NASA Technical Paper 2616

November 1986

Ground-Based Time-Guidance Algorithm for Control of Airplanes in a Time-Metered Air Traffic Control Environment

A Piloted Simulation Study

Charles E. Knox
and Nicole Imbert

NASA

NASA
Technical
Paper
2616

1986

Ground-Based Time-Guidance Algorithm for Control of Airplanes in a Time-Metered Air Traffic Control Environment

A Piloted Simulation Study

Charles E. Knox
Langley Research Center
Hampton, Virginia

Nicole Imbert
ONERA/CERT
Toulouse, France

National Aeronautics
and Space Administration

Scientific and Technical
Information Branch

Summary

A piloted simulation experiment was used to study and evaluate a time-guidance algorithm concept designed to provide guidance for an airplane to cross a metering fix at a designated time. The guidance provided to the pilot during these tests consisted of two airspeed commands and one heading command that were based upon time errors at three intermediate fixes on a nominal flight path to the airport. Eight different test conditions were evaluated to determine initial time-error effects, airspeed-limit effects, and the wind-modeling unknown effect upon the capability of the time-guidance algorithm to null the time error at the final metering fix. These cases were compared to a set of baseline tests in which no errors were artificially induced.

The Federal Aviation Administration's 250-knot airspeed limit for flight at an altitude less than 10 000 ft mean sea level can reduce the time controllability of the algorithm when higher airspeeds are required to null the time error. The severity of the reduction of time controllability of the algorithm is variable and is a function of the path design.

The effects of mismodeled winds were examined by adding a 10-knot bias to the wind for all altitudes during two test scenarios, one with a prevailing head wind and the other with a tail wind. The test results with these scenarios showed that most of the time error at the metering fix was accrued on the last path segment after the final heading command was issued. The magnitude of the error accumulated on the last path segment would be dependent upon the length of this segment, the magnitude of the wind modeling error, and the time exposed to the wind modeling error.

An initial time error of ±60 sec was induced in three more test scenarios. Final mean time errors of 8.4 sec or less resulted when both airspeed and heading command corrections were computed by the time-guidance algorithm. However, in the scenario in which the 250-knot airspeed limit precluded an increase in airspeed to null the time error, the initial 60-sec time error was reduced to 21.3 sec through use of only the heading command correction.

The subject pilots reported that the airspeed and heading commands generated by the time-guidance algorithm were easy to follow and did not increase their work load above normal levels. Airspeed and heading errors recorded during each of the test runs were within normal operating tolerances.

Introduction

The rapidly increasing cost of flight operations and the necessity for fuel conservation have made it necessary to develop more efficient ways to operate individual airplanes and to control air traffic for arrival and departures to the terminal area. Airborne flight management systems have been designed and implemented that can result in an individual airplane fuel savings of 2 to 6 percent (ref. 1). Advanced air traffic control (ATC) procedures and systems are being designed to reduce traffic delays in the terminal area by metering and sequencing arrival and departure airplanes. Two of these air traffic control systems (one is being designed for Eurocontrol (ref. 2) and one is on an operational basis in the United States (ref. 3)) utilize time control to meter arriving traffic. In the time-based ATC systems, a time is assigned for each airplane inbound to the terminal area to cross a metering fix. This time is computed such that when airplanes cross the metering fix at their assigned times, they may continue along a nominal path to the runway without conflicts from other arrival traffic.

In the United States airports at Dallas-Ft. Worth, Texas, and Denver, Colorado, time-based-metering operational procedures require the ATC controller to provide radar vectors and airspeed commands so that each airplane will cross the metering fix (typically located 35 to 50 flying miles from the runway) at the assigned time. These vectors and commands are determined by the controller and, depending upon his skill, result in metering-fix crossing-time accuracies of between 1 and 2 min (ref. 4).

If this time error can be reduced at the metering fix or nulled along a nominal path prior to the point at which all airplanes are merged, the extra flight time required for final sequencing and spacing for landing can be reduced. This reduction of extra flight time can potentially save a significant quantity of fuel. Flight tests have shown that airborne electronically computed guidance may be used to fly fuel-conservative trajectories while maintaining a desired time schedule (refs. 5 and 6). However, airborne electronically computed time guidance is not readily available on the current generation of commercial transport airplanes.

As an alternative to airborne computations, time guidance could be computed on the ground and provided to each arriving airplane. The ONERA/CERT of Toulouse, France, has developed a time-guidance algorithm concept in which heading and speed command corrections are computed for a pilot to follow in order to cross a metering fix at a designated time. Once a time has been assigned for an airplane to cross a metering fix, command corrections may be radioed to the pilot as he approaches the metering fix. The command corrections are computed based on the difference between desired and actual times in crossing intermediate time checkpoints that lie on a nominal path to the metering fix. A fast-time computer simulation study (ref. 7) using the ONERA/CERT guidance with three ATC corrections (two airspeed and one heading) to a metering fix located about 10 n.mi. from the runway resulted in a mean crossing-time error of 8.5 sec (late) with a standard deviation of 9 sec.

Software of the ONERA/CERT time-guidance algorithm was then integrated into a real-time piloted simulation by NASA to study and evaluate the operational concepts and to determine the effects that various operational constraints had on time controllability of the algorithm. In this study, the guidance algorithm was applied to a path that began 53.5 flying miles from the runway. A final metering fix was established at the outer marker of an Instrument Landing System (ILS) approach 5.7 n.mi. from the runway threshold. As the pilot flew along a nominal path toward the airport, he was given heading and calibrated-airspeed command corrections required to satisfy a time objective for crossing the metering fix. This report will summarize the computations of the time-metering guidance algorithm, describe the piloted simulation tests and facilities, and present the results of this study. A summation of the test conditions and results is presented in tables I and II.

Symbols and Abbreviations

ATC	air traffic control
a_1, a_2, a_3	coefficients for quadratic equation to evaluate airspeed changes at time checkpoint 1
$b_{1,k}, b_{2,k}, b_{3,k}$	coefficients for quadratic equation to evaluate airspeed changes at time checkpoint 2
CRT	cathode ray tube
$c_{1,k}, c_{2,k}, c_{3,k}$	coefficients for quadratic equation to evaluate heading changes at time checkpoint 3
ILS	Instrument Landing System
MSL	mean sea level
S.D.	standard deviation
$t_{e,1}, t_{e,2}, t_{e,3}$	time error at time checkpoints 1, 2, and 3, respectively, sec
t_i	time required to fly between time checkpoints and metering fix, sec
$t_{i,k}$	time to fly between time checkpoint 2 and metering fix at an off-nominal calibrated airspeed, sec
t_{nom}	nominal time to fly between time checkpoint 1 and metering fix at 250 knots, sec
$t_{\text{nom},k}$	time to fly between time checkpoint 2 and metering fix at a nominal calibrated airspeed, sec
Δt_i	difference in time to fly the path at nominal and off-nominal calibrated airspeeds and/or headings, sec
$\Delta t_{i,k}$	difference in time to fly between time checkpoint 2 and metering fix at nominal and off-nominal calibrated airspeeds, sec
V_{cas}	calibrated airspeed, knots
V_i	commanded airspeed, knots
V_{nom}	nominal calibrated airspeed along path segment 1, knots
$V_{\text{nom},k}$	nominal calibrated airspeed along path segment 2, knots
V_1, V_2	airspeed commands for pilot to follow based on time error at time checkpoints 1 and 2, respectively
ΔV	change in airspeed computed at first and second time checkpoints, knots
ΔV_i	difference in nominal and off-nominal calibrated airspeeds along path segment 1, knots
$\Delta V_{i,k}$	difference in nominal and off-nominal calibrated airspeeds along path segment 2, knots
WAL	identification letters for the VORTAC navigation facility located on the airport

Ψ	heading command for pilot to follow based on time error at time checkpoint 3
Ψ_i	off-nominal heading along path segment 3, deg
Ψ_{nom}	nominal heading along path segment 3, deg
$\Delta\Psi$	change in heading computed at time checkpoint 3, deg
$\Delta\Psi_i$	difference between nominal and off-nominal headings along path segment 3, deg

Subscripts:

i	column elements of time, calibrated airspeed, and heading matrices
k	identifier of a particular time, calibrated airspeed, and heading matrix

Description of Time-Guidance Algorithm

The time-guidance algorithm is a digital computer program designed to provide guidance in the form of a limited number of discrete heading and airspeed commands for a pilot to follow that will result in his airplane crossing a metering fix at a preassigned time. The heading and airspeed commands are based on time errors determined as the airplane crosses intermediate time checkpoints along a nominal path.

The time-guidance algorithm has three major functions, as shown in the functional diagram in figure 1. The first two functions are performed in a fast-time mode and the last function in a real-time mode. The first function is a data-generation function that uses mathematical representations of an airplane, autopilot, and linear (with altitude) wind model to compute differences in time that result when off-nominal airspeeds and headings are used to fly along the approach path to the airport. The differences between the nominal and off-nominal airspeeds and headings are correlated to the time differences and stored in data tables for use in the quadratic curve-fit function.

Although a detailed model of a Boeing 737 airplane was used in the data-generation function during these simulation tests, it is anticipated that a generic airplane model for airplanes of similar weights and flight characteristics would be used by a ground-based ATC computer. It is believed that this use would not significantly affect the operational aspects of using the algorithm to control airplanes or affect the final time error at the metering fix.

The second function of the time-guidance algorithm is to compute the coefficients of a quadratic curve fit of the time-difference data stored in the data tables. A least-squares method is used and results in a matrix of coefficients that are used for computing airspeed and heading increments to be added to the nominal airspeed and heading commands.

The third function of the time-guidance algorithm, performed in a real-time mode, is to compute airspeed and heading commands to be given to the pilot. The coefficients generated in the quadratic curve-fit function are used to determine new calibrated airspeeds and/or headings to be flown based on the time error attained as the airplane crossed each intermediate time checkpoint. These computed airspeeds and headings are rounded to the closest 5-knot and 5° increment, respectively, and are limited to the appropriate maximum or minimum values determined for the path. These commands are then printed on a CRT display being used by an ATC controller. The controller would then issue the commands verbally to the pilot.

The software configuration of the time-guidance algorithm is a function of the number and type of time checkpoints prior to crossing the metering fix. Although the path used during these simulation tests (shown in fig. 2) was configured for two airspeed command checkpoints followed by one heading command checkpoint, other configurations, such as one speed command checkpoint followed by one heading command checkpoint, could have been used as well. The dimensions of the matrices produced by the data generation and, subsequently, the quadratic curve-fit functions of the algorithm are dependent upon the number and type (airspeed and/or heading) of computed commands designed in the nominal flight path. A more detailed discussion of these functions and their output, using the path configured for these simulation tests, may be found in appendix A.

Simulator Description

The time-metering guidance concept was evaluated in the Langley Visual/Motion Simulator (VMS). The VMS is a six-degree-of-freedom, motion-base simulator capable of presenting realistic acceleration and attitude cues to the pilot. A general-purpose, scientific mainframe computer with a nonlinear, high-fidelity digital representation of a Boeing 737 airplane provided inputs to drive the VMS motion-base system. Audio cues for engine thrust and aerodynamic buffet were also provided. The simulator had a generic cockpit with conventional airplane flight controls and instrumentation. The flight controls included a column and control wheel; rudder pedals; and throttle, speed brake, and flap controls located on a center console. Flight instrumentation included electromechanical flight and navigation instruments and engine instrumentation.

During these simulation tests, a pictorial representation of airplane position relative to the nominal flight path, representing an ATC controller's display, was shown to the test conductor (who was also acting as copilot). This display was not visible to the pilot during these tests. This pictorial representation was drawn by a general-purpose graphics computer connected to the mainframe computer that drove the motion-base system. The VMS facility is described in more detail in reference 8.

Test Objectives

The objectives of this test were (1) to evaluate the operational concept of providing heading and calibrated airspeed command corrections to the pilots from ATC for time-control purposes, and (2) to assess the effects of various operational and environmental constraints. These objectives were achieved through evaluation of operational data and subjective comments from the pilot test subjects recorded during a series of simulated flights along a nominal path to the airport.

Experiment Design

Experiment Tasks

The operational goal in this experiment was to cross the metering fix, located at the ILS outer marker, at an assigned time through the use of speed and heading corrections computed by the time-guidance algorithm. The pilot's task was to fly inbound to the airport along a VORTAC radial with reference to the terminal arrival-procedure chart depicted in figure 3. The pilot was to respond to ATC clearances and instructions that included descents and speed and heading changes required for intercepting and tracking the ILS localizer.

The test conductor acted as copilot during these descents and assisted the pilot with airplane configuration, radio tuning, and any other requests made by the pilot. The test conductor also issued ATC clearances and commands based upon information from a CRT display that showed the airplane position relative to the nominal path and showed speed and heading commands generated by the time-guidance algorithm. This display was not visible to the subject pilot during the tests.

Description of Nominal Test Path and Test Procedures

The nominal path used during these tests, shown in figure 2, began at time checkpoint 1 and continued to the outer marker located 5.7 n.mi. from the runway threshold. The nominal path was 53.5 n.mi. long and required 793.5 sec to fly if the programmed nominal speed and altitude profiles were maintained.

At the beginning of each test run, the airplane was located at time checkpoint 1 at an altitude of 10 000 ft MSL with a calibrated airspeed of 250 knots. A time check was performed automatically by the time-guidance algorithm to determine if a speed change was required. If required, an ATC clearance would be issued for the pilot to maintain a new airspeed. The pilot was also given a clearance to descend to 4000 ft when his commanded airspeed was obtained.

Airspeed changes were given in 5-knot increments about the nominal airspeed up to a maximum of ±15 knots. Although the time-guidance algorithm was capable of computing the exact airspeed necessary to null the time error, it was not considered operationally practical to issue changes in less than 5-knot increments to preclude successive speedup commands and then slowdown commands, or vice versa. Current ATC procedures of the Federal Aviation Administration (FAA) specify that airspeed changes commanded by an ATC controller will be made in multiples of 10 knots (ref. 9).

The maximum and minimum 15-knot calibrated airspeed deviations about the nominal airspeed resulted in reasonable time control for this path. Larger speed deviations would result in greater time control but could result in substantially higher fuel costs because of acceleration requirements for higher airspeeds or extra flight time necessary at the slower airspeeds. Longer nominal flight paths may be able to accommodate larger off-nominal airspeed restrictions without adverse effects. Each path should be individually assessed.

When the airplane crossed time checkpoint 2, a second time check was performed by the time-guidance algorithm to determine if another speed change was required. If the change was required, an appropriate ATC clearance was given. Airspeed changes were again issued in 5-knot increments, limited to a maximum speed of 265 knots or a minimum speed of 235 knots.

The airplane would typically reach the 4000 ft MSL altitude prior to reaching time checkpoint 3. Once an altitude of 4000 ft was attained, the pilot would maintain level flight. At time checkpoint 3, a third time check was performed by the time-guidance algorithm to determine the heading to which the airplane should be turned. An ATC clearance to reduce speed to 210 knots and to turn to the computed heading was issued at time checkpoint 3. The heading for the nominal path was 190°. Headings were issued in 5° increments up to a maximum of ±10° about the nominal heading for path adjustments to minimize the first time error.

After the turn to the computed heading was completed, an ATC clearance was given to descend to 1500 ft MSL. When the airplane was approximately 2.5 miles from the ILS localizer course, an ATC clearance was given to turn to a heading of 250°. This heading resulted in a 30° localizer intercept angle at a point more than 4 miles from the ILS outer marker. This clearance was followed by another clearance to conduct an ILS approach and to reduce the airspeed of the airplane to 140 knots. The pilot deployed the flaps and landing gear at his discretion. The test run was completed after the ILS outer marker was crossed.

Path Design, Time Controllability, and Time Resolution

The design of the path, including the various operating and geometric constraints, governs the total time controllability, which is defined as the maximum time error that the time-guidance algorithm can absorb through heading and speed corrections. The most significant factors affecting time controllability are path length and path stretch capability through turns (heading corrections). Time controllability is also affected by airplane performance capability (maximum and minimum airspeeds) and the ATC 250-knot airspeed limit for flight below 10 000 ft MSL.

The length and geometric shape of the path used in this simulation study (nominally 53.5 n.mi. long and requiring 793.5 sec to complete) were typical of a flight path contained within the boundaries of an ATC-approach control facility at a major airport. The total time controllability and the components due to airspeed commands and heading commands of the algorithm are listed in table III, with the operating constraints noted in the previous section entitled "Description of Nominal Test Path and Test Procedures." The total time controllability for the test path with no wind was −75.9 sec for an early arrival (requiring a reduced airspeed and a shorter path length to null the time error) and 71.7 sec for a late arrival (requiring an increased airspeed and a longer path to null the time error). However, when the ATC 250-knot airspeed limit was applied, higher airspeeds could not be commanded and the total time controllability was reduced to 39.0 sec for the late arrival.

The magnitudes of the time controllability components due to the heading and airspeed commands shown in table III indicate that a significant amount of time controllability can be obtained by changing the length of the path via different heading commands during turns. Although the magnitude of the time controllability due to heading commands would be dependent upon the actual path geometry, the results of these tests suggest that total time controllability could be increased by utilizing several turns in the approach path. Design trade-offs would have to be made between the added computational complexity and additional lateral airspace required for multiple turns versus the additional time controllability gained.

The operating and geometric constraints applied to path design also influence the time resolution, which is defined as the degree of accuracy that the airspeed and heading commands can null the final time error at the metering fix. The time-guidance algorithm is capable of computing an exact speed and heading command (within the defined airspeed and heading limits) that, if followed, would result in no time error at the metering fix. However, valid operational considerations may preclude exact airspeed and heading commands to be issued. These airspeed and heading operating constraints can result in commands that, even if followed exactly, will result in some time error at the metering fix.

During these simulation tests, heading increments in multiples of 5° were issued to the pilot for the turn at time checkpoint 3. Because of this particular path geometry and the nominal airspeed schedule, each 5° heading increment off the nominal path heading of 190° would change the arrival time by approximately 20 sec. The algorithm would not compute a heading change unless the time error at time checkpoint 3 was greater than 10 sec (i.e., one-half of the 20-sec increment). This limitation resulted in resolving the final time error to approximately 10 sec.

Test Conditions

Eight different test conditions (A to H), shown in table I, were flown by each subject pilot. Each test condition consisted of a different combination of three variable test parameters. Each test variable was changed to determine its effect on the resulting time error when the metering fix was crossed. The three variable test parameters were (1) the application of the ATC constraint of 250-knots maximum airspeed for flight at altitudes below 10 000 ft MSL, (2) an initial time error at time checkpoint 1, and (3) an unplanned head (or tail) wind.

ATC 250-knot airspeed limit. For ATC purposes, the FAA has imposed an airspeed limit that requires airplanes to be operated at an airspeed of 250 knots, or less, when flown at an altitude below 10 000 ft MSL. However, since this regulation is not imposed on an international basis, the time-guidance algorithm may be applied in some areas without this constraint. The impact of this operational constraint on the time-guidance algorithm is to limit time controllability if the altitude of the flight path is below 10 000 ft MSL and a command airspeed greater than 250 knots is required. The severity of this impact is dependent upon the nominal path design. For the nominal flight path used during these simulation tests, the guidance algorithm could command airspeeds and headings that would null an initial time error up to 71.7 sec (late). However, when the 250-knot speed limit was applied, the maximum time controllability was reduced to a 39.0-sec-late initial time error. This 39.0-sec controllability was obtained solely from the additional 10° of turn added to the nominal 190° heading computed at time checkpoint 3. The 250-knot speed limit would have no effect on the capability of the algorithm to null time errors requiring slower airspeeds.

Test conditions A and B were used to make direct comparisons of the effects of the 250-knot airspeed limit with no initial time errors or unplanned winds. Other test conditions were defined to examine the effects of the airspeed limit when initial time errors and unplanned winds were present.

Initial time error. Once the path is designed (including an airspeed and altitude profile and a wind model computed), a nominal time increment to fly between time checkpoint 1 and the final metering fix (ILS outer marker for these tests) can be determined. Then, when a time has been assigned by ATC for an airplane to cross the final metering fix, a corresponding time for the airplane to cross time checkpoint 1 would also be uniquely defined. Although it would be desirable to have the airplane cross checkpoint 1 with no time error, it is most likely that some time error will exist. The magnitude of this initial error will be dependent upon the scenario in which the guidance algorithm is designed to be used in the ATC system and by the process used to navigate the airplane to the initial fix.

In the scenario for these tests, it was assumed that the FAA's time-based enroute metering program (ref. 5) would be used to guide the airplane to the initial fix (time checkpoint 1) while satisfying a time constraint. Current control procedures in the FAA's time-based, enroute-metering ATC environment utilize radar vectors and result in time-delivery errors between 1 and 2 min. The time-guidance algorithm in these tests was then used to reduce further the time error at the initial metering fix. Initial 60-sec-late time errors (requiring higher airspeeds to null the time error) were formulated for test conditions C (with the 250-knot airspeed limit) and D (without the 250-knot airspeed limit). A 60-sec-early time error (requiring lower airspeeds to null the time error) was formulated for test condition E. These test conditions were used to examine initial time-error effects.

Unknown winds. The time-metering guidance algorithm utilized a linear wind model to compute airspeed commands for the pilot to follow. The airspeed commands were based on computations of the ground speed necessary to satisfy time constraints at each checkpoint along the decent path. In an operational environment, the wind model would be constructed based on forecasted and reported wind velocities. Since forecasted and reported wind data tend to be more than several hours old in the current operational environment, and since the atmosphere is very dynamic in nature, some wind modeling error should be expected.

Three test conditions (F, G, and H) were formulated to determine the effects of mismodeled winds upon the time guidance computed by the algorithm. For these tests, the time-guidance algorithm computed commands for the pilot based on a no-wind (zero-velocity) condition. However, while conducting the tests, a constant 10-knot wind velocity bias was included that resulted in an error of the ground speed calculated by the algorithm that further induced a time error at each time checkpoint.

For test conditions F and G, a 10-knot wind from 247°, constant at all altitudes, resulted in a prevailing head wind and thus tended to produce a late time arrival (positive time error) at each time checkpoint. The ATC-imposed 250-knot airspeed limit was applied during test condition F but was not applied during condition G. For test condition H, the wind was the same as that used in conditions F and G except that it was from the reciprocal heading 067° resulting in a prevailing tail wind. The prevailing tail wind encounter during these runs always resulted in slower speeds (250 knots or less) being commanded by the time-guidance algorithm. Hence, the 250-knot speed limit had no effect during these tail wind conditions.

Recorded Data

A data set that described the position, state, and configuration of the airplane was recorded once each second. The data set also contained navigational data such as the identification of the navigation radio facility tuned, distance measuring equipment (DME) mileage indication, and course selection and deviation; wind speed and direction; and heading and airspeed errors. All data were stored on magnetic tape for postflight analysis.

Test Subjects

Six subject pilots were used during these tests. Five were experimental test pilots and one was a NASA engineer. The five test pilots had flown, and were rated in, the 737 airplane. All the subject pilots had previous experience with the VMS simulation utilizing the 737 aerodynamic model.

Results and Discussion

Postflight Data Analysis

Data resulting from each test run were tabulated on a summary sheet for each test condition. The summary sheets for conditions A to H are presented in appendix B. (See tables BI to BVIII.) The data on these summary sheets included the time error at time checkpoints 1, 2, and 3 and at the metering fix (the ILS outer marker); the mean and standard deviation of the airspeed error on path segments 1 to 4; and the mean and standard deviation of the heading error on path segment 3. These data were used to quantify the accuracy with which the subject pilots maintained the ATC assigned airspeed. The mean and standard deviation of the resulting heading error along segment 3 were computed to determine how accurately the pilot maintained the heading assigned by ATC. Assigned headings were not used in path segments 1, 2, and the last part of segment 4 since the pilot was navigating with reference to the VORTAC or ILS radio signals.

The data used for the statistical computations of airspeed error and heading error were sampled at a rate of once per second. The data recorded for the mean and standard deviation computations for each segment started and finished at points that would normally have resulted in a constant airspeed along the path. (See fig. 4.) Airspeed changes required by the metering algorithm normally occurred outside of these segments. Statistical computations for airspeed maintained on segment 1 began 4.5 n.mi. past time checkpoint 1 and ended at time checkpoint 2. On segment 2 the computations began 3 n.mi. past time checkpoint 2 and ended just prior to the first commanded heading change and airspeed reduction at time checkpoint 3. On segment 3 the computations began just after completion of the turn for the first commanded heading change 10.0 n.mi. from the runway centerline and ended prior to the last ATC commanded airspeed reduction 2.5 n.mi. from the runway centerline. On segment 4 the computations began after the final-approach airspeed of 140 knots was attained, just prior to intercepting the ILS localizer signal, and ended at the ILS outer marker.

In order to compare the results of various test conditions, the mean and standard deviation of the time error at each of the time checkpoints and at the final metering fix were computed for each test condition. In addition, the average values of the means and standard deviations of the airspeed and heading errors determined for each run (in the same test condition) were also computed. These values were individually recorded on each of the summary sheets (tables BI to BVIII) in appendix B and in total in table II.

Effects of 250-Knot Airspeed Limit on Nominal Descent

A comparison was made between test runs conducted both with (test condition A) and without (test condition B) application of the ATC 250-knot airspeed limit regulation. All airplane state initial conditions and atmospheric modeling were the same for both test conditions.

Table II shows that the mean and standard deviation of the final time error for test condition A were −1.0 sec (early) and 16.7 sec, respectively, and for condition B they were −4.0 sec (early) and 16.4 sec, respectively. These results, as well as the time errors at the intermediate time checkpoints, were judged to be comparable. The time errors attained in both test conditions A and B were not large enough for corrective airspeed or heading commands to be computed by the time-guidance algorithm. The design of this particular flight path and quantification of airspeed and heading commands resulted in an insensitivity to the time errors accrued through typical operational piloting procedures.

Test runs were also conducted in which time errors were artificially induced to produce speed commands greater than 250 knots. These time errors were induced by setting an initial time error at time checkpoint 1 (test conditions C and D) and by purposely mismodeling the actual wind velocity (test conditions F and G). The effects of the 250-knot speed limit during these conditions will be discussed in subsequent sections of the report.

Effects of Initial Time Error

Three test conditions, with an initial time error of 1 min, were investigated to determine the effects of an initial time error on the time-guidance algorithm. Test conditions C and D were begun with a 60-sec time error at the initial time checkpoint to simulate a late arrival. This time error would cause the time-guidance algorithm to command higher airspeeds and/or corrective headings to shorten the flight path to null the time error. In test condition C, the ATC-imposed 250-knot airspeed limit was applied and resulted in only corrective headings being utilized to reduce the time error. The 250-knot speed limit was not imposed in test condition D. Test condition E was begun with a −60-sec time error to simulate an early arrival at time checkpoint 1. This time error would cause lower airspeeds and/or corrective headings to lengthen the flight path to reduce the time error. The 250-knot speed limit had no effect in this test condition since commanded airspeeds were always less than 250 knots.

Table II shows that the initial time error at checkpoint 1 was substantially reduced at the metering fix in all three test conditions. In test condition C, the metering fix (ILS outer marker) was crossed with a mean time error of 21.3 sec (late) and with a standard deviation of 13.0 sec. No speed corrections were applied at time checkpoints 1 and 2 because of the ATC-imposed 250-knot speed limit. This limit resulted in little change in the time error until reaching time checkpoint 3. At this point, the time error of approximately 1 min caused the time-metering guidance algorithm to compute the heading command to be 200° (instead of the nominal 190°) to shorten the path length resulting in a time-error reduction. The theoretical maximum time correction, with only the heading command correction at 250 knots, was computed to be 39.0 sec, as shown in table III. This computed maximum time correction compares favorably with the resulting time correction of 35.9 sec attained during these tests. (A 57.2-sec error at time checkpoint 3 minus the final time error of 21.3 sec equals 35.9 sec.)

In test conditions D and E at time checkpoint 1, the time error was 60 sec (late arrival) and −60 sec (early arrival), respectively. The 250-knot speed limit was not applied in either case. The time error at time checkpoint 1 caused the speed command to increase to a maximum of 265 knots in condition D and to a minimum of 235 knots in condition E. In both cases these speed commands were unchanged until time checkpoint 3 was crossed and a heading correction was applied. The time error was reduced progressively throughout the descent as shown in table II. A 5° heading command correction was computed for all runs in condition D and for 8 of the 12 runs in condition E. Four of the runs in condition E had a 10° heading command computed because of a slightly larger time error at time checkpoint 3. The mean time error at the metering fix was 2.8 sec (late) with a standard deviation of 16.5 sec for condition D. For condition E the mean time error was 8.4 sec (early) with a standard deviation of 19.2 sec.

The results of test conditions C, D, and E have shown that the time-guidance algorithm can compute speed and heading commands to null an initial time error. However, the initial error must be within the time-control capability of the algorithm. The time-control capability of the algorithm is governed by several factors including path design and operating constraints. Operating constraints, such as the ATC 250-knot speed limit, limited the capability of the time-guidance algorithm to null an initial time error greater than 39 sec (late) for the particular path geometry used in these tests. The 250-knot speed limit will have no effect on time-control capability for an early arrival.

Effects of Unknown Winds

Table II shows that all three of the test conditions with mismodeled winds (a 10-knot speed at a constant direction) resulted in larger time errors when the metering fix was crossed compared with the time error resulting in test condition A (a mean of −1.0 sec (early) and a standard deviation of 16.7 sec) where the winds were not mismodeled. For test condition F (prevailing head wind and ATC-imposed 250-knot airspeed limit), the mean and standard deviation of the time error at the metering fix were 28.1 sec (late) and 16.6 sec, respectively. For test condition G (prevailing head wind but 250-knot airspeed limit not imposed), the mean time error was 36.0 sec (late) with a standard deviation of 15.9 sec. For test condition H (prevailing tail wind), the mean time error was −32.5 sec (early) with a standard deviation of 9.3 sec.

It had been anticipated that a larger mean time error (absolute value) would have resulted at the metering fix in test condition F where the descent airspeed was constrained by the ATC-imposed 250-knot speed limit. However, the time errors for each of the runs in this test condition were 4.4 to 7.9 sec less than the errors attained in similar test conditions in which the airspeed limit was not applied. An explanation for the lower time error resulting in test condition F may be found by comparing the accrued time error at each time checkpoint during the run with the subsequent speed and heading commands for conditions F, G, and H as shown in table II.

At time checkpoint 1 the time error is 0 and the subsequent speed command is 250 knots for each of the test conditions. At time checkpoint 2, a time error accrued along segment 1 for each case as a result of the mismodeled winds. This time error would have caused a speed command of 255 knots in test condition F; however, the ATC 250-knot speed limit was applied and then the command speed remained at 250 knots. In conditions G and H, the commanded airspeed was changed 5 knots to 255 knots and 245 knots, respectively, to null the accumulated time error.

At time checkpoint 3, the time error for condition F had increased further since no speed correction had been applied. On approximately one-half of the test runs for condition F, the time error was sufficiently large for the guidance algorithm to command a 195° heading (5° greater than nominal) to reduce the accrued time error. During all the runs in test conditions G and H and in about one-half the runs in condition F, the time error at time checkpoint 3 was small enough that the nominal 200° heading command was issued. When the nominal heading command was issued, the mismodeled winds caused an additional time error to accrue during the subsequent flight to the outer marker. However, when the off-nominal 195° heading command was issued, the flight path was shortened and the resulting time error at the metering fix was reduced.

This example illustrates that the final time error is an interactive function of path design, operational constraints (increments of 5° heading command and 5-knot airspeed command), initial time error, and wind modeling error. Application of the 250-knot airspeed limit will eliminate the time controllability portion of the time-guidance algorithm when an airspeed command greater than 250 knots is computed by the guidance algorithm. However, depending upon the amount of error accumulated and on the path design, this error may be eliminated or reduced through heading corrections as demonstrated by the results in test condition F.

Pilot Comments

All the subject pilots commented that the heading and speed commands were easy to accommodate and did not increase normal pilot work load. These comments were expected since the time-metering guidance algorithm was designed to utilize common ATC instructions used in the present radar environment to control aircraft.

Pilot Performance

The magnitude of the final time error is dependent upon how closely the pilot maintained the assigned airspeeds and headings. The average of the mean and standard deviation computed for the airspeed and heading errors resulting during each test run has been listed for each test condition in table II.

The average mean airspeed error was typically less than 10 knots faster than the target speed. The averages of the standard deviations for the test conditions were typically less than 6 to 8 knots except for path segment 2 where the averages of the standard deviations were between 9 and 19 knots. The larger speed excursions on path segment 2 were attributed to the airplane being in a descent and to more time being required to stabilize on a desired airspeed. However, this segment was sufficiently short (approximately 10 n.mi.) that large time errors did not accrue.

Table II shows that the average of the mean heading errors along path segment 3 for all test conditions was less than 2°. The magnitude of this error was judged to be within standard operating limits. The averages of the standard deviations for heading error were between 8° and 11°. The magnitude of these errors was judged to be of appropriate value but could be improved with the use of flight director guidance. It is anticipated that a reduction in the magnitude of the standard deviation for heading error would result in a more consistent time error at the final metering fix.

Concluding Remarks

The rapidly increasing total cost of flight operations and the requirement for increased fuel conservation have made it necessary to develop more efficient ways to operate individual airplanes and to control air traffic for arrivals and departures to the terminal area. Advanced air traffic control procedures and airborne- and ground-generated guidance systems are being designed to reduce traffic delays in the terminal area by time metering and sequencing arrival and departure aircraft.

One of these systems developed by ONERA/CERT used a time-guidance algorithm that computed airspeed and heading commands for a pilot to follow that would result in the airplane crossing a metering fix at a preassigned time. These airspeed and heading commands were based on time errors attained at intermediate time checkpoints located along a nominal path to the airport. This concept was studied and evaluated during joint NASA and ONERA/CERT piloted simulation tests.

During the piloted simulation tests, eight different test scenarios were evaluated to determine initial time-error effects, airspeed-limit effects, and wind-modeling-error (representing the unknowns in wind-aloft forecasts and modeling form) effects upon the capability of the time-guidance algorithm to null the time error at the final metering fix. A baseline set of test runs without initial time errors or wind modeling errors resulted in a mean time error at the metering fix of −1.0 sec (early) with a standard deviation of 16.7 sec.

The Federal Aviation Administration's 250-knot airspeed limit for flight at altitudes less than 10 000 ft mean sea level can reduce the time controllability of the algorithm when higher airspeeds are required to null the time error. The severity of the reduction of time controllability of the algorithm is a function of path design. The 250-knot airspeed limit reduced time controllability from 71.7 to 39.0 sec for the path used during these tests, but the speed limit had no effect on time controllability when slower airspeeds were required.

The effects of wind modeling unknowns were examined by adding a 10-knot bias to the wind for all altitudes during three test scenarios, two with a prevailing head wind and the other with a tail wind. The test results with these scenarios showed that most of the time error at the metering fix was accrued on the last path segment after the final heading command was issued. The severity of the error accumulated on the last path segment was dependent upon the magnitude of the wind error and the length of this segment; that is, the longer the segment length, the greater the time to be exposed to the wind causing the error, thus resulting in a larger accrued time error.

An initial time error of ±60 sec was artificially induced in two more test scenarios. Final mean time errors of less than 8.4 sec resulted when both airspeed and heading commands were computed by the time-guidance algorithm. However, when the 250-knot airspeed limit was applied, the time error that was reduced only by the heading command resulted in a time error of 21.3 sec.

The subject pilots reported that the airspeed and heading commands generated by the time-guidance algorithm were easy to follow and did not increase their work load above normal levels.

NASA Langley Research Center
Hampton, VA 23665-5225
June 26, 1986

Appendix A

Description of Time-Guidance Algorithm and Equations

This appendix contains a more detailed functional description of the time-guidance algorithm. The test path described in this report will be used to illustrate the concept of the algorithm.

Data-Table Generation Function

The data-table generation portion of the program contains a description of the nominal flight path, a detailed aerodynamic and thrust model of the airplane, a representation of the autopilot in the airplane, and a wind model. The airplane and wind models are used to compute the time required to fly the path at various airspeeds with consideration given to the dynamics of airplane performance responses. Details on a generic formulation of the airplane model and wind model may be found in reference 7.

Time checkpoint 1 (airspeed command). The first step in the data-table generation function was to use the mathematical representation of the airplane and autopilot to compute the time t_i required to fly between time checkpoint 1 and the final metering fix (fig. 2) for different airspeeds V_i between the selected minimum and maximum airspeeds (235 knots and 265 knots, respectively). The specific airspeeds used in these time computations for this test path were given by

$$V_i = 230 + 5i \qquad \text{[knots]} \qquad \text{for } i = 1, 7$$

The time required to fly the path was computed by summing the times required to complete successive path elements between time checkpoint 1 and the final metering fix. These elements were divided according to the type of flight required and consisted of constant altitude and airspeed elements, constant airspeed descent elements, and constant altitude and airspeed change elements. The distance involved in flying each of these elements was computed. The distance of the constant altitude and airspeed element flown prior to time checkpoint 3 was adjusted as required so that the sum of the element lengths was equal to a fixed path length of 52.5 n.mi.

The first path element was begun at time checkpoint 1 and was started at a constant altitude of 10 000 ft and an airspeed of 250 knots. This element was used to allow time for the ATC controller to issue a descent clearance and airspeed change if required. The time for this element was fixed at 0.4 min. The distance traveled was approximately 2 miles in a no-wind condition.

In the next path element, the airspeed was changed from 250 knots to V_i while at level flight. The magnitude of the acceleration was computed with the thrust and aerodynamic model as a function of the airspeed and altitude. The time required and distance traveled during this airspeed change could then be computed through digital integration techniques until the desired airspeed was obtained.

In the next path element, begun after V_i was obtained, a constant airspeed descent at idle-thrust power settings was completed. Vertical speed, as a function of altitude and airspeed, was computed using the thrust and aerodynamic models. The time to complete the descent from 10 000 to 4000 ft was then computed. Ground speed varied as a function of the wind model and true airspeed (both varied as a function of altitude) throughout the descent. The total distance traveled during the descent was computed by summing the incremental distances traveled during small increments of time.

When an altitude of 4000 ft was obtained, the path element was flown at a constant altitude and at a constant commanded airspeed V_i. The length of this element was computed as the difference between 28.5 n.mi. (length of the path to the first turn) and the distance traveled in the previous elements. The time to complete the element was computed as the distance traveled divided by the ground speed. The ground speed was constant throughout this element.

The next element was a turn to a 190° airplane heading at a constant altitude and airspeed V_i. Ground speed and ground track of the airplane varied during the turn as a result of the wind. The distance traveled (lateral drift included) and time were summed incrementally during the turn. The turn was completed when the desired heading of 190° was obtained.

In the next path element, airspeed was reduced from V_i to 210 knots at a constant altitude of 4000 ft. The time and distance required to complete the speed change were computed by summing incremental changes during small time increments until the desired airspeed was obtained.

In the remaining elements of the path to the final metering fix, the airplane was descended to 1500 ft of altitude and turned to a heading of 250° to intercept the ILS localizer. Airspeed was then reduced to 140 knots via a nominal approach schedule that conformed to flap deployment and approach constraints. The ILS localizer was then intercepted and provided lateral path guidance to the final metering fix.

The next step in the data-table generation function was to determine the difference in airspeed and the difference in time Δt_i (where $i = 1,7$) to fly to the metering fix at the nominal calibrated airspeed V_{nom} of 250 knots and the time to fly at each of the off-nominal speeds V_i (where $i = 1,7$). These airspeed differences and time differences were computed as follows and correlated to form the 7×2 matrix shown in figure 5(a):

$$\begin{aligned} \Delta V_i &= V_i - V_{\text{nom}} \quad \text{[knots]} \quad (i = 1,7) \\ \Delta t_i &= t_i - t_{\text{nom}} \quad \text{[sec]} \end{aligned}$$

in which

$$\begin{aligned} V_{\text{nom}} &= V_4 = 250 \quad \text{[knots]} \\ t_{\text{nom}} &= t_4 = 793.5 \quad \text{[sec]} \end{aligned}$$

The quadratic curve-fit function was then applied to the 7×2 time-and-airspeed difference matrix. This application resulted in a 1×3 coefficient matrix for the following equation that is used to compute an airspeed change based on the time error $t_{e,1}$ determined when the airplane crossed time checkpoint 1:

$$\Delta V = a_1 + a_2 t_{e,1} + a_3 t_{e,1}^2 \quad \text{[knots]}$$

Time checkpoint 2 (airspeed command). The next task in the data-table generation function was to construct time-and-airspeed difference tables for flight between time checkpoint 2 and the metering fix (fig. 2). This task was accomplished using the same computations executed for the first time checkpoint except for a constant altitude and airspeed change element after time checkpoint 2 had been passed.

The nominal airspeed used at time checkpoint 2 was defined as the airspeed commanded at time checkpoint 1. This resulted in seven different nominal airspeeds (between 235 and 265 knots) being considered in the time-and-airspeed difference computations. Hence, the following time-and-airspeed difference computations yielded a $7 \times 2 \times 7$ matrix (i.e., a 7×2 matrix for each of the seven nominal airspeed commands) as shown in figure 5(b):

$$\left.\begin{aligned} \Delta V_{i,k} &= V_i - V_{\text{nom},k} \quad \text{[knots]} \\ \Delta t_{i,k} &= t_{i,k} - t_{\text{nom},k} \quad \text{[sec]} \end{aligned}\right\} \quad \begin{matrix} (i = 1,7; \\ k = 1,7) \end{matrix}$$

in which

$$\left.\begin{aligned} V_{\text{nom},k} &= 230 + 5k \quad \text{[knots]} \\ t_{\text{nom},k} &= t_{i,k} \quad \text{[sec]} \end{aligned}\right\} \quad \begin{matrix} (k = 1,7) \\ (i = k = 1,7) \end{matrix}$$

The quadratic curve-fit function was then applied to each set of time-difference data associated with each of the seven possible nominal airspeeds to form a $1 \times 3 \times 7$ coefficient matrix (i.e., a 1×3 coefficient matrix for each of the seven possible nominal airspeed commands) as shown in figure 5(c). This coefficient matrix was used as follows to compute the required airspeed change based on the time error $t_{e,2}$ determined at time checkpoint 2:

$$\Delta V = b_{1,k} + b_{2,k} t_{e,2} + b_{3,k} t_{e,2}^2 \quad \text{[knots]}$$

for $k = 1,7$. The value of k is the kth element corresponding to the nominal airspeed command $V_{\text{nom},k}$.

Time checkpoint 3 (heading command). The last task in the data-table generation function was to compute time-and-heading difference tables for flight between time checkpoint 3 and the metering fix (fig. 2). This task was accomplished by first computing the time t_i required to fly between time checkpoint 3 and the metering fix for each 5° increment of heading command Ψ_i. These computations were repeated for each possible airspeed $V_{\text{nom},k}$ commanded at time checkpoint 2. Next, a time-and-heading difference matrix, shown in figure 5(d), was constructed with the following computations:

$$\left.\begin{aligned} \Delta \Psi_i &= \Psi_i - \Psi_{\text{nom}} \quad \text{[deg]} \\ \Delta t_i &= t_i - t_{\text{nom}} \quad \text{[sec]} \end{aligned}\right\} \quad (i = 1,5)$$

in which

$$\Psi_{\text{nom}} = 190 \quad \text{[deg]}$$

and

$$t_{\text{nom}} = t_i \quad \text{[sec]} \quad \left\{\begin{aligned} \Psi_{\text{nom}} &= 190 \quad \text{[deg]} \\ V_k &= 230 + 5k \\ k &= 1,7 \end{aligned}\right.$$

This procedure resulted in a $5 \times 2 \times 7$ matrix (i.e., a 5×2 matrix for each of the seven possible airspeeds that could be commanded at time checkpoint 2).

The quadratic curve-fit function was applied to each set of time difference data associated with each of the seven possible airspeeds at time checkpoint 2 to form a $1 \times 3 \times 7$ coefficient matrix (i.e., a 1×3 coefficient matrix for each of the seven possible airspeed commands) as shown in figure 5(e). This coefficient matrix was used to compute the correction to the nominal heading based on the time error $t_{e,3}$ at time checkpoint 3 for $k = 1,7$:

$$\Delta \Psi = c_{1,k} + c_{2,k} t_{e,3} + c_{3,k} t_{e,3}^2 \quad \text{[deg]}$$

Command Generation Function

The third function of the time-guidance algorithm was to compute the actual airspeed commands V_1

and V_2 and heading command Ψ for the pilot to follow. Using the appropriate coefficients, these computations were accomplished on a real-time basis by evaluating the airspeed or heading correction equations with the time error resulting as the airplane crossed each of the time checkpoints. The speed and heading corrections were summed to the nominal airspeed or heading, respectively, and rounded to the nearest 5-knot or 5° increment. The airspeed commands were limited between a range of 235 and 265 knots. If the ATC 250-knot airspeed limit for flight below 10 000 ft MSL was applied, the maximum airspeed command would be limited to 250 knots. The heading command was limited to be between 180° and 200°.

Appendix B

Summary Sheets for Each Test Condition

Data resulting from each test run were tabulated on a summary sheet for each test condition. The summary sheets for conditions A to H are presented in this appendix.

TABLE BI. SUMMARY SHEET FOR TEST CONDITION A

[Time: (+) late; (−) early
Speed: (+) fast; (−) slow]

Parameter		Test run number 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Summary of test runs Average	S.D.
Checkpoint 1																			
Time error, sec		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	[a]0	
V_{cas} command on seg. 1, knots		250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250		
V_{cas} error on seg. 1, knots	Mean	0.9	1.4	3.3	−1.1	1.2	2.6	1.8	0.3	2.9	4.2	5.3	1.4	2.8	2.0	3.2	−5.7	1.7	
	S.D.	3.8	3.6	5.5	3.3	1.6	2.3	2.8	2.0	2.5	2.7	4.8	3.8	3.6	6.3	5.4	2.4	3.5	
Checkpoint 2																			
Time error, sec		−1.9	−2.5	−2.7	0.3	−0.8	−2.9	−3.2	−0.5	−2.1	−2.8	−3.7	−0.9	−3.0	−0.8	−3.2	−2.5	[a]−1.8	1.6
V_{cas} command on seg. 2, knots		250	250	250	250	250	250	250	250	250	250	250	250	250	250	250	250		
V_{cas} error on seg. 2, knots	Mean	8.9	8.5	8.2	3.7	5.5	6.4	10.2	4.3	7.9	6.0	−1.2	7.0	11.2	13.9	11.3	5.4	7.3	
	S.D.	16.1	13.7	12.5	11.3	13.0	13.3	16.6	13.4	13.6	13.8	14.6	14.4	15.2	16.1	13.0	14.9	14.1	
Checkpoint 3																			
Time error, sec		−5.2	−5.0	−4.9	−0.7	−1.9	−4.4	−6.6	−1.0	−4.3	−4.2	0.2	−2.6	−6.7	−6.3	−8.1	−1.4	[a]−3.8	2.7
Heading command, deg		190	190	190	190	190	190	190	190	190	190	190	190	190	190	190	190		
Heading error, deg	Mean	−1.1	−0.7	0.3	−1.4	0.1	−1.2	−1.2	0.7	0.2	−0.8	−1.7	−0.6	0.6	1.1	1.6	−1.2	−0.4	
	S.D.	10.2	9.6	10.2	9.5	9.3	9.3	11.5	9.7	8.1	10.7	9.6	9.2	9.2	8.4	10.6	9.9	9.7	
V_{cas} command on seg. 3, knots		210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210		
V_{cas} error on seg. 3, knots	Mean	0.4	5.3	0.9	1.3	6.0	4.2	8.4	5.3	6.2	0.4	11.5	0.7	7.0	0.7	8.5	2.6	3.7	
	S.D.	4.8	3.9	2.6	3.5	6.3	2.9	8.3	4.8	4.9	2.6	8.9	4.2	9.5	5.3	7.2	2.2	5.1	
V_{cas} command on seg. 4, knots		140	140	140	140	140	140	140	140	140	140	140	140	140	140	140	140		
V_{cas} error on seg. 4, knots	Mean	−2.6	−1.0	1.5	5.4	−0.1	−0.1	−0.9	2.1	2.1	−1.1	−6.0	−1.8	−0.9	2.9	1.7	5.3	0.4	
	S.D.	4.5	3.7	5.5	6.0	2.8	2.5	3.5	4.2	2.9	4.8	4.8	5.0	3.1	6.2	6.1	6.0	4.5	
Metering fix																			
Time error at metering fix, sec		6.0	24.0	1.5	10.8	1.8	13.8	−14.9	−1.5	−9.8	−3.8	15.8	16.6	−16.7	−20.8	−41.3	1.9	[a]−1.0	16.7

[a]Mean value.

TABLE BII. SUMMARY SHEET FOR TEST CONDITION B

[Time: (+) late; (−) early
Speed: (+) fast; (−) slow]

Parameter	Test run number 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Summary of test runs: Average	S.D.
Checkpoint 1																		
Time error, sec	0	0	0	0	0	0	0	0	0	0	0	0					[a]0	
V_{cas} command on seg. 1, knots	250	250	250	250	250	250	250	250	250	250	250	250						
V_{cas} error on seg. 1, knots: Mean	0.5	2.1	−0.9	1.0	−2.8	3.1	−1.4	10.3	3.0	4.0	1.5	3.1					2.0	
V_{cas} error on seg. 1, knots: S.D.	5.9	3.5	4.8	2.4	6.1	2.8	3.0	10.0	3.6	2.9	1.6	2.7					4.1	
Checkpoint 2																		
Time error, sec	−1.8	−2.0	−0.2	−3.1	−1.6	−2.9	−0.2	−6.0	−3.2	−3.3	−2.5	−2.2					[a]−2.4	1.6
V_{cas} command on seg. 2, knots	250	250	250	250	250	250	250	245	250	250	250	250						
V_{cas} error on seg. 2, knots: Mean	6.7	3.5	4.9	7.4	5.4	0.8	2.2	4.4	10.1	10.1	6.7	6.6					5.7	
V_{cas} error on seg. 2, knots: S.D.	15.4	15.2	16.5	14.1	13.4	15.6	12.4	13.9	16.0	13.4	14.8	13.2					14.6	
Checkpoint 3																		
Time error, sec	−3.8	−3.2	−0.5	−6.0	−5.4	−2.8	−0.7	−4.5	−7.5	−6.6	−4.4	−4.8					[a]−4.2	2.1
Heading command, deg	190	190	190	190	190	190	190	190	190	190	190	190						
Heading error, deg: Mean	−1.2	1.8	−1.4	−0.9	−2.0	−0.9	0.6	0.1	1.3	0.2	−4.8	−0.9					−0.7	
Heading error, deg: S.D.	9.6	9.4	9.3	9.6	10.5	12.1	9.5	8.3	7.0	9.7	14.7	9.3					9.9	
V_{cas} command on seg. 3, knots	210	210	210	210	210	210	210	210	210	210	210	210						
V_{cas} error on seg. 3, knots: Mean	−1.5	0.1	1.4	1.3	0.7	0.0	12.8	1.4	7.3	6.5	3.1	1.5					2.9	
V_{cas} error on seg. 3, knots: S.D.	3.9	5.0	5.5	2.9	5.3	7.4		5.3	6.8	5.5	5.0	3.9					5.1	
V_{cas} command on seg. 4, knots	140	140	140	140	140	140	140	140	140	140	140	140						
V_{cas} error on seg. 4, knots: Mean	−3.3	−0.2	4.4	0.1	2.0	−3.8	−4.3	−1.1	−4.1	−1.3	2.3	2.2					−0.6	
V_{cas} error on seg. 4, knots: S.D.	4.2	2.7	5.8	2.0	2.7	4.3	3.3	3.1	3.3	4.9	3.5	3.5					3.6	
Metering fix																		
Time error at metering fix, sec	19.5	1.3	−3.4	−5.5	−10.0	−12.7	6.2	−7.8	−32.6	−25.8	25.1	−2.0					[a]−4.0	16.4

[a]Mean value.

TABLE BIII. SUMMARY SHEET FOR TEST CONDITION C

[Time: (+) late; (−) early
Speed: (+) fast; (−) slow]

Parameter		Test run number 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Summary of test runs: Average	S.D.
Checkpoint 1																			
Time error, sec		60	60	60	60	60	60	60	60	60	60							[a]60	
V_{cas} command on seg. 1, knots		250	250	250	250	250	250	250	250	250	250								
V_{cas} error on seg. 1, knots	Mean	−2.1	0.4	0.8	1.7	2.6	3.5	2.3	2.3	2.6	2.0							1.6	
	S.D.	4.4	4.5	2.8	4.2	3.3	5.4	6.8	5.4	1.9	2.4							4.1	
Checkpoint 2																			
Time error, sec		60.3	59.3	57.7	58.7	58.1	58.1	60.0	59.0	57.2	58.3							[a]58.7	1.0
V_{cas} command on seg. 2, knots		250	250	250	250	250	250	250	250	250	250								
V_{cas} error on seg. 2, knots	Mean	7.6	1.7	7.7	4.0	9.5	3.8	5.8	11.5	7.2	7.4							6.6	
	S.D.	14.2	14.5	13.8	13.5	14.0	12.4	16.9	15.0	11.5	12.8							13.9	
Checkpoint 3																			
Time error, sec		58.4	60.4	54.7	58.7	55.4	58.4	59.4	55.7	54.6	56.0							[a]57.2	2.1
Heading command, deg		200	200	200	200	200	200	200	200	200	200								
Heading error, deg	Mean	−2.9	−3.3	−0.8	−1.8	−3.3	−2.3	−0.8	−1.6	−1.9	−1.8							−2.0	
	S.D.	10.4	9.6	11.8	12.9	11.7	11.3	8.0	7.6	11.3	10.9							10.5	
V_{cas} command on seg. 3, knots		210	210	210	210	210	210	210	210	210	210								
V_{cas} error on seg. 3, knots	Mean	−0.5	1.4	0.8	3.6	1.9	2.5	−1.2	3.0	3.5	−3.5							1.1	
	S.D.	5.6	3.3	5.2	6.5	5.8	2.9	5.6	5.8	5.7	4.6							5.1	
V_{cas} command on seg. 4, knots		140	140	140	140	140	140	140	140	140	140	140							
V_{cas} error on seg. 4, knots	Mean	−1.0	1.5	−0.6	1.1	10.0	0.1	−5.3	−1.0	−2.0	4.2							0.7	
	S.D.	3.9	2.7	3.3	3.2	7.8	3.1	5.4	4.7	2.2	1.9							3.8	
Metering fix																			
Time error at metering fix, sec		37.8	27.7	15.7	7.6	−1.8	19.5	36.3	28.1	30.6	11.8							[a]21.3	13.0

[a]Mean value.

TABLE BIV. SUMMARY SHEET FOR TEST CONDITION D

[Time: (+) late; (−) early
Speed: (+) fast; (−) slow]

Parameter		Test run number 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Summary of test runs Average	S.D.
Checkpoint 1																			
Time error, sec		60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	[a]60	
V_{cas} command on seg. 1, knots		265	265	265	265	265	265	265	265	265	265	265	265	265	265	265	265		
V_{cas} error on seg. 1, knots	Mean	8.8	0.7	2.7	2.7	2.4	1.4	5.4	6.5	5.6	1.8	−0.9	−3.7	3.3	1.1	−3.0	4.8	2.5	
	S.D.	11.8	4.8	4.7	2.5	4.2	4.7	5.8	5.6	3.8	3.5	4.3	5.4	6.4	3.0	4.6	4.9	5.0	
Checkpoint 2																			
Time error, sec		23.8	26.7	26.6	23.4	22.7	24.2	23.3	24.3	23.1	25.3	26.4	28.1	24.3	25.8	25.3	21.8	[a]24.7	1.7
V_{cas} command on seg. 2, knots		265	265	265	265	265	265	265	265	265	265	265	265	265	265	265	265		
V_{cas} error on seg. 2, knots	Mean	15.8	8.4	6.7	10.4	8.7	9.0	11.7	11.1	15.5	6.5	11.2	4.0	15.4	9.6	3.2	10.5	9.8	
	S.D.	18.0	18.4	21.6	18.7	19.4	18.6	20.7	18.7	19.9	18.3	17.5	19.5	15.9	17.7	19.8	17.8	18.8	
Checkpoint 3																			
Time error, sec		18.3	25.3	26.3	19.0	18.0	20.3	20.7	21.6	17.4	23.8	22.7	28.7	19.8	22.6	25.3	16.8	[a]21.7	3.5
Heading command, deg		195	195	195	195	195	195	195	195	195	195	195	195	195	195	195	195		
Heading error, deg	Mean	−1.1	−1.0	−1.6	−1.1	−2.1	−2.2	−2.7	−0.6	0.3	−0.8	0.4	−2.1	−0.2	−1.1	−0.4	−1.3	−1.1	
	S.D.	9.5	10.3	10.3	9.8	12.6	11.3	10.2	11.4	11.0	10.1	15.3	13.5	8.5	9.6	7.5	12.9	10.9	
V_{cas} command on seg. 3, knots		210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210		
V_{cas} error on seg. 3, knots	Mean	3.4	5.2	8.3	5.3	8.2	9.8	7.1	9.8	10.3	6.3	23.9	4.4	0.9	3.1	3.8	9.4	7.5	
	S.D.	7.8	6.5	7.3	6.5	8.6	11.9	9.4	9.8	8.2	4.0	15.2	9.3	5.4	5.2	7.8	7.5	8.2	
V_{cas} command on seg. 4, knots		140	140	140	140	140	140	140	140	140	140	140	140	140	140	140	140		
V_{cas} error on seg. 4, knots	Mean	−1.2	−1.3	17.9	0.2	−1.2	0.4	16.6	−1.3	−3.4	0.6	3.4	3.2	−1.5	4.2	−2.3	3.0	2.3	
	S.D.	2.7	2.4	14.2	6.0	2.8	2.5	17.0	5.9	4.1	2.5	3.5	2.7	6.7	10.1	2.4	2.4	5.5	
Metering fix																			
Time error at metering fix, sec		29.3	16.7	−20.9	13.3	1.6	−0.1	−19.5	3.6	9.7	24.7	−26.3	−2.2	7.4	−12.9	21.1	−1.6	[a]2.8	16.5

[a]Mean value.

TABLE BV. SUMMARY SHEET FOR TEST CONDITION E

[Time: (+) late; (−) early
Speed: (+) fast; (−) slow]

Parameter		Test run number																Summary of test runs	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Average	S.D.
Checkpoint 1																			
Time error, sec		−60	−60	−60	−60	−60	−60	−60	−60	−60	−60	−60	−60					[a]−60	
V_{cas} command on seg. 1, knots		235	235	235	235	235	235	235	235	235	235	235	235						
V_{cas} error on seg. 1, knots	Mean	4.1	2.76	0.0	4.2	0.1	2.8	1.0	1.1	1.2	2.1	0.8	−0.4					1.7	
	S.D.	6.2	3.35	4.7	4.9	3.4	3.2	3.3	3.2	6.3	3.1	3.5	1.7					4.2	
Checkpoint 2																			
Time error, sec		−29.3	−27.5	−27.4	−29.9	−26.1	−28.2	−23.8	−27.1	−27.0	−27.4	−26.6	−24.6					[a]−27.1	1.7
V_{cas} command on seg. 2, knots		235	235	235	235	235	235	235	235	235	235	235	235						
V_{cas} error on seg. 2, knots	Mean	5.7	4.7	7.5	5.7	1.4	7.8	1.1	4.5	7.5	8.5	4.7	4.7					5.3	
	S.D.	9.0	10.4	9.1	8.9	8.4	9.8	6.7	10.0	9.9	9.3	7.2	10.9					9.1	
Checkpoint 3																			
Time error, sec		−32.1	−28.6	−30.9	−31.4	−26.2	−31.7	−22.1	−28.5	−29.4	−31.9	−28.9	−24.6					[a]−28.9	3.2
Heading command, deg		180	185	185	180	185	180	185	185	185	180	185	185						
Heading error, deg	Mean	−2.5	−1.4	−0.8	−3.7	−1.2	−0.2	−0.2	1.0	−1.5	1.3	−2.2	−2.0					−1.1	
	S.D.	14.1	10.1	10.2	15.0	10.0	10.6	8.4	10.4	9.4	10.1	10.9	10.1					10.8	
V_{cas} command on seg. 3, knots		210	210	210	210	210	210	210	210	210	210	210	210						
V_{cas} error on seg. 3, knots	Mean	2.1	1.0	1.1	1.6	−2.1	0.4	3.5	0.7	1.4	0.2	1.9	3.5					1.3	
	S.D.	7.6	4.2	4.6	4.7	5.8	3.5	6.5	7.4	6.6	4.8	3.3	4.3					5.3	
V_{cas} command on seg. 4, knots		140	140	140	140	140	140	140	140	140	140	140	140						
V_{cas} error on seg. 4, knots	Mean	1.6	−1.9	5.7	1.6	−2.1	3.1	−1.9	6.2	−6.5	−4.5	2.4	−0.4					0.3	
	S.D.	2.7	5.3	6.3	2.6	3.3	3.7	4.3	2.8	3.4	3.3	2.2	1.8					3.5	
Metering fix																			
Time error at metering fix, sec		27.5	−20.4	−10.0	22.9	−11.6	−1.8	−12.9	−44.3	−7.6	−17.6	−3.4	−21.1					[a]−8.4	19.2

[a]Mean value.

TABLE BVI. SUMMARY SHEET FOR TEST CONDITION F

[Time: (+) late; (−) early
Speed: (+) fast; (−) slow]

Parameter	Test run number																Summary of test runs	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Average	S.D.
Checkpoint 1																		
Time error, sec	0	0	0	0	0	0	0	0	0	0	0						[a]0	
V_{cas} command on seg. 1, knots	250	250	250	250	250	250	250	250	250	250	250							
V_{cas} error on seg. 1, knots: Mean	3.2	5.7	2.4	2.1	1.6	0.8	0.9	6.0	5.9	−1.1	2.8						2.8	
V_{cas} error on seg. 1, knots: S.D.	5.4	6.9	3.0	2.6	3.8	3.6	1.7	5.2	6.6	5.6	3.2						4.3	
Checkpoint 2																		
Time error, sec	6.0	0.2	5.1	5.6	6.4	8.4	4.6	3.5	2.8	7.0	5.6						[a]5.0	2.2
V_{cas} command on seg. 2, knots	250	250	250	250	250	250	250	250	250	250	250							
V_{cas} error on seg. 2, knots: Mean	3.8	7.1	10.4	5.7	9.2	6.4	7.1	8.1	8.2	4.6	6.6						7.0	
V_{cas} error on seg. 2, knots: S.D.	14.3	9.9	14.4	16.3	14.5	12.6	15.2	12.8	13.0	14.5	11.8						13.6	
Checkpoint 3																		
Time error, sec	12.6	−0.3	7.2	12.0	10.4	13.8	8.8	8.9	6.4	12.9	10.1						[a]9.4	4.0
Heading command, deg	195	190	190	195	195	195	190	190	190	195	195							
Heading error, deg: Mean	1.0	−0.6	0.7	−2.4	−1.6	−1.5	−0.5	−1.0	4.0	−1.0	−0.3						−0.3	
Heading error, deg: S.D.	8.5	9.3	9.0	8.9	8.6	8.6	10.3	8.7	8.3	7.1	6.5						8.5	
V_{cas} command on seg. 3, knots	210	210	210	210	210	210	210	210	210	210	210							
V_{cas} error on seg. 3, knots: Mean	2.4	3.7	7.7	3.2	2.8	3.4	3.2	6.1	3.2	−1.2	−0.9						3.1	
V_{cas} error on seg. 3, knots: S.D.	3.8	5.6	6.7	3.1	7.0	4.2	7.6	7.2	5.4	3.8	5.8						5.5	
V_{cas} command on seg. 4, knots	140	140	140	140	140	140	140	140	140	140	140							
V_{cas} error on seg. 4, knots: Mean	1.2	10.3	3.7	0.7	2.7	−4.8	3.6	4.7	8.2	3.3	0.8						3.1	
V_{cas} error on seg. 4, knots: S.D.	2.6	7.4	2.5	4.1	3.3	3.6	3.6	7.8	2.2	3.4	4.4						4.1	
Metering fix																		
Time error at metering fix, sec	54.5	14.9	35.2	31.1	30.0	38.8	25.2	39.9	−7.5	34.7	12.3						[a]28.1	16.6

[a]Mean value.

TABLE BVII. SUMMARY SHEET FOR TEST CONDITION G

[Time: (+) late; (−) early
Speed: (+) fast; (−) slow]

Parameter		Test run number																Summary of test runs	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Average	S.D.
Checkpoint 1																			
Time error, sec		0	0	0	0	0	0	0	0	0	0	0						[a]0	
V_{cas} command on seg. 1, knots		250	250	250	250	250	250	250	250	250	250	250							
V_{cas} error on seg. 1, knots	Mean	1.5	4.1	0.3	−0.9	0.8	0.9	−0.4	0.7	0.9	1.2	2.5						1.1	
	S.D.	3.7	5.6	2.8	3.4	7.3	3.7	2.2	9.1	3.2	3.5	2.9						4.3	
Checkpoint 2																			
Time error, sec		5.2	4.9	6.2	6.6	5.7	4.6	6.8	5.9	6.2	5.1	4.1						[a]5.6	0.9
V_{cas} command on seg. 2, knots		255	255	255	255	255	255	255	255	255	255	255							
V_{cas} error on seg. 2, knots	Mean	7.4	13.2	7.7	15.7	6.9	12.8	7.5	8.4	11.7	8.4	12.1						10.2	
	S.D.	15.9	14.3	12.1	15.7	14.2	14.7	16.6	17.5	15.2	13.4	15.5						15.0	
Checkpoint 3																			
Time error, sec		2.2	−2.3	3.6	−2.5	1.3	−1.9	4.1	2.4	0.1	0.8	−2.4						[a]0.5	2.5
Heading command, deg		190	190	190	190	190	190	190	190	190	190	190							
Heading error, deg	Mean	0.7	−0.2	0.1	−1.0	0.1	−1.3	0.0	1.2	−0.1	0.0	0.0						−0.1	
	S.D.	9.8	9.5	9.2	9.5	9.4	9.4	10.0	8.1	8.6	5.9	8.4						8.9	
V_{cas} command on seg. 3, knots		210	210	210	210	210	210	210	210	210	210	210							
V_{cas} error on seg. 3, knots	Mean	4.7	3.1	6.9	4.0	1.6	3.0	3.7	1.2	2.4	−0.5	1.8						2.9	
	S.D.	5.3	3.6	8.6	5.7	4.8	6.9	10.7	4.8	3.7	9.2	9.0						6.6	
V_{cas} command on seg. 4, knots		140	140	140	140	140	140	140	140	140	140	140							
V_{cas} error on seg. 4, knots	Mean	1.0	1.8	4.9	3.4	1.4	−0.1	4.0	3.1	0.5	10.7	2.5						3.0	
	S.D.	4.0	5.1	4.1	3.7	3.0	4.6	2.5	2.9	3.2	5.7	5.0						4.0	
Metering fix																			
Time error at metering fix, sec		64.1	29.0	50.3	42.0	39.7	53.9	13.7	30.4	32.4	26.4	14.5						[a]36.0	15.9

[a]Mean value.

ORIGINAL PAGE IS OF POOR QUALITY

TABLE BVIII. SUMMARY SHEET FOR TEST CONDITION H

[Time: (+) late; (−) early
Speed: (+) fast; (−) slow]

Parameter		Test run number 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Summary of test runs: Average	S.D.
Checkpoint 1																			
Time error, sec		0	0	0	0	0	0	0	0	0	0	0						[a]0	
V_{cas} command on seg. 1, knots		250	250	250	250	250	250	250	250	250	250	250							
V_{cas} error on seg. 1, knots	Mean	1.7	6.7	1.1	5.1	1.4	4.0	0.7	4.4	1.9	2.5	6.0						3.2	
	S.D.	3.7	7.9	2.8	3.7	3.5	3.2	2.8	1.9	5.1	3.9	2.9						3.8	
Checkpoint 2																			
Time error, sec		−8.5	−11.5	−9.6	−13.0	−8.3	−9.3	−7.8	−9.0	−7.4	−10.5	−10.4						[a]−9.6	1.7
V_{cas} command on seg. 2, knots		245	245	245	245	245	245	245	245	245	245	245							
V_{cas} error on seg. 2, knots	Mean	7.9	0.5	3.6	3.5	7.8	1.6	5.2	3.0	3.2	1.4	1.5						3.6	
	S.D.	14.6	12.6	13.0	11.4	14.2	12.7	14.8	12.5	14.0	11.9	12.5						13.1	
Checkpoint 3																			
Time error, sec		−9.2	−8.3	−9.3	−6.6	−7.9	−7.2	−5.7	−6.0	−5.0	−10.4	−7.8						[a]−7.6	1.7
Heading command, deg		190	190	190	190	190	190	190	190	190	190	190							
Heading error, deg	Mean	0.6	−2.8	−1.3	−0.7	−0.5	−0.3	0.6	0.5	−1.6	−1.4	−1.9						−0.8	
	S.D.	9.8	9.7	9.6	10.8	10.4	9.4	10.6	9.9	10.9	8.5	9.0						9.9	
V_{cas} command on seg. 3, knots		210	210	210	210	210	210	210	210	210	210	210							
V_{cas} error on seg. 3, knots	Mean	4.6	6.3	4.5	1.7	−0.5	0.7	3.2	6.9	−0.8	−2.4	2.4						2.4	
	S.D.	3.7	5.3	4.8	4.2	3.2	7.2	4.3	8.2	5.5	4.4	6.0						5.2	
V_{cas} command on seg. 4, knots		140	140	140	140	140	140	140	140	140	140	140							
V_{cas} error on seg. 4, knots	Mean	0.0	2.5	0.2	−0.6	0.5	−2.6	3.7	2.5	1.1	8.6	−3.3						1.1	
	S.D.	3.9	3.4	4.9	2.5	4.2	2.5	4.2	3.2	3.3	4.1	2.7						3.5	
Metering fix																			
Time error at metering fix, sec		−27.5	−22.4	−22.5	−44.7	−25.8	−35.8	−46.6	−43.2	−33.2	−21.5	−34.5						[a]−32.5	9.3

[a]Mean value.

References

1. Gershkoff, I.: *The Use of Flight Management Computers in Air Carrier Operations in the 1980s.* FAA-EM-81-10, Aug. 1981. (Available from DTIC as AD A105 621.)
2. Benoît, A.; and Swierstra, S.: *Optimum Use of Cruise/Descent Control for the Scheduling of Inbound Traffic.* Doc. No. 802013, Division El, European Organisation for the Safety of Air Navigation (Belgium), Feb. 10, 1980.
3. Cunningham, F. L.: The Profile Descent. AIAA Paper 77-1251, Aug. 1977.
4. Heimbold, R. L.; Lee, H. P.; and Leffler, M. F.: *Development of Advanced Avionics Systems Applicable to Terminal-Configured Vehicles.* NASA CR-3280, 1980.
5. Knox, Charles E.; and Cannon, Dennis G.: *Development and Test Results of a Flight Management Algorithm for Fuel-Conservative Descents in a Time-Based Metered Traffic Environment.* NASA TP-1717, 1980.
6. Knox, Charles E.; Vicroy, Dan D.; and Simmon, David A.: *Planning Fuel-Conservative Descents in an Airline Environment Using a Small Programmable Calculator—Algorithm Development and Flight Test Results.* NASA TP-2393, 1985.
7. Pelegrin, Marc; and Imbert, Nicole: Accurate Timing in Landings Through Air Traffic Control. *Guidance and Control Design Considerations for Low-Altitude and Terminal-Area Flight.* AGARD-CP-240, Apr. 1978, pp. 20-1—20-14.
8. Staff of the NASA Langley Research Center; and Boeing Commercial Airplane Company: *Terminal Configured Vehicle Program—Test Facilities Guide.* NASA SP-435, 1980.
9. *Air Traffic Control.* 7110.65D, FAA, U.S. Dep. Transportation, Oct. 25, 1984.

TABLE I. TEST CONDITIONS AND VARIABLE TEST PARAMETERS

Test condition	Variable test parameters		
	Was ATC 250-knot airspeed limit applied?	Initial time error, sec (a)	Unplanned wind component
A	Yes	0	0
B	No	0	0
C	Yes	60	0
D	No	60	0
E	Yes	−60	0
F, G	No	0	247°; 10 knots (prevailing head wind)
H	No	0	067°; 10 knots (prevailing tail wind)

[a]A positive time error denotes a late arrival requiring greater airspeed commands.

TABLE II. SUMMARY OF TEST RESULTS FOR EACH TEST CONDITION

[Time: (+) late; (−) early
Speed: (+) fast; (−) slow]

Parameter		Test condition A	B	C	D	E	F	G	H
Checkpoint 1									
Time error, sec		0	0	60	60	−60	0	0	0
V_{cas} command on seg. 1, knots		250	250	250	265	235	250	250	250
V_{cas} error on seg. 1, knots	Av. Mean	1.7	2.0	1.6	2.5	1.7	2.8	1.1	3.2
	Av. S.D.	3.5	4.1	4.1	5.0	4.2	4.3	4.3	3.8
Checkpoint 2									
Time error, sec	Mean	−1.8	−2.4	58.7	24.7	−27.1	5.0	5.6	−9.6
	S.D.	1.6	1.6	1.0	1.7	1.7	2.2	0.9	1.7
V_{cas} command on seg. 2, knots		250	250	250	265	235	250	255	245
V_{cas} error on seg. 2, knots	Av. Mean	7.3	5.7	6.6	9.8	5.3	7.0	10.2	3.6
	Av. S.D.	14.1	14.6	13.9	18.8	9.1	13.6	15.0	13.1
Checkpoint 3									
Time error, sec	Mean	−3.8	−4.2	57.2	21.7	−28.9	9.4	5.4	−14.1
	S.D.	2.7	2.1	2.1	3.5	3.2	4.0	2.4	2.0
Heading command, deg		190	190	200	195	180/185	190/195	190	185/190
Heading error, deg	Av. Mean	−0.4	−0.7	−2.0	−1.1	−1.1	−0.3	−0.1	−0.8
	Av. S.D.	9.7	9.9	10.5	10.9	10.8	8.5	8.9	9.9
V_{cas} command on seg. 3, knots		210	210	210	210	210	210	210	210
V_{cas} error on seg. 3, knots	Av. Mean	3.7	2.9	1.1	7.5	1.3	3.1	2.9	2.4
	Av. S.D.	5.1	5.1	5.1	8.2	5.3	5.5	6.6	5.2
V_{cas} command on seg. 4, knots		140	140	140	140	140	140	140	140
V_{cas} error on seg. 4, knots	Av. Mean	0.4	−0.6	0.7	2.3	0.3	3.1	3.0	1.1
	Av. S.D.	4.5	3.6	3.8	5.5	3.5	4.1	4.0	3.5
Metering fix									
Time error at metering fix, sec	Mean	−1.0	−4.0	21.3	2.8	−8.4	28.1	36.0	−32.5
	S.D.	16.7	16.4	13.0	16.5	19.2	16.6	15.9	9.3

TABLE III. COMPONENTS AND TOTAL TIME CONTROLLABILITY OF TEST PATH[a]

Speed command component, sec	Heading command component, sec	Total time controllability, sec	Comments
−34.6	−41.3	−75.9	Early-arrival time error
33.1	38.6	71.7	Late-arrival time error; 250-knot speed limit not applied
0	39.0	39.0	Late-arrival time error; 250-knot speed limit applied

[a]Zero wind speed.

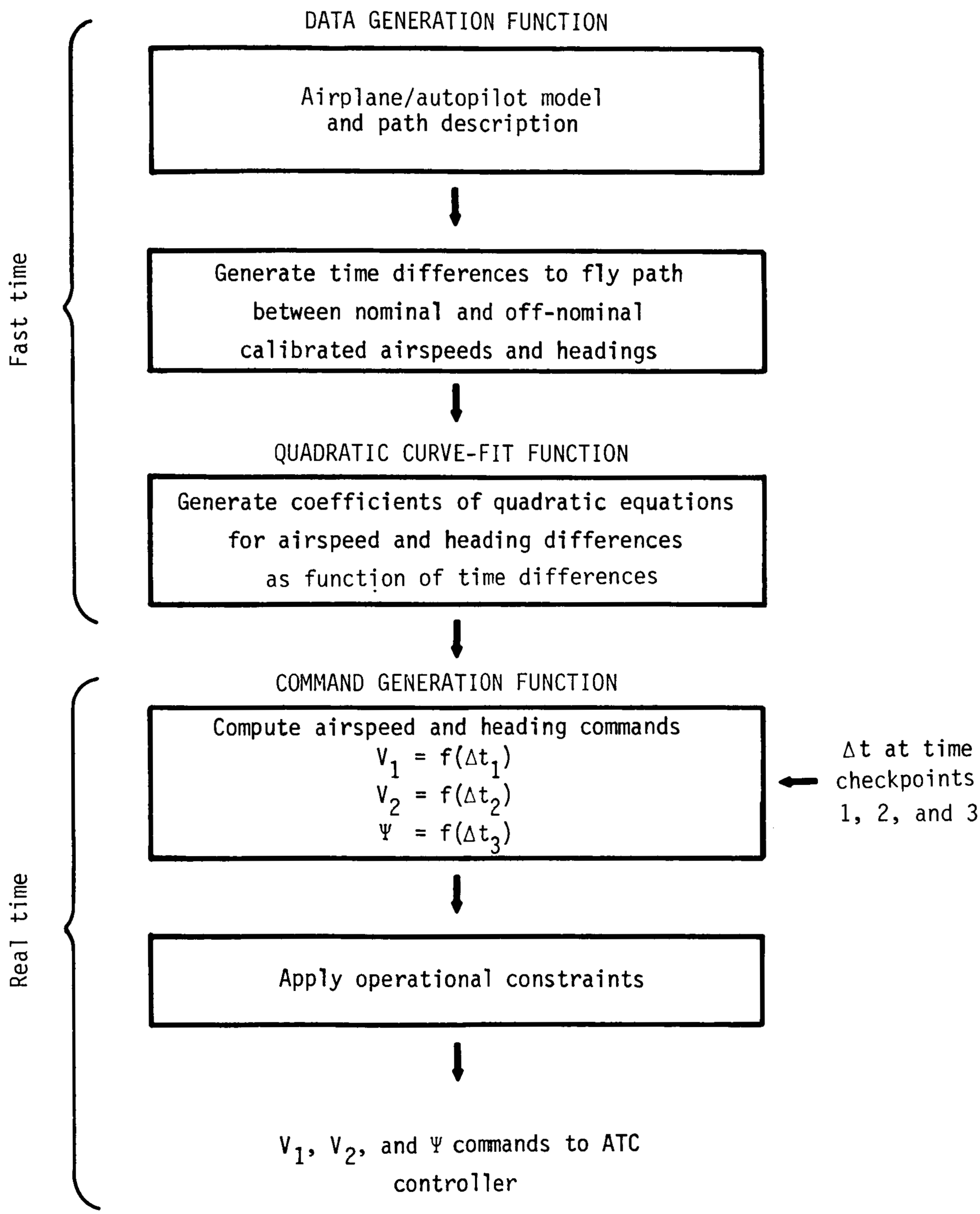


Figure 1. Functional diagram of time-guidance algorithm.

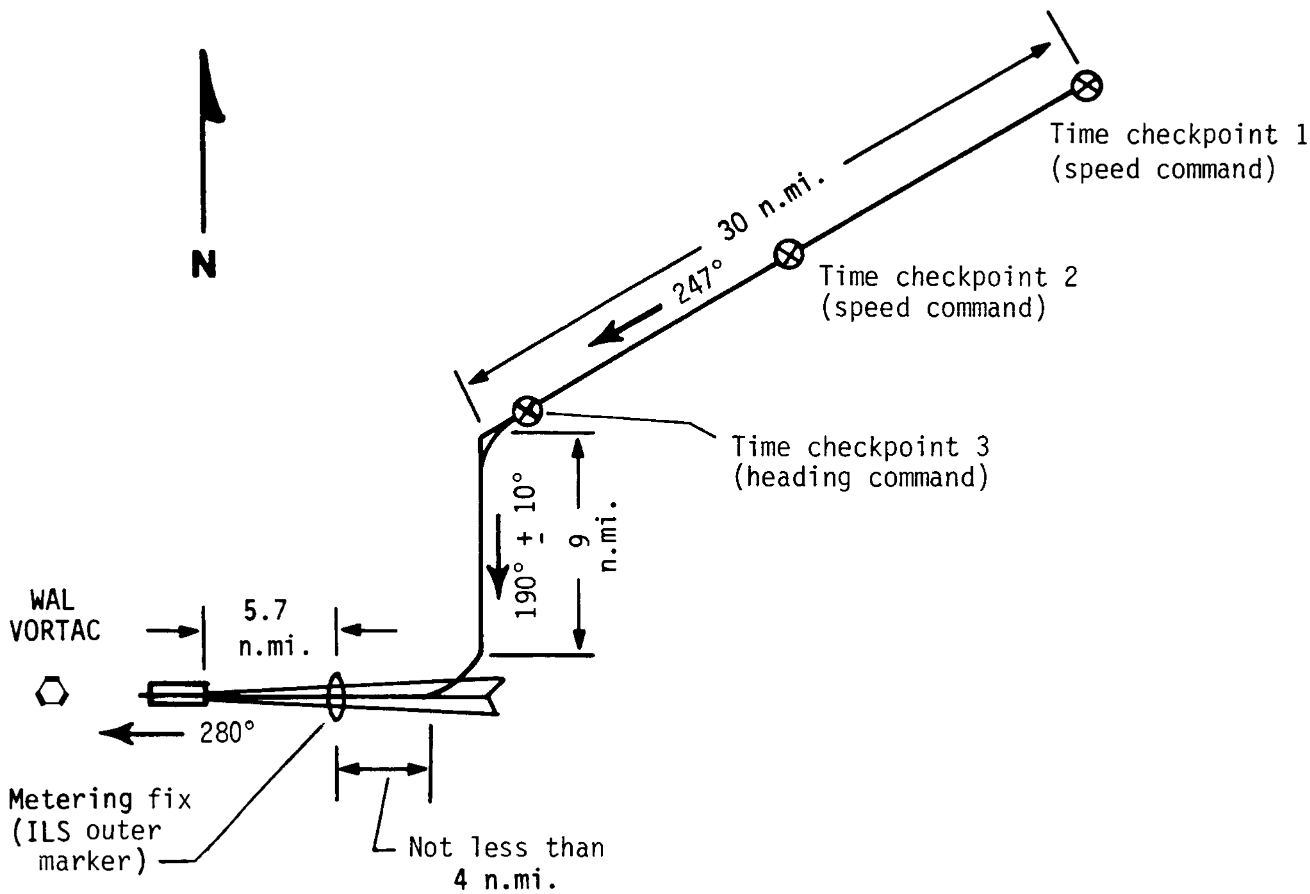


Figure 2. Nominal test path.

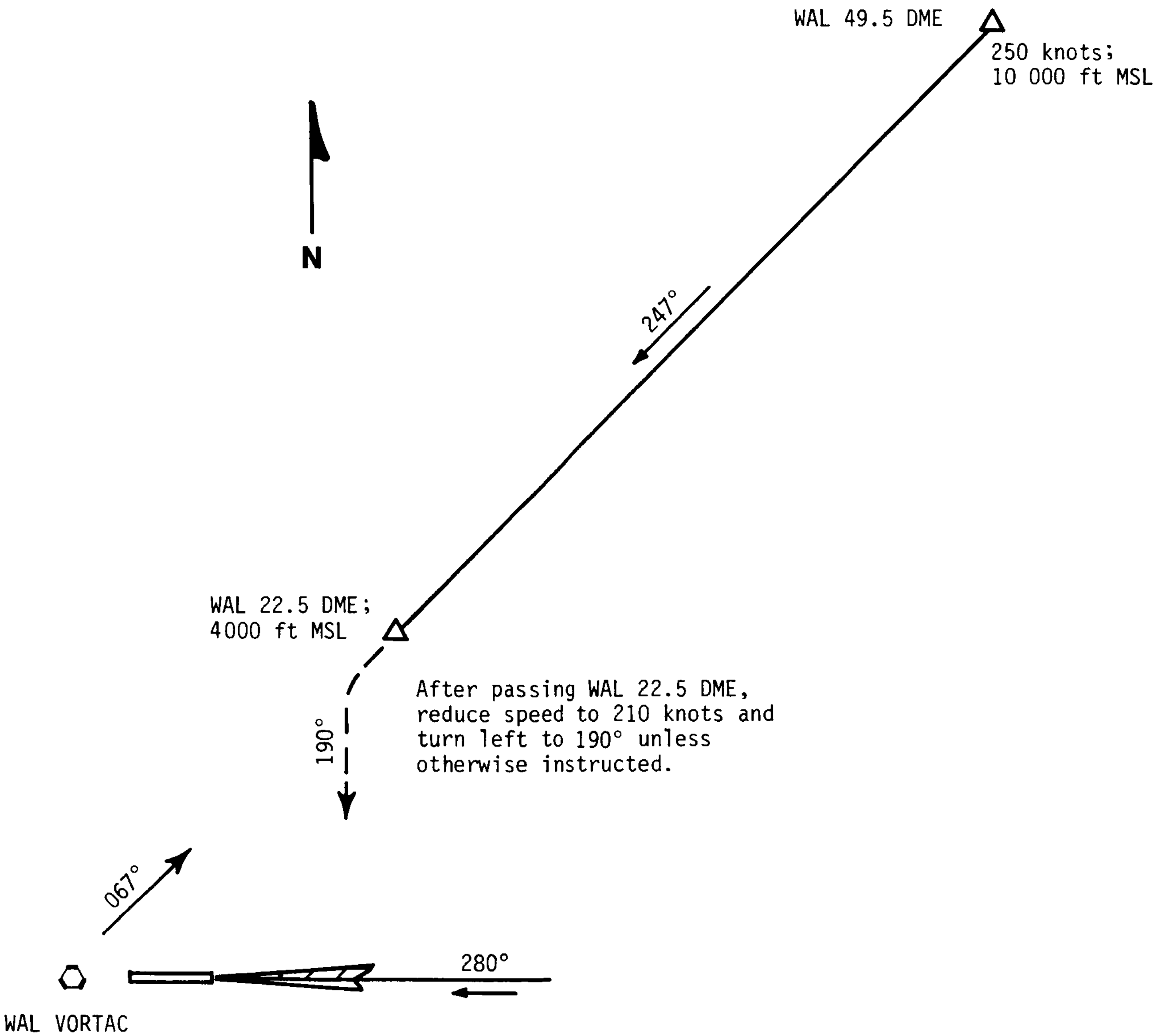


Figure 3. Terminal arrival-procedure chart.

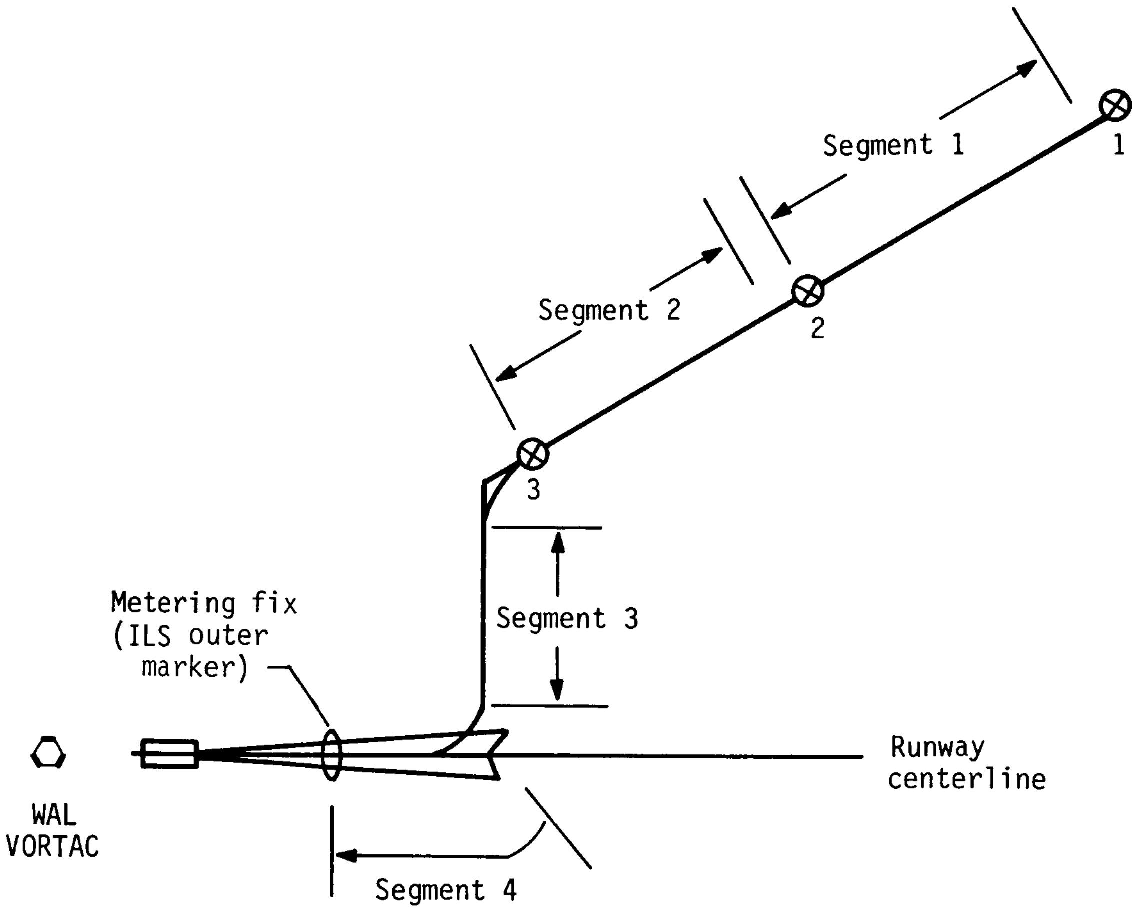
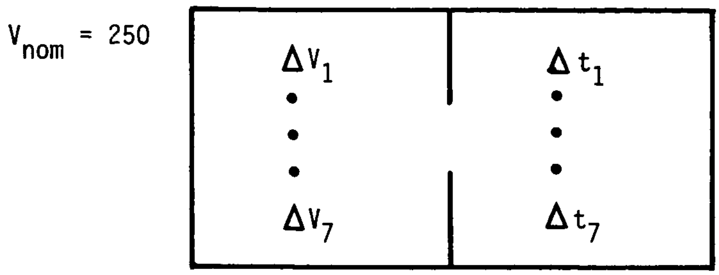
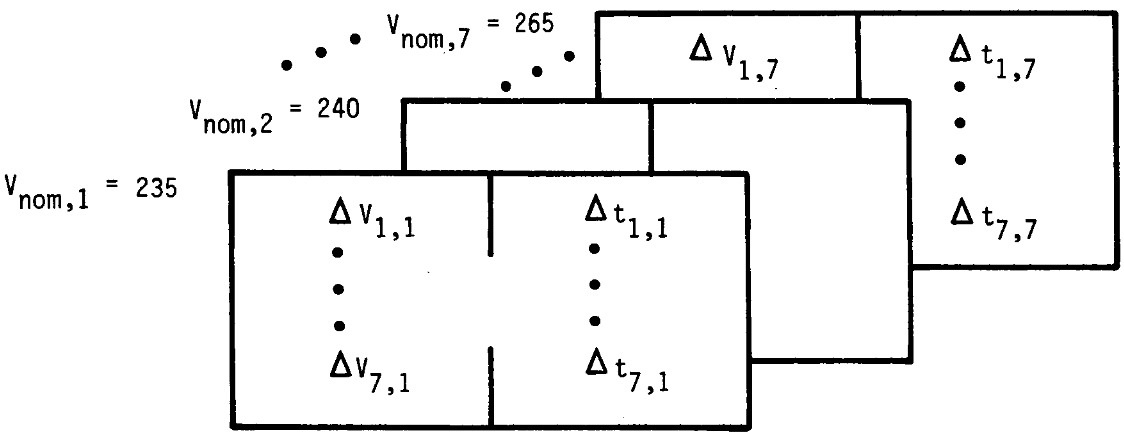


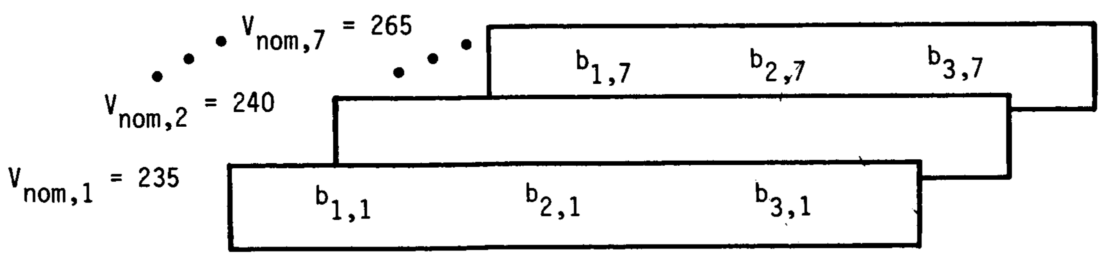
Figure 4. Path segments for postflight data analysis.



(a) Airspeed differences and time differences correlated to form 7 × 2 matrix for time checkpoint 1.

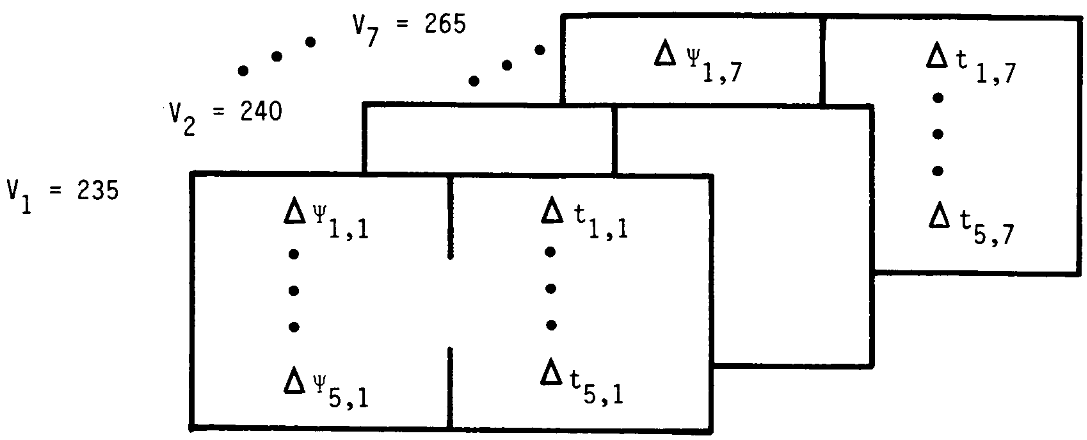


(b) Airspeed differences and time differences correlated to form 7 × 2 × 7 matrix for time checkpoint 2.

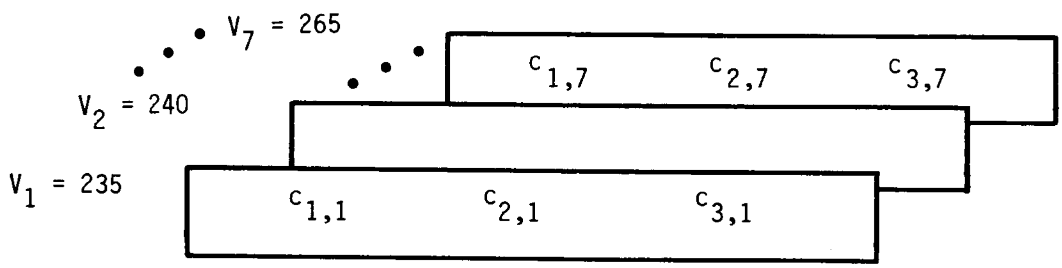


(c) 1 × 3 × 7 coefficient matrix for time checkpoint 2.

Figure 5. Difference and coefficient matrices for airspeed and heading command computations. Time is given in seconds, velocity is given in knots, and heading is given in degrees.



(d) Heading differences and time differences correlated to form $5 \times 2 \times 7$ matrix for time checkpoint 3.



(e) $1 \times 3 \times 7$ coefficient matrix for time checkpoint 3.

Figure 5. Concluded.

Standard Bibliographic Page

1. Report No. NASA TP-2616	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Ground-Based Time-Guidance Algorithm for Control of Airplanes in a Time-Metered Air Traffic Control Environment—A Piloted Simulation Study		5. Report Date November 1986
		6. Performing Organization Code 534-04-13-52
7. Author(s) Charles E. Knox and Nicole Imbert		8. Performing Organization Report No. L-16116
9. Performing Organization Name and Address NASA Langley Research Center Hampton, VA 23665-5225		10. Work Unit No.
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546-0001		13. Type of Report and Period Covered Technical Paper
		14. Sponsoring Agency Code

15. Supplementary Notes
Charles E. Knox: Langley Research Center, Hampton, Virginia.
Nicole Imbert: ONERA/CERT, Toulouse, France.

16. Abstract
The rapidly increasing costs of flight operations and the requirement for increased fuel conservation have made it necessary to develop more efficient ways to operate airplanes and to control air traffic for arrivals and departures to the terminal area. One concept of controlling arrival traffic through time metering has been jointly studied and evaluated by NASA and ONERA/CERT in piloted simulation tests. From time errors attained at checkpoints, airspeed and heading commands issued by air traffic control were computed by a time-guidance algorithm for the pilot to follow that would cause the airplane to cross a metering fix at a preassigned time. These tests resulted in the simulated airplane crossing a metering fix with a mean time error of 1.0 sec and a standard deviation of 16.7 sec when the time-metering algorithm was used. With mismodeled winds representing the unknown in wind-aloft forecasts and modeling form, the mean time error attained when crossing the metering fix was increased and the standard deviation remained approximately the same. The subject pilots reported that the airspeed and heading commands computed in the guidance concept were easy to follow and did not increase their work load above normal levels.

17. Key Words (Suggested by Authors(s))	18. Distribution Statement
Fuel conservation Flight management systems Airplane Air traffic control Time-based metering	Unclassified—Unlimited Subject Category 06

19. Security Classif.(of this report)	20. Security Classif.(of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	33	A03

For sale by the National Technical Information Service, Springfield, Virginia 22161

NASA-Langley, 1986