamlined by reducing the number of required steps. This is significant since most pilots do not want to have to interact with the FMS during the transition and approach phases of flight, when workload can be high. Many of the pilots commented on the value of having the complete arrival and approach path depicted on the ND, resulting in increased situation awareness. The results from this group of pilots indicates that with slight improvements a procedure such as this could be acceptable to pilots for use in congested terminal areas, and could even become preferable over current-day procedures in some instances.

4. Concluding Remarks

A piloted simulation was conducted to evaluate instrument and crew procedures for integrating functions of CTAS, a ground-based decision support tool for air traffic controllers with an airplane's Flight Management System. The goal was to document errors in arrival time predictions that could be achieved with and without use of the FMS for lateral guidance in conjunction with CTAS on the ground. Results from a limited number of subject pilot runs indicate that the CTAS arrival time prediction can be improved significantly by keeping the aircraft coupled in FMS lateral navigation throughout the transition from arrival to approach until localizer capture. The arrival time error standard deviation was half as great in these cases than with the current-day procedure, which consists of vectors from ATC for the same segment of flight.

A significant issue that needs to be addressed in future studies is better aircraft speed conformance during the flight segment just prior to final approach. Differences in predicted and actual speeds during the 2 to 4 nmi segment prior to the Final Approach Fix caused several seconds of additional delay in arrival time in this experiment. This additional time error can negate much of the benefit achieved by flying the precise LNAV path.

Important success criteria for integrating the two systems are development of crew and controller procedures, including charts that are acceptable to pilots and easy to interpret and use. The candidate charts and crew procedures developed for this study were well received by the subject pilots, with minimal suggestions for improvements. However, during periods of high workload, such as those encountered during arrivals to high-density terminal areas during very busy periods, the additional CDU interaction required might not be as acceptable to pilots. Controller procedures were not tested in this study.

Some technical considerations that need to be taken into account for future studies include database accuracy (CTAS and FMS must have the same coordinates for waypoints), and synchronization of time references. Although waypoint coordinates were crosschecked for the two systems in this experiment, round-off errors surfaced during data analysis. Though the errors did not affect the overall results in this case, accurate navigation databases are necessary to achieve the best results possible in operational use.

Allowing an aircraft to remain engaged in FMS guidance throughout the TRACON airspace can improve the accuracy with which it can be tracked, since it will be on a more predictable path than can be achieved with vectoring. This could help improve capacity in some of the nations busiest terminal areas by allowing reduction of excess spacing buffers currently used to account for uncertainties in airplane position.

Although the FMS-CTAS data link procedures worked well for this group of pilots, other implementations can also be tested, such as non-data link procedures that maintain the path-following accuracy of the FMS for aircraft that are not data link equipped. In this study, the modified procedure did not show the substantial improvement over current-day procedures that was achieved with the data link procedure, but could be improved to allow the aircraft to remain in FMS lateral guidance mode. Another important consideration that must be addressed in future studies is the acceptability of ground-based procedures for the controllers interfacing with CTAS. This was not an issue for the study documented here, but is an important factor in being able to successfully integrate the FMS and CTAS functions to achieve their fullest advantage.

5. Appendix

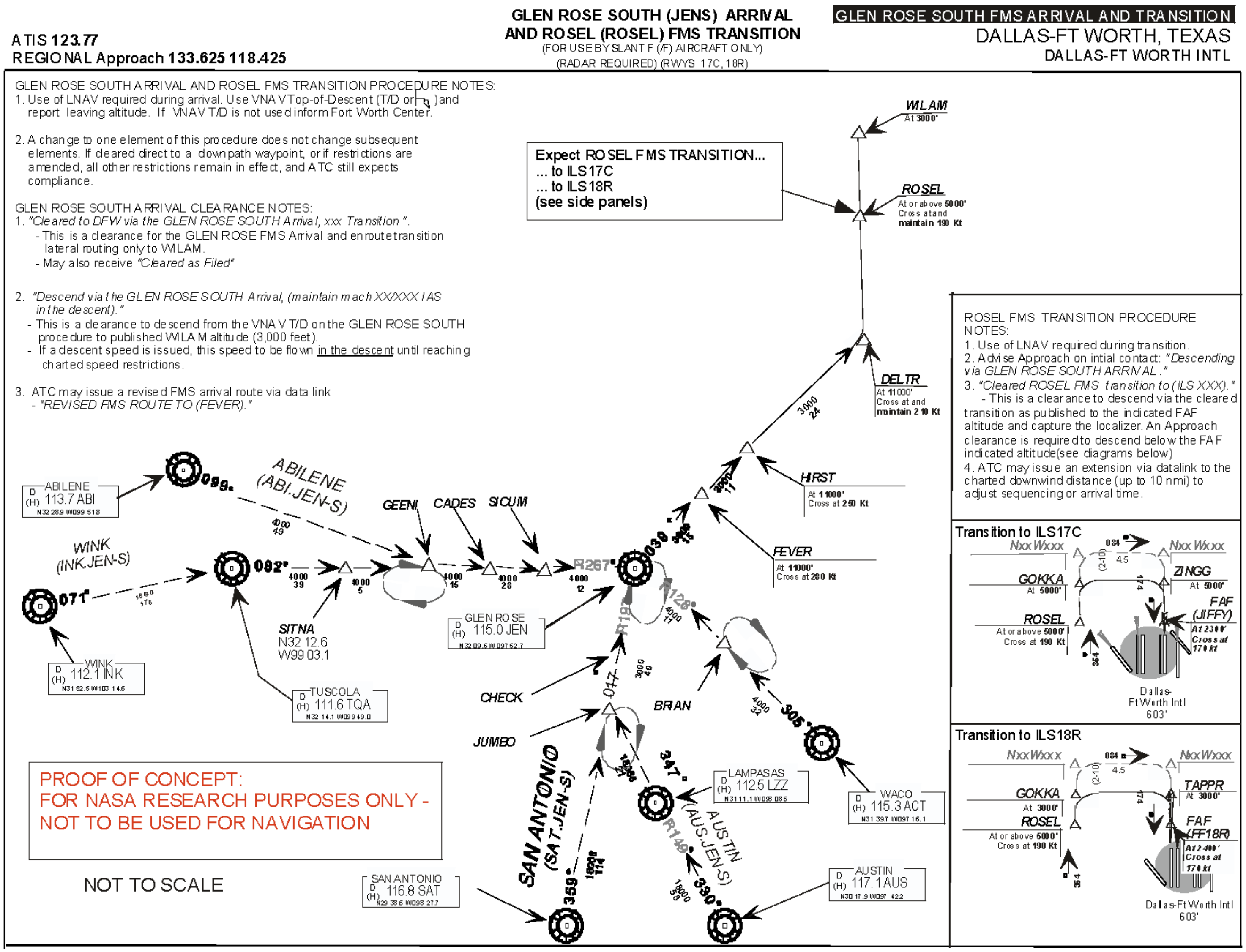

Figure A1. – Glen Rose South (JENS) Arrival chart.

6. References

[1] Erzberger, Heinz; Davis, Thomas J.; and Green, Steven: Design of Center-TRACON Automation System. "Machine Intelligence in Air Traffic Management," Andre Benoit, ed., AGARD CP-538, Oct. 1993, pp. 11-1-11-12.

[2] Lee, Katharine K. and Davis, Thomas J.: "The Development of the Final Approach Spacing Tool (FAST): A Cooperative Controller-Engineer Design Approach," NASA TM-110359, August 1995.

[3] Davis, T.J.; Isaacson, D. R.; Robinson III, J. E.; den Braven, W.; Lee, K. K.; and Sanford, B.: "Operational Test Results of The Passive Final Approach Spacing Tool," Published at the IFAC 8th Symposium on Transportation Systems 97, Chania, Greece, June 1997.

[4] Green, Steven M.; den Braven, W.; and Williams, David H.: "Development and Evaluation of a Profile Negotiation Process for Integrating Aircraft and Air Traffic Control Automation", NASA TM-4360, April 1993.

[5] Williams, David H. and Green, Steven M.: "Flight Evaluation of Center-TRACON Automation System Trajectory Prediction," NASA TP-1998-208439, July 1998.

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13. ABSTRACT *(Maximum 200 words)*

A piloted simulation experiment was conducted to document the trajectory errors associated with use of an airplane's Flight Management System (FMS) in conjunction with a ground-based ATC automation system, Center-TRACON Automation System (CTAS) in the terminal area. Three different arrival procedures were compared: current-day (vectors from ATC), modified (current-day with minor updates), and data link with FMS lateral navigation. Six active airline pilots flew simulated arrivals in a fixed-base simulator. The FMS-datalink procedure resulted in the smallest time and path distance errors, indicating that use of this procedure could reduce the CTAS arrival-time prediction error by about half over the current-day procedure. Significant sources of error contributing to the arrival-time error were crosstrack errors and early speed reduction in the last 2-4 miles before the final approach fix. Pilot comments were all very positive, indicating the FMS-datalink procedure was easy to understand and use, and the increased head-down time and workload did not detract from the benefit. Issues that need to be resolved before this method of operation would be ready for commercial use include development of procedures acceptable to controllers, better speed conformance monitoring, and FMS database procedures to support the approach transitions.

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