Flight Experience with Aircraft Time-of-Arrival Control

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A research program on STOL operating systems is underway at the Ames Research Center. One investigation is concerned with design, analysis, and flight test of promising 4-D RNAV (four-dimensional area navigation) system concepts. While the flight paths that can be flown and the control system are aircraft dependent, the 4-D RNAV system concept is not. Hence, the work is applicable to CTOL aircraft. One promising system generates a capture flight path from the present aircraft position to a waypoint on a selected fixed-approach route. It predicts arrival time at the runway and controls time and position along the path. The system was flight tested, using a digital avionics system, on a Convair 340 and on an experimental powered-lift STOL airplane. Flight tests in the flight director mode show that the pilot can choose and change the desired time of arrival and meet this time within a few seconds, in spite of navigation errors and varying winds. Initial tests of the automatic mode using the NASA Augmentor Wing Jet STOL Research Aircraft (AWJSRA) show that good time control was achieved without objectionable throttle activity.

Introduction

A RESEARCH program on STOL operating systems is underway at the Ames Research Center. One facet of this program is concerned with an investigation of the benefits that may result from the use of advanced 4-D RNAV and guidance concepts for aircraft operation in the terminal area. The system described here will navigate and guide an aircraft to arrive over the runway threshold at a prespecified time.

In this program, two groups of questions are considered. One group, given that many aircraft are equipped with 4-D RNAV, concerns the associated air traffic control procedures to sequence aircraft in the terminal area and the benefits resulting from aircraft equipped with such advanced area navigation systems. These questions are addressed in a joint NASA-FAA simulation study.[1] The second group of questions, which will be partially answered in this paper, concerns the problem of design, implementation, and flight testing of an airborne 4-D RNAV system. Previously reported systems, such as those in Ref. 2, were tested in simulation studies only, and they did not have to contend with real, varying winds and measurement uncertainties.

The system concept was first developed and refined using ground-based simulators and then flight tested using both a Convair 340 and the NASA Augmentor Wing Jet STOL Research Aircraft (AWJSRA) which are equipped with an advanced digital avionics system called STOLAND.[3] This paper presents and discusses flight test results concerning the time-of-arrival (TOA) control aspects of the system. For completeness, the STOLAND system is described briefly, as well as the 4-D RNAV system.

System Description

STOLAND is an integrated digital avionics research system having a computer of sufficient size, speed, and capability to perform all the onboard computations required to conduct research in terminal area navigation guidance and control concepts for advanced STOL aircraft. The major components of the system are a general-purpose digital computer and a data adapter that interfaces the computer with all the navigation aids, displays, controls, and servo actuators (Fig. 1). The system components installed in the cockpit of the aircraft (Fig. 2) include the horizontal situation indicator (HSI), control wheel, electronic attitude director indicator (EADI), multifunction display (MFD), MFD control panel, mode select panel (MSP), status panel, and data entry panel. During automatic operation, the pilot monitors the system operation through the various cockpit displays. During flight director operation, the pilot uses the same set of displays to control the aircraft along the reference flight path and to monitor the system.

Four-Dimensional RNAV System

A brief description of the 4-D RNAV system and its anticipated use in the terminal area follows.[4] When the aircraft enters the airspace controlled by the terminal air traffic control (ATC), it is assigned a specific approach route (as

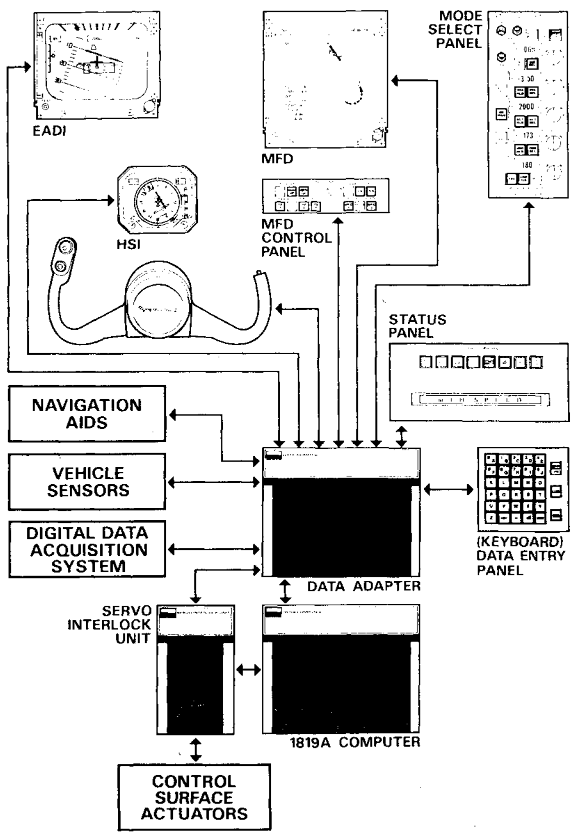

Fig. 1 STOLAND flight-test system.

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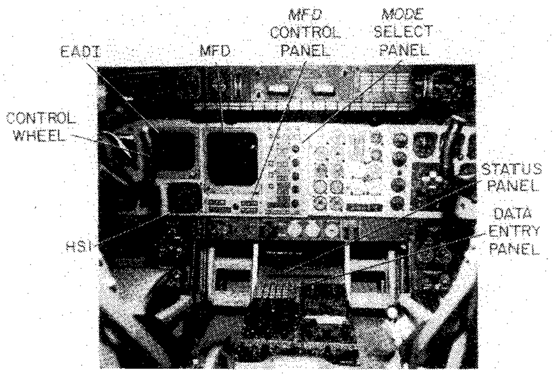

Fig. 2 STOLAND cockpit installation as installed in the Augmentor Wing aircraft.

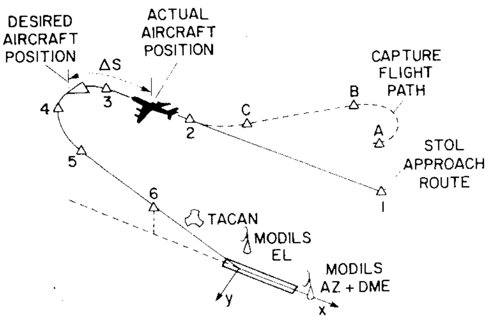

Fig. 3 Reference STOL approach route and capture flight path.

shown in Fig. 3), and a required TOA at a waypoint that is a short distance from the runway threshold (e.g., waypoint 6, which is on the glide slope 1 min from touchdown). In the STOLAND system there are four stored trajectories with a maximum of 30 waypoints each. The waypoints define any flyable complex flight path which is a combination of straight and circular flight segments. Thus, a delay fan with four legs can be defined, and the simulated ATC can specify to the pilot which leg to fly.

To achieve the specified TOA, the aircraft position and velocity must be known accurately, and a complete flight path from its present position to the runway threshold must be defined. As a first step in generating this complete flight path, a so-called capture flight path must be generated which connects the present aircraft position with a selected waypoint on the assigned STOL approach route. The capture flight path, together with the STOL approach route, form the complete flight path which is needed for time-controlled guidance.

Navigation

The navigation portion of the system provides an estimate of the aircraft position and velocity with respect to a local runway-referenced coordinate frame and also with respect to the reference flight path.[5] The external navigation signals are TACAN and the scanning beam Microwave Landing System (MODILS) for precision navigation during the approach and landing. The measurements obtained from onboard sensors are body axis accelerations, pitch, roll, and yaw angles, barometric altitude, radar altitude, and airspeed. The position data derived from the ground-based navaids and the onboard measurements are transformed to the local coordinate frame in the digital computer. The transformed quantities are then smoothed in X, Y, and Z complementary filters to estimate speeds and positions.

A wind vector is estimated for use in the TOA calculations. To minimize the effect of short-term changes in the wind estimate which would cause excess throttling activity, the wind component estimates, which were obtained by differencing the X and Y components of ground speed and true airspeed, were filtered by 100-sec time-constant, first-order, low-pass filters.

The success of the 4-D RNAV system depends heavily on smooth navigation data for all of the path and on accurate navigation estimates for the final portion of it. Smooth estimates are required for guidance with low-control activity, and precise estimates are required to permit precise TOA control to the final waypoint. Smoothing the navigation estimates requires special logic and signal blending, so that input transients will not affect speed and position estimates. These transients occur when navigation signals have momentary dropouts (extremely large errors) with or without loss of receiver valids. They also occur when switching between various ground-based navaids, each of which has a different set of bias errors.

The final system accuracy is limited to the final ground-based navaid error. To allow the guidance system to remove errors developed while flying in nonprecision navaid coverage, the 4-D RNAV flight paths must be designed in such a manner that sufficient time is spent in precision navaid coverage.

Guidance

The guidance system has two operational modes: the predictive mode and the track mode. The predictive mode allows the pilot to select a TOA via path stretching, while the track mode allows the pilot to make good the selected TOA via speed control. These modes are discussed in order. For each mode, the concept will be explained first by means of an example, and then display aspects of the system will be discussed.

Predictive Mode

The predictive mode is based on the capture flight-path concept. The capture flight path (shown as a dashed line in Fig. 3) connects the present aircraft position with a waypoint (e.g., waypoint 2) on the STOL approach route. The capture path consists of a turn (*A-B*), a straight segment (*B-C*), and another turn (*C-2*). It is defined based on an algorithm that computes waypoints A to C.[6] The aircraft may have any initial position, altitude, heading, and airspeed which permit a flyable turn-straight-turn flight path from the aircraft position to the selected waypoint. Such a path will not exist: 1) if the aircraft-to-selected-waypoint distance is too short so that no turn-straight-turn flight path is computed (due to limitation of the simplified onboard algorithm); 2) if the present aircraft airspeed is too different from the required airspeed at the selected capture waypoint so that the aircraft cannot decelerate sufficiently in the straight segment of the capture flight path; and 3) if the aircraft altitude is too different from that of the selected waypoint so that the aircraft cannot descend or ascend in the available path length.

While the aircraft maneuvers in the terminal area, a new capture flight path and TOA at waypoint 6 are continuously recomputed and (as discussed later) displayed to the pilot. Otherwise, messages are displayed giving reasons why a capture flight path is not possible, such as NOCAP HOR for reason 1) in the preceding, NOCAP VEL for reason 2), and NOCAP ALT for reason 3).

The complete path from the aircraft's present position to the runway threshold is stored in the airborne digital computer by storing the waypoint coordinates of the fixed approach route and of the time-varying capture flight path. Also stored are the radius of turn (in case of a circular flight path), nominal airspeeds, and maximum and minimum allowable airspeeds between waypoints.

The predicted TOA is computed once every 10 sec by integrating the time to travel between each waypoint on the flight path

$$\Delta t_i = \int_0^{d_i} \frac{ds_i}{V_{\text{air}_{\text{nom}}} + V_w \cos \alpha} \tag{1}$$

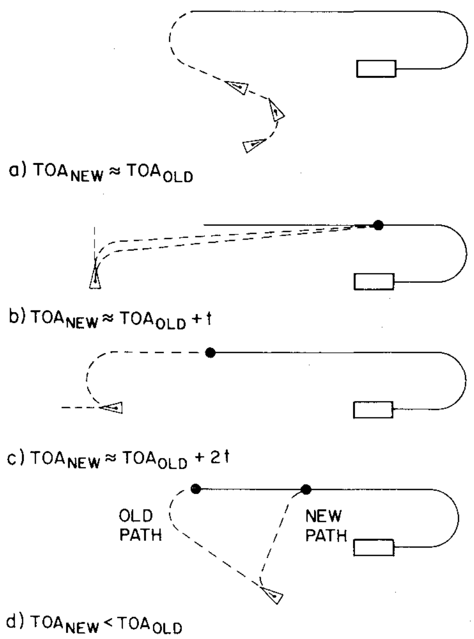

Fig. 4 Predicted TOA adjustment using the capture flight path.

where α is the wind angle with the path, $V_w \cos\alpha$ is the head wind component, and $V_{air_{nom}}$ is the nominal airspeed. To achieve the ATC-specified arrival time at waypoint 6, the pilot flies a path-stretching or path-shortening maneuver until the predicted TOA agrees with the specified TOA. Figure 4 shows various ways the pilot might maneuver the aircraft to adjust the predicted TOA. The predicted TOA will remain practically constant if the aircraft is flown along the nominal capture trajectory (Fig. 4a). It will increase at about the same rate as real time when the aircraft is flying perpendicular to the reference flight path since the length of the capture flight path changes little as time passes (Fig. 4b). The TOA increases at about twice the rate as real time if flying in the opposite direction to the reference flight path since the capture flight path gets longer as time passes (Fig. 4c). The TOA can also be adjusted for an earlier arrival by capturing a higher numbered waypoint than the one previously specified (Fig. 4d). When the predicted and required TOA's agree, the pilot commands the system to fix the complete approach path and to begin tracking the path, thus terminating the predictive mode.

In the predictive mode, as shown in Fig. 5a, the computed flight path is displayed to the pilot on the MFD in the form of a map. In addition, in the lower left corner of the MFD there is a four-line message which is labeled in the left margin of the figure as "next waypoint data." In the first line, the message indicates that the next waypoint (capture waypoint) is waypoint 2, and the flying time to waypoint 2 is 2 min, 33 sec. The second line displays the altitude for waypoint 2. The third line displays the predicted TOA at the final waypoint, 1300 hr, 42 min, 12 sec. The fourth line is important for the track mode and is dicussed later. As previously discussed, other messages are displayed if the algorithm cannot compute a capture flight path.

Track Mode

Once the system begins tracking the capture flight path, control of arrival time at waypoint 6 is accomplished by controlling the autothrottle as a function of an airspeed command signal or, in the case of the flight director mode, by displaying to the pilot an airspeed error signal on the EADI. The airspeed command V_c is defined as the algebraic sum of a prescribed nominal airspeed (V_{nom}) and an error proportional to an aircraft position error (ΔS)

$$V_c = V_{nom} + 0.04\Delta S (\mathrm{m/sec}) \qquad (2)$$

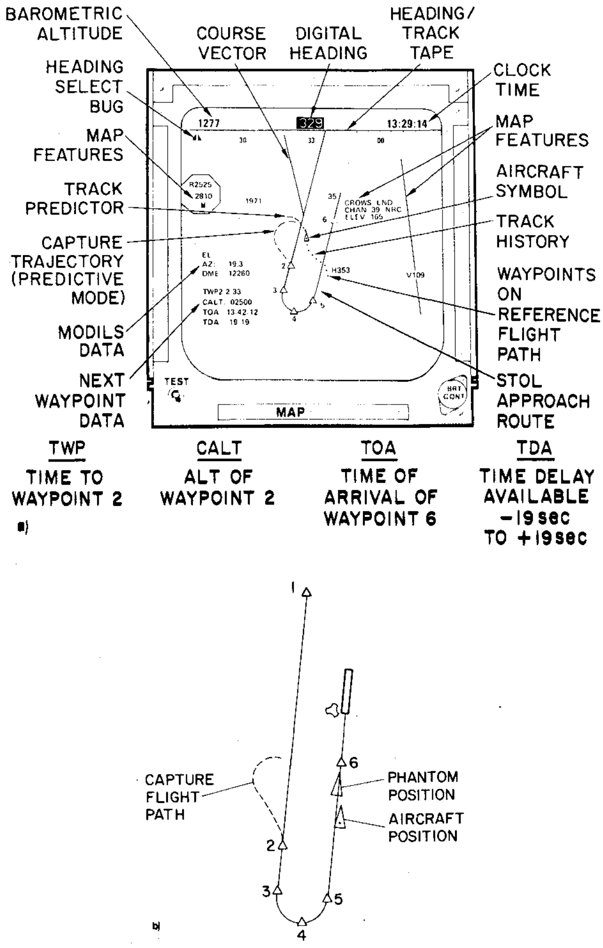

Fig. 5 MFD display: a) predictive mode; b) track mode.

where ΔS (see Fig. 3) is the distance along the track between the estimated aircraft position and the desired aircraft position, called the phantom position. The phantom position which is needed to calculate ΔS in Eq. (2) is calculated using the nominal arrival times computed at waypoints t_i. It is computed as a third-order polynomial.

$$S(t) = (V_{air_{nom}} + V_w \cos\alpha)(t - t_i) + A(t - t_i)^2 + B(t - t_i)^3 \qquad (3)$$

where A and B are functions of flight time and the nominal airspeeds and head wind components at the beginning and end of the flight-path segment. Functions A and B are chosen so that the constraints of time and velocity at the endpoints of the flight-path segment are met. When the segment is linear and the nominal airspeed constant, then $A = B = 0$.

The initially computed TOA at waypoint 6 is based on the time is takes to fly from the position at which the pilot engages the system to waypoint 6 (Fig. 3), provided the aircraft flies the path exactly at the nominal airspeed and the wind remains constant. In the automatic mode, the long-term throttle activity is very slow because the first-order control law, Eq. (2), has a 1/0.04 = 25-sec time constant, and the wind filter has a 100-sec time constant.

To compensate for variations in arrival time caused by wind variations, values for t_i, on which the position calculations of the phantom depend, are recomputed every 10 sec based on the latest estimate of wind velocity and direction. This results in step changes in the throttle command. To smooth the throttle activity, the time rate of change in the value of ΔS in Eq. (2) is limited to a maximum of 6.1 m/sec, which results in a 0.47-knot/sec acceleration for a constant V_{nom}. During later tests with the AWJSRA, the rate limit was removed from ΔS and placed on V_c. Both methods still leave an objectionable

10-sec periodic throttle variation, which is largely eliminated by methods to be discussed later.

Once the system is in the track mode, there are two reasons why the pilot might want to adjust TOA by a few seconds without having to disengage the mode. First, as the pilot engages the track mode, the computed TOA will usually differ by a few seconds with the ATC-specified TOA, or ATC may request a change in the TOA. For this purpose, a time delay command (TDC) is provided through the data entry panel (Fig. 2). Upon receiving this command, the 4-D RNAV system will automatically adjust the nominal airspeed profile so that TOA will change in the desired direction.

After engaging the track mode, the capture flight path previously displayed as a dashed line is now displayed as a solid line (Fig. 5b), and both phantom and aircraft positions are displayed to indicate the guidance error. The increment of time by which TOA can be advanced or delayed through use of the TDC command is indicated in the fourth line of the next waypoint data (±19 sec) on the MFD. The TDC range is originally centered to provide the pilot with equal flexibility in advancing or delaying TOA after the system is placed in the track mode. As the flight progresses toward the final waypoint, the available TDC interval shrinks, as there is less time available to accomplish the TOA adjustment using speed changes only. To accomplish the TDC (adjustment of TOA), The pilot enters on the keyboard TDC = *XX*, where *XX* stands for the number of seconds of arrival-time adjustment desired.

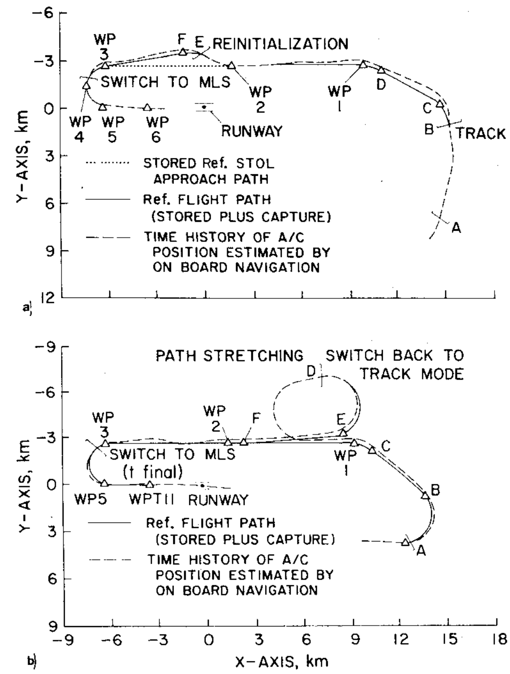

Fig. 6 **Flight paths flown in the CV 340 in pilot evaluation of predictive mode: a) path 1; b) path 2.**

Results and Discussion

Two types of flight tests were performed using the above described system in the CV 340 in the flight director mode. The first type of test was of an operational nature using the predictive mode to answer the question, "Is the continuously recomputed capture flight path, displayed on the MFD, an aid to the pilot in adjusting his approach path to meet the ATC-specified time of arrival?" The second type of test using the track mode was performance oriented to answer the question, "How well can the required arrival time be met?" In this test, the pilot followed flight director commands for path and speed control. We are concerned here with TOA control only (TOA error performance). The path-control-performance measures (crosstrack and altitude errors) for the two types of tests are given in Refs. 4 and 7, respectively. Initial simulator tests of the system (described in the following) when operated in the automatic mode have shown that the throttle activity is high and hence unacceptable to the pilot. Therefore, research has been conducted on methods for reducing throttle activity. Results of this investigation are discussed in a separate section.

Predictive Mode Operation

As previously noted, tests were conducted on the pilot's use of the predictive mode to achieve a predicted TOA under various operational circumstances. The selected flight paths and pilot operations were chosen to be similar to those that might occur in an operational ATC system. During the flight, the pilot was asked to perform a sequence of operations and to evaluate the difficulty of performing these operations in a typical ATC environment. After explaining the symbols in Fig. 6, which shows the flight paths, we will give the purpose of each operation as it may pertain to an operational system and then describe the resulting pilot and system responses. Finally, an overall pilot assessment of the system features is given.

Two of the flight paths flown in the flight test are shown in Figs. 6a and 6b, which will be referred to as paths 1 and 2, respectively. The dotted line, defined by waypoints 1 to 6, represents the fixed, stored reference, STOL approach path similar to the one shown as a solid line in Fig. 3. The solid lines in Fig. 6 represent the reference flight paths, which include the capture flight path and the fixed STOL approach path from the capture waypoint to the final waypoint. In each of the cases illustrated in Fig. 6, the airplane was intentionally flown away from the reference flight path to illustrate and to test different operational features of the airborne system. The dashed lines are the time histories of position of the aircraft as estimated by the onboard navigation system.

In the first test, the ability of the pilot and of the system to make small TOA adjustments to meet an ATC-specified TOA was examined. It was assumed that, in an operational system, the aircraft communicates its predicted TOA to the ATC as it enters the terminal area. Then ATC may assign a required TOA to the ATC as it enters the terminal area. Then ATC may assign a required TOA which would not be very different from the predicted TOA. Thus, the pilot needs to maneuver the aircraft only a small amount to make the predicted and required TOA's coincide. This was simulated from points *A* to *B* on path 1. At point *A*, the pilot was given a simulated ATC instruction to delay the TOA by 30 sec. From point *A* to *B* the pilot executed a slight path-stretching maneuver to accomplish the 30-sec delay. At point *B* the pilot engaged the track mode and began tracking via flight director.

An operational 4-D RNAV system must be capable of changing its nominal flight path temporarily and still accomplish the mission. This path change may be required because of a system malfunction, such as engine-out, or it may be changed purposefully to execute a collision avoidance maneuver, or even because ATC requests a slightly different TOA or arrival route. For these reasons, the system can be taken out of the track mode and reinitialized, then placed back into the track mode. To evaluate this provision, the along-track and crosstrack errors were deliberately allowed to build up near waypoint 2 (Fig. 6a, point *E*) to an *X* (along-track) error of 1583 m and a *Y* (crosstrack) error of 536 m. The reinitialization process, which includes synthesizing a capture flight path to waypoint 3 and a new speed profile plus returning the system to the track mode with a new TOA, took only 1 sec. If it is assumed that the error buildup at *E* was a simulated collision avoidance maneuver, it would be desirable to arrive at the original TOA. Hence, near waypoint 3, the pilot adjusted the TOA to the original desired TOA by entering on the keyboard TDC = 5 sec. The pilot continued tracking the flight path and achieved an arrival time error of 3.1 sec.

Sometimes it becomes necessary for ATC to delay a flight that is already on the STOL approach route. This was simulated on path 2. On this path, while the aircraft was in the track mode between waypoints 1 and 2, the pilot was told to delay his predicted TOA by 3 min. This delay time was beyond the range of shifting TOA by speed control alone (TDC), and therefore, path stretching was necessary. Halfway between waypoints 1 and 2, the pilot started to fly the aircraft away from the reference trajectory in a right turn and initiated path stretching similar to beginning a standard holding pattern. Fifty seconds later, halfway around the first 180° turn, the system was switched to the predictive mode to observe the varying TOA, as displayed on the MFD. Twenty seconds later (at *D*), the new desired TOA was on display on the MFD, and the pilot switched the system back to the track mode, resulting in a new TOA within 1 sec of the desired TOA. Ten seconds later, the pilot adjusted TOA to the desired value by exercising the TDC command. Note that the overall path-stretching maneuver resulted in a conventional holding pattern. The pilot continued tracking the flight path and achieved an arrival time error of 3.2 sec.

Pilot Acceptance of Predictive Mode

The following are pilot comments on the operational suitability of the predictive mode:

Although the flight test environment was not fully representative of an operational situation (e.g., single aircraft, ATC simulation, and visual flight conditions), the pilot felt that the system had the potential for being acceptable in an operational environment. Some specific observations were noted.

1) Arriving at the specified TOA was an easy task. It was easy to adjust the initial flight path to allow track mode engagement so that the specified TOA was made. TOA adjustments subsequent to engagement of the track mode were also easily accomplished.

2) The STOLAND displays (EADI, MFD, HSI, and status panel) permitted the progress of the flight to be monitored easily. The map display on the MFD was particularly useful for a quick assessment of situation data.

Track Mode Performance

To test the track mode, 27 flights were made in the NASA CV 340 aircraft in the flight director mode which included flight director speed commands. The flight consisted of 9 racetrack flight patterns flown at constant altitude with the long axis oriented along the runway centerline and 18 landing approach flight paths of the shape shown in Fig. 3. In these tests, the capture flight-path computation was not implemented. Instead, the aircraft was guided toward the first flight-path segment via an untimed capture control law similar to a localizer capture, and it was assumed to have zero time error when it passed the first selected waypoint. However, the track guidance laws[7] were improved over those in the system, which included the capture flight path.[4]

Figure 7 presents the longitudinal guidance error (ΔS), the commanded airspeed, the true airspeed, and the ground speed for the approach shown in Fig. 3. Also shown are the nominal airspeed specified for one reference path (Fig. 3) and the boundaries of the allowable airspeed commands, designated by the unshaded area, which are based on the aircraft performance capabilities. A comparison of the ground speed and true airspeed in Fig. 7 indicates the strong headwind conditions experienced by the aircraft on the flight path between waypoints 1 and 3. In these tests, the nominal TOA was calculated for zero wind condition. Hence, for the given wind, the aircraft should fly at an airspeed above the nominal to meet the specified arrival time. As shown, the rate-limited longitudinal error ΔS increased linearly, and the airspeed command increased above the nominal airspeed for the first 3000 m of track distance. Note, in this example, the decrease of nominal airspeed along the path is just offset by the increase due to the 0.04 ΔS term in Eq. (2). From waypoints 3 to 4, ΔS decreased linearly at its rate limit, as the aircraft caught up with the target and the commanded airspeed approached the nominal. In this approach, a longitudinal error of 76 m, which is equivalent to a 1.3-sec time error, remained to be corrected at waypoint 6.

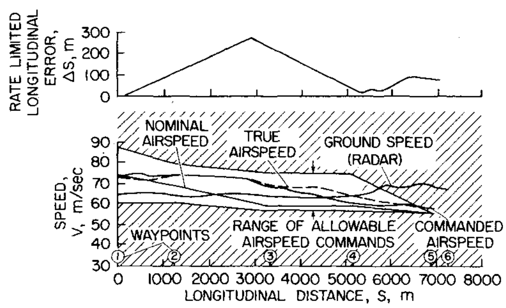

Fig. 7 Longitudinal guidance in the CV 340 flight director mode.

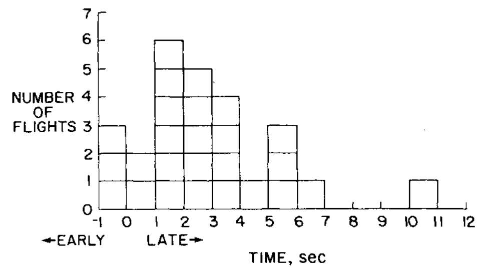

Fig. 8 Arrival time error histogram for 27 flights in a CV 340.

Figure 8 shows the arrival time errors experienced in the flights in the form of a histogram. The figure shows, for example, that there were 15 flights which were between 1 and 4 sec late arriving at the final waypoint. The preponderence of late arrivals was caused by navigation errors, which in turn were caused by both TACAN and MODILS DME errors. The errors were such that the DME's indicated a range shorter than the actual range. With the navaids positioned as shown in Fig. 3, these errors caused a path to be flown that was, on the average, 350 m longer than the reference path. Therefore, the path had to be flown at a speed above the nominal airspeed. From the speed control law [Eq. (2)], the increased speed $V_c > V_{nom}$ can be achieved only by the phantom leading the aircraft. Since the phantom always arrives at the final waypoint at the proper time, the resulting actual TOA errors of the aircraft were mostly positive (late arrival). The spread of the TOA errors is caused by wind measurement errors, navigation errors, and loose tracking of the speed commands by the pilot. As shown in Fig. 8, one of the flights had a TOA error of 10.8 sec. For this particular flight, the estimated TOA was based on flying at nominal airspeeds under zero wind conditions. In this case, the system was engaged at waypoint 1 at the nominal airspeed of 150 knots. For the downwind leg there was a strong headwind of about 23 knots. The phantom aircraft moved along the path at a ground speed of 150 knots, thus immediately building up a ΔS error. However, as discussed previously, the ΔS error is limited to a maximum 0.47-knot/sec acceleration command. Therefore, the system slowly commanded an increase in airspeed up to the maximum value of 170 knots to compensate for the headwind. The data indicated that it took 85 sec to increase the airspeed from 150 to 170 knots. The maximum allowable airspeed of 170 knots was too low to allow the aircraft to catch up with the phantom aircraft despite the fact that the headwind became a tailwind after the turn (past waypoint 5) and the maximum airspeed was still maintained. As the data in Fig. 8 indicate, when the winds were in the range of the system capability, the TOA control was very good.

Pilot Acceptance of Track Mode

The workload associated with controlling the longitudinal and lateral flight director was quite low, allowing adequate time to monitor the progress of the flights. To minimize throttle activity and to keep workload to an acceptable level, the pilot did not follow the speed commands tightly, but made gross throttle adjustments after a substantial buildup in the error. As the aircraft approached the final waypoint, the pilot tended to close the speed control loop more tightly (observe the ΔS curve in Fig. 7 for a typical flight). Using the preceding procedure, arriving at the specified TOA was an easy task. Similar to the predictive mode, the STOLAND displays permitted the progress of the flight to be monitored easily.

In these preliminary flight tests, no attempt was made to study the use of simpler displays. However, the STOLAND mechanical HSI is programed to display altitude error, lateral path error, and distance to the next waypoint. If, in addition, the written information in the MFD display is maintained to simulate a simple alphanumeric display, this information, together with a printed approach plate, would provide all the information for successful 4-D RNAV operation. Such tests may be flown during commercial pilot evaluation of the system.

Throttle Activity

To investigate the system performance in the automatic mode, several simulation and flight tests of the previously described system were conducted in the AWJSRA. It was determined that varying winds and navigation errors result in large throttle activity which would probably be unacceptable to the pilots. Two methods of reducing throttle activity were investigated. These methods, which may be used independently or jointly, are aimed at reducing throttle activity by 1) arrival time estimate smoothing and 2) by scheduling velocity command gains as a function of distance from the final waypoint.

Method 1 – Arrival Time Estimate Smoothing

As shown previously, the position of the displayed phantom aircraft is based on an estimate of nominal arrival times t_i at each waypoint. The estimated t_i's change every 10 sec with the change in the wind estimate. This makes ΔS jump every 10 sec as shown in Fig. 9a. If computer time were available to evaluate Eq. (1) every computer cycle, such jumps would not occur. As an alternative, to prevent the jumps in ΔS, the old arrival times from 10 sec ago t_{io} are saved at each update interval and are used with the new arrival time estimates t_{in} to obtain a smoothly varying linear interpolation of t_i

$$t_i = \frac{t_{io}(10-t) + t_{in}t}{10}; \quad 0<t<10 \tag{4}$$

These continuously varying estimates of the t_i's are now used in the polynomial expressions for $S(t)$ [Eq. (3)] to obtain a smooth variation of ΔS (see Fig. 9b). Since ΔS is now a smoothly varying value with time, the speed commands also vary smoothly with time, resulting in a reduction of short-term throttle activity.

Method 2—Velocity Command Gain Scheduling with Time-to-Go to the Final Waypoint

This method is based on reducing the variation in velocity commands and hence throttle commands when the aircraft is farthest from its destination where jumps in ΔS are largest. These large changes in ΔS are caused by changes in the wind estimates, which result in a change in the phantom position roughly proportional to the time-to-go to the final waypoint. When the aircraft is far from its destination, there is more time to correct TOA errors and therefore no need to tightly track the phantom. As a result, the speed control law was

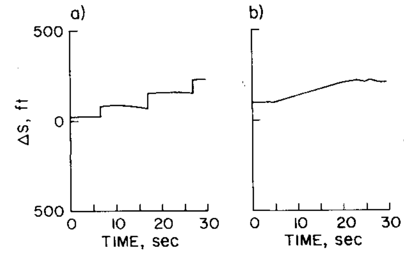

Fig. 9 Plot of phantom aircraft position error vs time from CV 340 simulation: a) no smoothing; b) with smoothing.

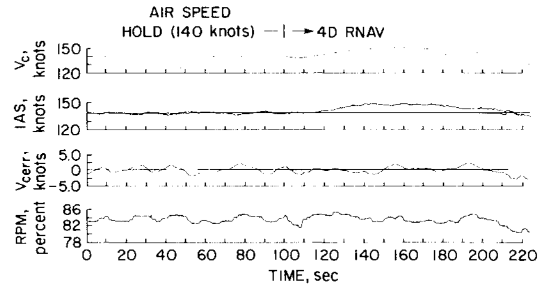

Fig. 10 Comparison of Augmentor Wing flying in airspeed hold and 4-D RNAV.

modified to have a time-to-go dependent varying gain, 0.04 $(200/T)$, where T is the time-to-go

$$V_c = V_n + 0.04 \left| \frac{200}{T} \right|_{\leq 1} \Delta S \tag{5}$$

This speed control law was test flown in the AWJSRA aircraft. Preliminary flight results indicate that throttle activity is reduced in the early portion of the flight path. Simulator tests indicate that there is no penalty in increased TOA errors.

Methods 1 and 2 Combined

As previously noted, for minimum throttle activity, methods 1 and 2 can be used jointly. In spite of the implementation of the preceding methods 1 and 2 to provide speed control without objectionable throttle activity, some throttle activity still occurred which was acceptable to the pilots, but which may be objectionable in passenger service. It was hypothesized that a portion of the throttle activity was inherent in the basic airplane autothrottle. To test this hypothesis, the Augmentor Wing aircraft was flown first with the autothrottle in the airspeed hold mode and then with speed commands from the 4-D RNAV system, which had methods 1 and 2 implemented. Figure 10 shows data for 100 sec each of flight in the airspeed hold mode and the 4-D RNAV mode. The nominal airspeed for both modes was 140 knots. Due to an increase in the measured wind in the x-direction, the 4-D RNAV system commanded an airspeed increase of a maximum of 10.5 knots. The graph shows that the command is smooth (Fig. 10a), and the airspeed is noisy (Fig. 10b). The difference between the two quantities is a noisy airspeed error, V_{cerr} (Fig. 10c), which results in varying engine rpm (Fig. 10d).

Analysis of the data from this flight, as well as from two other flights, indicates that the throttle activity in 4-D RNAV is indistinguishable from the activity when the autothrottle is operated in airspeed hold. Therefore, if future experience indicates that the throttle activity is too high for passenger service, the basic autothrottle itself needs to be redesigned.

The previously discussed methods reduced short-term throttle activity. Now a method which uses a simple wind model for reducing long-term throttle activity will be discussed.

Table 1 Simulation results

Quantities averaged over 20 flights (sec)	Wind assumption		
	Constant	Interpolated	Exact
Mean arrival time error	0.364	0.363	0.31
Standard deviation	0.95	0.32	0.058
Mean $[\sigma V_{com} - V_{nom})]$	4.43	3.63	0.742
$\sigma[\sigma(V_{com} - V_{nom})]$	1.71	1.25	0.0624

Method 3 – Wind Profile Modeling

In the present speed control system, it is assumed that winds are constant along the whole approach path. This assumption is not very realistic, especially if the altitude changes drastically along the path. As a better approximation, one can assume a wind profile that varies linearly from the wind estimated at the present altitude of the airplane to the wind measured at the airport.[2] Using this wind profile in the Δt_i calculations [Eq. (1)], the estimated nominal TOA at each waypoint would change much less with time, thereby resulting in a reduction in throttle activity. Since the values of the t_i are obtained by numerically integrating over the path where each step contains the wind estimate, use of this wind profile could easily be incorporated in the present system.

A simulation was conducted on the IBM 360 computer to study system performance improvement due to wind modeling. In this simulation, 20 widely varying wind profiles measured at the Oakland, Calif. Weather Service Station were used. For a complex flight profile with an altitude variation of 3500 ft, performance measurements were obtained for the following three systems: 1) existing system, which assumes that the wind is constant over the remaining path for updating the t_i calculation every 10 sec; 2) interpolated winds as described in the preceding; and 3) exact knowledge of the wind profile, as a standard check for other inaccuracies of the computations. The results are shown in Table 1.

Even with exact knowledge of the wind, system errors occur. These are primarily due to deceleration commands in the last part of the flight path, which are not followed immediately due to a 3-sec lag in the aircraft speed response. The main improvement using interpolated wind compared to the present method is in the reduction of the arrival time dispersion to one-third of the original value.

The mean over 20 flights of the standard deviations for each flight of the difference between nominal and commanded airspeed (Mean $[\sigma(V_{com} - V_{nom})]$), is also reduced by 18%, and the variance of this quantity by 30%. This means that the aircraft stays more closely at the nominal airspeed when the winds are interpolated. This may improve aircraft sequencing operations somewhat. Since we are dealing with slowly varying quantities, throttle "thrashing" is not reduced by this method.

Concluding Remarks

Although the flight test environment was not fully representative of that which might be experienced in a typical terminal area, the pilot felt that the system concepts had the potential for use in an operational environment.

1) In the predictive mode, it was easy for the pilot to adjust the initial flight path to allow track mode engagement so that the ATC-specified time of arrival was made. TOA adjustments subsequent to track mode engagement were also easily accomplished.

2) In the track mode, arriving at the specified TOA was an easy task. The workload associated with controlling the longitudinal and lateral flight director was quite low. However, to minimize throttle activity and to keep workload at an acceptable level, the pilot did not follow speed commands tightly, but made gross throttle adjustments after a substantial buildup in the error. As the aircraft approached the final waypoint, the pilot closed the speed control loop more tightly.

3) The TOA errors at a point about 2 miles from touchdown were ± 5.14 sec (2σ).

4) The STOLAND displays permitted the progress of the flight to be monitored easily. The map display on the MFD was particularly useful for quickly assessing the horizontal situation of the aircraft.

5) Simulator and flight tests showed that with the methods described in this paper, throttle activity in the automatic mode was held within levels acceptable to the pilot.

References

[1]Tobias, L. and Erzberger, H., "Simulation of 4-D RNAV in the Terminal Area," *Proceedings of the IEEE Systems, Man, and Cybernetics Society,* Dallas, Tex., Oct., 1974.

[2]Hemesath, N.B., Bruckner, J.N.H., Krippner, R.A., "Three- and Four-Dimensional Area Navigation Study," Department of Transportation, Federal Aviation Administration, Washington, D.C., FAA-RD-74-150, June, 1974.

[3]Neuman, F., Watson, D.M., and Bradbury, P., "Operational Description of an Experimental Digital Avionics System for STOL Airplanes," NASA TM X-62, 448, 1975.

[4]Lee, H.Q., Neuman, F., and Hardy, G.H., "Four-Dimensional Area Navigation System Description and Flight-Test Results," NASA TN D-7874, 1975.

[5]Neuman, F. and Warner, D.N., "A STOL Terminal Area Navigation System," NASA TM X-62, 348, 1974.

[6]Pecsvaradi, T., "Four-Dimensional Guidance Algorithms for Aircraft in an Air Traffic Control Environment," NASA TN D-7829, 1975.

[7]Smith, D.W., Neuman, F., Watson, D.M., and Hardy, G.H., "A Flight Investigation of a Terminal Area Navigation and Guidance Concept for STOL Aircraft," NASA TM X-62, 375, 1974.