TEST RESULTS OF FLIGHT GUIDANCE FOR FUEL CONSERVATIVE DESCENTS IN A TIME-BASED METERED AIR TRAFFIC ENVIRONMENT

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ABSTRACT

The NASA has developed, implemented, and flight tested a flight management algorithm designed to improve the accuracy of delivering an airplane in a fuel-conservative manner to a metering fix at a time designated by air traffic control. This algorithm provides a 3-D path with time control (4-D) for the TCV B-737 airplane to make an idle-thrust, clean configured (landing gear up, flaps zero, and speed brakes retracted) descent to arrive at the metering fix at a predetermined time, altitude, and airspeed. The descent path is calculated for a constant Mach/airspeed schedule from linear approximations of airplane performance with considerations given for gross weight, wind, and nonstandard pressure and temperature effects. This report describes the flight management descent algorithms and presents the results of the flight tests.

SUMMARY

The Federal Aviation Administration has developed an automated time-based metering form of air traffic control for arrivals into the terminal area called local flow management/profile descent (LFM/PD). The LFM/PD concept provides fuel savings by matching the airplane arrival flow to the airport acceptance rate through time control computations and by allowing the pilot to descend at his discretion from cruise altitude to the metering fix. Substantial fuel savings have resulted from LFM/PD but air traffic control workload is high since the radar controller maintains time management for each airplane through either speed control or path stretching with radar vectors. Pilot workload is also high since the pilot must plan the descent to the metering fix using various rules-of-thumb.

The NASA has implemented and flight tested a flight management descent algorithm designed to improve the accuracy of delivering the airplane to a metering fix at a time designated by air traffic control in its Terminal Configured Vehicle (TCV) Boeing 737 airplane. This algorithm provides a 3-D path with time control (4-D) for the TCV Boeing 737 airplane to make an idle-thrust, clean-configured descent to arrive at the metering fix at a predetermined time, altitude, and airspeed. The descent path is calculated for a constant Mach/airspeed schedule using linear approximations of airplane performance accounting for gross weight, wind, and nonstandard pressure and temperature effects.

Flight test data were obtained on 19 flight test runs to the metering fix. The standard deviation of metering fix arrival time error was 12 sec with no arrival time error greater than 29 sec. Comparable statistics for time error accumulated between the top of descent and the metering fix (approximately 40 n.mi.) are a 6.9-sec standard deviation with no error greater than 15 sec. The airspeed and altitude error at the metering fix have standard deviations of 6.5 KCAS and 23.7 m (77.8 ft), respectively, and the maximum errors were less than 12.9 KCAS and 51.51 m (169 ft).

INTRODUCTION

Rising fuel costs combined with other economic pressures have resulted in industry requirements for more efficient air traffic control and aircraft operations. The Federal Aviation Administration (FAA) has developed an automated form of time-based metering air traffic control (ATC) for arrivals into airport terminals called local flow management/profile descent (LFM/PD). This concept provides for increased airport capacity and fuel savings by combining time-based metering with profile descent procedures. Time-based metering procedures provide for sequencing airport arrivals through time control of airplanes at metering fixes located 30 to 40 n.mi. from the airport. Time metering airplanes at these fixes reduce the low altitude vectoring (and subsequent fuel burned) required to position the airplanes into a final queue for landing. In addition, delays due to terminal area sequencing may be absorbed at higher altitudes further minimizing fuel usage (refs. 1 and 2).

Profile descent procedures allow the pilot to descend at his discretion so that he passes the metering fix at a specified altitude and airspeed. This procedure allows the pilot to plan his descent in a fuel-conservative manner accounting for the performance characteristics of his particular airplane.

In the original operational concept of the time based metering LFM/PD program, the flight crew was responsible for both the descent and time navigation to the metering fix. However, the pilots had little, or no, electronically computed guidance to aid them with this highly constrained (fuel efficient descent with a fixed time objective), 4-D navigation problem. Flight crews were forced to rely on past experience and various rules-of-thumb to plan descents. This resulted in unacceptably high cockpit workloads and the full potential of fuel savings from a planned descent not being obtained (ref. 3).

In an effort to reduce the cockpit workload, the responsibility of delivering the airplane to the metering fix at an assigned time was transferred to the ATC controller. The ATC controller directs each airplane to arrive at the metering fix at the assigned time through path stretching radar vectors and/or speed control commands to the pilot. These operations have resulted in airplane arrival time accuracy at the metering fix of approximately ±2 min (ref. 4). This arrival time accuracy may be improved with a significant increase in workload for the ATC controller, but an even further reduction of the time dispersions at the metering fix can produce further fuel savings.

Splitting the navigation responsibilities between the flight crew and ATC controller reduced the pilot's workload. However, when the ATC controller must apply path stretching or speed control for time management purposes, the pilot is forced to deviate from his planned descent profile; thus, more than the minimum fuel required is used.

The NASA has flight tested in its Terminal Configured Vehicle (TCV) Boeing 737 research airplane a flight management descent algorithm designed to increase fuel savings by improving the accuracy of delivering the airplane to the metering fix at an ATC designated time and by transferring the responsibility of time navigation from the radar controller to the flight crew. The algorithm computes a profile descent to the metering fix based on airplane performance at idle-thrust and in a clean configuration (landing gear up, flaps zero, and speed brakes retracted). Time and path guidance is provided to the pilot for a constant Mach, constant airspeed descent to arrive at the metering fix at a predetermined (ATC specified) time, altitude, and airspeed.

Flight tests using the flight management descent algorithm were conducted in the Denver, Colorado, LFM/PD ATC environment. The purpose of these flight tests was to quantify the accuracy of the airplane's descent algorithm and to investigate the compatibility and pilot acceptability of an airplane equipped with a 4-D navigation system in an actual ATC environment. This report will present the results of these tests.

SYMBOLOGY

ACLT	actual computed landing time
ARTCC	air route traffic control center
ATC	air traffic control
CLR	clearance
CRT	cathode ray tube
EADI	electronic attitude director indicator
EHSI	electronic horizontal situation indicator
ETA	estimated time of arrival
GW	gross weight
h_{AP}	altitude at the aim point
h_C	altitude at cruise
h_{MF}	altitude at the metering fix

h_{XO}	altitude to transition from a constant Mach to a constant airspeed descent
KCAS	calibrated airspeed, knots
LFM/PD	local flow management/profile descent
MF	metering fix
M_C	Mach number at cruise
M_d	Mach number in descent
NCDU	navigation control and display unit
NCU	navigation computer unit
RNAV	area navigation
TAT	total air temperature
TCV	terminal configured vehicle
VORTAC	very high frequency omnidirectional range and distance measuring equipment facility

ARTCC AUTOMATED LOCAL FLOW MANAGEMENT/PROFILE DESCENT DESCRIPTION

The ATC concept of automated local flow management/profile descents utilizing time-based metering is designed to permit operators of high performance turbine-powered aircraft to descend in a clean configuration at idle thrust to a point within the airport terminal area. Significant fuel savings are accomplished on a fleet-wide (all users) basis by matching the airplane arrival rate into the terminal area to the airport's arrival acceptance rate which reduces the need for holding and low altitude vectoring for sequencing. Fuel savings are also achieved on an individual airplane basis by permitting the pilot to descend in a fuel efficient manner at his discretion. In addition to arrival fuel savings, safety, noise abatement, and standardization of arrival procedures are all enhanced (ref. 5).

The Denver Air Route Traffic Control Center's (ARTCC) automated version of LFM/PD employs four metering fixes located around the Stapleton International Airport. All arriving high performance aircraft are time-based metered to one of these four metering fixes. Metering is accomplished with the ARTCC computer with consideration given to the following parameters:

1. Airport acceptance rate specified by the Stapleton International Airport tower (number of arrivals per unit time).

2. Nominal paths and airspeed profiles associated with each of the four metering fixes to the runways.

3. True airspeed filed on the airplane's flight plan.

4. Airplane position detected by ATC radar.

5. Forecast winds-aloft data from several stations in the Denver ARTCC area and/or measured winds from pilot reports.

These parameters are processed by the ARTCC computer to determine an estimated time of arrival (ETA) that each metered airplane would land on the runway assuming no conflicts. The ETA's for all metered airplanes are chronologically ordered and compared to determine if any of the airplanes are in conflict. Landing times are reassigned by the computer to resolve any time conflicts. The adjusted landing time is referred to as the actual computed landing time (ACLT). If the ACLT and the ETA are different, the difference indicates the delay that an airplane must accommodate prior to the metering fix through holding, speed control or path stretching. The metering fix arrival time (MFT) assigned to each airplane is found by subtracting a nominal transition time from the metering fix to the runway from the ACLT.

FLIGHT MANAGEMENT DESCENT ALGORITHM DESCRIPTION

The flight management descent algorithm computes a five segment descent profile (fig. 1) between an arbitrarily located entry fix to an ATC defined metering fix. A sixth segment from the metering fix to the next fix (specified by ATC and called the aim point) is also generated. Time and path guidance descent information based on these six segments is provided to the pilot.

The first segment after the entry fix is a level flight and constant Mach segment. The remaining level flight segments in the profile are for speed changes. The descent is divided into two segments, the first being an upper altitude constant Mach segment followed by a transition to the second which is a constant calibrated airspeed segment. The constant Mach/airspeed descent and the level flight airspeed change segments were used to be consistent with standard airline operating practices. The descent profile calculations are based on linear approximations of airplane performance for an idle-thrust, clean configuration. Airplane gross weight, maximum and minimum operational speed limits, wind, and nonstandard temperature and pressure effects are also considered in the calculations. A complete discussion of the equations and their development may be found in reference 6.

The flight management descent algorithm may be used in either of two modes. In the first mode, the pilot may input the Mach/airspeed descent schedule to be flown. This mode does not require a metering fix time assigned for the descent profile to be calculated. Once the profile is generated, a metering fix time may be assigned for time guidance. However, some time error, which must be nulled by the pilot, may result since an arbitrary specification of the descent speed schedule will not satisfy the time boundary conditions.

In the second mode, the entry fix and the metering fix times are pilot inputs which are time constraints that the algorithm must satisfy through an iterative process to determine an appropriate Mach/airspeed schedule. The initial Mach/airspeed schedule is proportional to the difference in times specified for the entry fix and the metering fix and the times required to fly between these fixes at the lower and the upper Mach/airspeed operational limits (0.62/250 KCAS and 0.78/340 KCAS, respectively). Subsequent iterations produce the descent Mach/airspeed profile that lies within the specified operational speed limits. The convergence criterion is that the computed metering fix arrival time error be less than 5 sec. This convergence criterion was normally satisfied in less than five iterations.

The algorithm checks to ensure that the final Mach/airspeed schedule selected is within the operational speed limit range. If a selected metering fix time requires a speed which violates one of these speed limits, the descent parameters are computed using the exceeded speed limit and the resultant difference in desired time and programmed time of arrival at the metering fix is displayed to the pilot.

DESCENT ALGORITHM INPUT/OUTPUT REQUIREMENTS

Data required for profile descent calculations are obtained from the NCU navigation data base, from pilot inputs through the NCDU, and from real-time sensor inputs through a data bus to the NCU.

Parameters contained in the NCU navigation data base include

(1) Aim point: location (latitude and longitude), programmed altitude, and programmed airspeed

(2) Metering fix: location (latitude and longitude), maximum and minimum programmed altitudes, and programmed airspeed

(3) Maximum and minimum airplane operational descent Mach number and airspeed

(4) Wind speed and direction gradients

Inputs required for the profile descent calculations inserted through the NCDU by the pilot include

(1) Entry fix description: location, programmed altitude, programmed ground speed, and programmed crossing time; the entry fix is the last waypoint the pilot has defined on his path before using the LFM/PD algorithm

The remaining pilot inputs through the NCDU are made on the profile descent display format shown in figure 2. Data entry is accomplished by pushing the appropriate numeric key corresponding to the data labels on the display followed by the actual data entry. The data may be entered in any order, or changed at any time, prior to the profile descent algorithm calculations.

(2) Descent Mach/CAS schedule (not allowed if both the metering fix and entry fix times are specified)

(3) Metering fix time (not allowed if the pilot selects the descent Mach/CAS schedule)

(4) Surface winds (zero is not data entered)

(5) Airport altimeter setting (29.92 if no data entered)

(6) Airplane gross weight (limited to not less than 333 600 N (75 000 lb) and not greater than 444 800 (100 000 lb))

(7) Total air temperature

Information required for the profile descent calculations input to the navigation computer automatically through a data bus include (magnitudes at time of profile descent calculation)

(1) Winds-aloft speed and direction

(2) Cruise Mach number

(3) Cruise altitude

The flight management descent algorithm calculates and outputs the following parameters to be used by the guidance and display system:

(1) All descent way-point distances relative to the metering fix, programmed altitudes, and programmed ground speeds

(2) The magnetic direction of the entry fix relative to the metering fix (all waypoints used to describe the descent profile lie in the vertical plane defined between the metering fix and entry fix)

(3) Mach/CAS descent schedule

FLIGHT TEST OBJECTIVES

The objectives of the flight tests were to (1) document the descent path parameters determined by the descent flight management algorithms including wind modeling effects, (2) establish the compatibility of the airborne flight management descent concept with time control in the cockpit while operating in the time-based metered LFM/PD air traffic control environment, (3) determine pilot acceptance of the cockpit procedures to program and fly a fuel efficient, time controlled descent, and (4) obtain data for estimates of fuel usage. These objectives were achieved using qualitative data in the form of pilot and ARTCC radar controller comments, audio recordings of controller, cockpit, and air-to-ground conversations, and video recordings from the ARTCC radar scope and with quantitative data in the form of speed, altitude, and time error recorded onboard the airplane.

DESCRIPTION OF AIRPLANE AND EXPERIMENTAL SYSTEMS

The test airplane is the TCV Boeing 737 research airplane (a twin-jet commercial transport). The experimental systems consist of a digital flight control system, a digital navigation and guidance system, and an electronic CRT display system integrated into a separate research flight deck. The research flight deck, shown in figure 3, is full-scale and located in the airplane cabin just forward of the wing (ref. 7).

The triply redundant digital flight control system provides both automatic and fly-by-wire control wheel steering options. The velocity vector control wheel steering mode (ref. 7) was utilized during these flight tests.

The navigation computer is a general purpose digital computer designed for airborne computations and data processing tasks. It utilizes a 24-bit word length and has a 32K word directly addressable core memory.

Major software routines (refs. 8 and 9) in the navigation computer include the (1) navigation position estimate, (2) flight route definition, (3) guidance commands to the flight control computer system, (4) piloting display system computations, and (5) flight data storage for navigation purposes. The flight management descent algorithm software was also included in the navigation computer.

The captain and the first officer each have three CRT displays and conventional airspeed and altimeter instrumentation for guidance. The three CRT displays include the EADI, the EHSI, and a digital display of various navigation information in the NCDU.

The EADI display is formatted much like a conventional attitude indicator but has numerous additional symbology to help the pilot navigate and control the airplane. A detailed explanation of the EADI display may be found in reference 8. Two options of the EADI display used for lateral and vertical path navigation on these flight tests are the vertical and lateral course deviation indicators and the "star and flight path angle wedges."

The vertical and lateral course deviation indicators are presented in a conventional needle and tape format shown in figure 4. The vertical tape on the right hand side of the EADI shows the vertical path error. A standard "fly to" deviation convention is employed where the needle represents the desired path and the center of the tape represents the airplane (i.e., if the airplane is below the desired path the needle will be displaced above the center of the tape). The indicated range of the tape scale is 152.4 m (500 ft.)

The lateral course deviation indicator is displayed on the bottom of the EADI. The "fly to" deviation convention is utilized and the indicated range of the horizontal tape is ±1829 m (6000 ft.)

The second EADI navigation option used during this test was the "star and flight path angle wedges" shown in figure 4. The star represents the next waypoint on the programmed route. The star's vertical displacement on the EADI pitch grid represents the flight path angle at which the airplane must be flown to arrive at the programmed altitude at the next waypoint. The star is also displaced laterally in the same manner to provide lateral path tracking guidance.

The flight path angle wedges used with the star display represent the inertially referenced flight path of the airplane. If the airplane flight path angle and track angle are adjusted so that the flight path angle wedges center directly on the star, the airplane will be flying directly to the waypoint.

Figure 5 shows a drawing of the CRT EHSI display operated in a track-up mode. This display is a plan view of the desired route and optionally displayed features such as radio fixes, navigation aids, airports, and terrain drawn relative to a triangular airplane symbol. A trend vector has been drawn in front of the airplane symbol to aid the pilot with route capture and tracking and with time guidance utilization. The trend vector is composed of three consecutive 30-sec lines which predict where the airplane will be in the next 30, 60 and 90 sec based on the airplane's current ground speed and bank angle. The EHSI display also provides the pilot with time guidance and an altitude predictive arc to aid the pilot during altitude changes.

Time guidance is provided on the EHSI by a box that moves along the programmed path. The time box represents the position along the route where the airplane should be based on the programmed ground speeds and the time profile. The pilot nulls the time error by maneuvering the airplane so that the airplane symbol is inside the time box.

During climbs and descents, the pilot may select the range/altitude arc option to be drawn on the CRT EHSI. This option generated an arc on the EHSI, as shown in figure 5, that depicts the range in front of the airplane where a pilot selected reference altitude will be achieved. This symbol is drawn based on the airplane's current altitude and flight path angle and the desired reference altitude.

The range/altitude arc was used on the descent profile during these tests by setting the magnitude of the reference altitude to the programmed altitude of the next waypoint. Then the pilot would adjust the flight path angle of the airplane so that the arc would lie on top of the next waypoint displayed on the EHSI. This would result in the airplane crossing the next waypoint at the programmed altitude.

The NCDU display contains numerous navigational data for the pilot to select including programmed route information, tracking and navigational error information, and systems status checks. This information is presented in digital form. A complete description of the NCDU and its operations may be found in reference 8.

DATA ACQUISITION

Data were recorded onboard the airplane by a wide-band magnetic tape recorder at 40 samples/sec. These data include 93 parameters describing the airplane configuration, attitude, control surface activity, and 32 selectable parameters from the navigation computer. Airborne video recordings of the EADI and the EHSI displays were made throughout the flight. In addition, audio records of test crew conversations and air/ground communications were recorded.

On the ground, the radar controller's scope presentation and the ARTCC computer generated time-based metering update list were video recorded.

FLIGHT TEST CREW

The flight test crew consisted of a captain and first officer. The captain was responsible for flying the airplane in the velocity vector control wheel steering mode and for operation of the thrust levers. The first officer was responsible for program inputs to the navigation computer, selecting appropriate display guidance, and assisting the captain as requested. In addition, the first officer recorded flight notes of various parameters describing the profile descent for post-flight analysis.

Two NASA test pilots and four management/line airline pilots served as captain during the flight tests. Both NASA pilots had extensive previous flight and simulation experience with the TCV airplane and its experimental flight control and display systems. The four airline pilots each had approximately 6 hours of simulator training prior to the flight tests. One of the airline pilots had 4 hours of flight time in the TCV airplane on unrelated flight tests 9 months earlier.

A NASA engineer served as first officer on all flights. He had previous flight crew experience in simulation and flight with the TCV airplane and its experimental systems.

TASK

Other than requiring the time navigation responsibility to be in the cockpit, the experiment task required the flight crew to operate the airplane as a normal arrival flight to the Denver airport participating in the time-based metered LFM/PD air traffic control system. Each test run was started with the airplane at cruise altitude and speed on a 4-D programmed path to an entry fixed 100 n.mi. from Denver. Prior to passing the entry fix, the flight crew received a profile descent clearance and an assigned metering fix time from the Denver ARTCC. The flight crew then keyed the appropriate parameters into the NCDU so that an idle thrust descent path to the metering fix would be generated. Then the crew flew to the metering fix using 4-D path guidance presented on the EADI and EHSI displays. Each test run was terminated at the metering fix and the airplane was repositioned for another test run (or flown back to the airport).

The flight crew was expected to null lateral and vertical path errors throughout the test and null the time error prior to the top of descent waypoint. During the descent to the metering fix, thrust was at flight idle and speed brakes were not used regardless of any time error so that the effects of wind modeling on the predicted descent path could be observed. Path deviations for air traffic control purposes or for weather were accepted and accommodated during the test runs.

The flight test path, including the profile descent segments, flown for each run is shown in figure 6. This test path was 420 n.mi. long and took approximately 1 hour to fly. The first officer would program path guidance to the entry fix prior to arriving at the Gill VORTAC. After the final metering fix arrival time was computed by the Denver ARTCC and radioed to the airplane, guidance for the profile descent between the entry fix and the aim point was computed with the navigation computer using the flight management descent algorithm.

The pilot was instructed to null small time errors (less than 20 sec) through speed control and larger time errors through path stretching (with ATC concurrence) maneuvers. However, the pilot was to have attained the programmed ground speed and altitude at the top-of-descent waypoint regardless of the time error.

Between the top-of-descent and the metering fix waypoints, the airplane was flown at idle thrust and the use of speed brakes was not permitted. The captain used path guidance on the EHSI display and the lateral path deviation indicator on the EADI for lateral path guidance. For vertical guidance, he used the star and flight path angle wedges on the EADI and the range altitude arc on the EHSI display. It was the responsibility of the first officer to select the desired altitude for the range/altitude arc option so that the captain could devote his full attention to flying the airplane.

The captain would anticipate leveling the airplane for the programmed altitude at the bottom-of-descent waypoint with reference to a conventional barometric altitude and then would proceed to the meeting fix. After passing the metering fix, the test run was complete and the captain would turn the airplane to reposition for another test run (or continue to the airport for landing).

RESULTS AND DISCUSSION

Airborne Algorithm Flight Performance

The prime indicator of performance of the flight management descent algorithm and concept of time control in the cockpit was the accuracy in terms of time, airspeed, and altitude with which the airplane passed the metering fix. This accuracy was quantified through the calculation of the mean and standard deviation of the altitude error, airspeed error, and time error for 19 test runs.

The mean, standard deviation, and maximum value for the altitude, airspeed, and time errors are summarized in the following table:

	Altitude error, m (ft)	Airspeed error, KCAS	Absolute time error, sec
Mean	10.2(33.6) high	0.3 slow	6.6 late
Std Dev	23.7(77.8)	6.5	12.0
Maximum Error	51.5(169) high	12.9 fast	29.0 late

The values of these errors were judged by the pilots to be very good for this flight environment. These data demonstrated that highly accurate fuel efficient descent profiles that satisfy terminal time boundary constraints can be generated and flown using a relatively simple and straightforward empirical model for the aerodynamic and performance characteristics of the airplane. Because of the simplicity of modeling these characteristics, this algorithm could be applied to various flight management/planning systems that are much less sophisticated than the NASA TCV Boeing 737 experimental system.

The standard deviation and the maximum value of the altitude error were slightly higher than expected. This was attributed to the fact that the pilots had been instructed not to make minor altitude corrections after the initial level-off at the bottom of descent waypoint so that the difference between the actual and predicted airspeed change between the bottom of descent and metering fix waypoints could be accurately assessed.

The absolute time error of the airplane crossing the metering fix resulted in a significant error reduction with time control in the cockpit (6.6 sec compared to approximately ±2 min). The pilots felt that they could have reduced the time error even further had they been allowed to modulate thrust and/or speed brakes during the descent. Since the thrust was at flight idle and the speed brakes not employed during the descent, the absolute time error was a function of the initial time error at the top of descent as well as a function of the flight management descent algorithms (which included wind modeling).

The time error accumulated between the top of descent and the metering fix waypoints more appropriately reflects the accuracy with which the performance of the airplane and the winds had been modeled in the flight management descent algorithm. The mean and standard deviation of the accumulated time error for the 19 test runs were 2.5 sec and 6.9 sec, respectively. The maximum accumulated time error was 15 sec, but typically less than 9 sec.

The mean and standard deviation of the time errors associated with crossing the metering fix may have been influenced by the time error in the Mach/airspeed descent speed schedule convergence test. During these flights, the descent speed schedule was computed based upon a 5-sec time error convergence criterion. Five sec was chosen because the descent speed schedule could be computed in less than six iterations and would result in a reasonable bound upon the time error with the resulting descent speed schedule. However, if more computational iterations to compute the descent speed schedule are permissible, then the convergence criterion could be reduced and a corresponding reduction of the time error crossing the metering fix expected.

Wind Modeling

The direction and speed gradients of a two-segment linear wind model were entered into the descent flight management software each day prior to flight. The gradients for the wind model were based on the winds aloft forecast for the Denver area for the time period of the test flights. Since the winds aloft forecast was made 6 to 8 hours before the flight tests, the actual winds aloft measured onboard were recorded during the climb to cruise altitude on the first test run of the day. This wind information was plotted and compared to the forecast to determine if the wind model gradients should be modified. The gradients could be changed in flight for succeeding test runs, if required. The wind speed gradient was changed on only two of the test runs - one of these changes is shown on figure 7.

Figure 7 shows the original and modified wind models used and the winds measured for two consecutive test runs. The first test run used a model based on the winds aloft forecast obtained before the flight. The second run used a wind model based on the winds measured during the first test run. The wind speed gradient on the first model was not steep enough and resulted in wind speeds modeled faster than encountered during the run. The accumulated time error resulting on this run was 15 sec.

The gradient of the wind speed model was steepened for the second test run. The direction gradient was unchanged. The resulting accumulated time error was reduced to 2 sec.

While the wind model had predetermined speed and direction line gradients, the position of these lines was defined by the magnitudes of the inertially measured wind speed and direction when the profile descent was calculated by the flight management descent algorithm. These measured initial conditions are shown in figure 7 with a circle around the data point. During these test flights this point of calculation was typically 100 n.mi. before the top of descent waypoint. This resulted in the possibility of a bias error in the modeled wind speed and/or direction due to a wind shift between the point where the descent calculation was executed and the top of descent. This phenomena occurred in the direction gradient of the second run as shown in figure 7. The measured wind direction at the point of descent calculation (115 n.mi. from the top of descent) was 304° and at the top of descent the measured wind direction was 291°. Hence, a 13° bias error in direction resulted. The resulting accumulated time error during descent due to a wind direction error is dependent upon the magnitude of the wind, the wind's direction relative to the airplane's path (headwind component error), and the total time required for descent.

Airborne and Ground System Compatibility

The profile descent calculated by the flight management descent algorithm, pilot's guidance, and cockpit procedures was designed to be compatible with current time-based metering LFM/PD ATC procedures and with other traffic participating in the ATC system. The test airplane was treated by the automated time-based metering LFM/PD computer program in the same manner as other airplanes inbound to the Denver airport. The only ATC procedural difference during the flight tests was that the test airplane pilots were responsible for time management, which resulted in no path stretching radar vectors or speed control commands required for sequencing purposes. Controller comments indicated that this difference allowed a reduction in their workload due to less required ground-to-air radio transmissions.

Pilot comments indicated the task of flying profile descents with time control using the electronic displays was very easily accomplished. The descent algorithm and the path guidance substantially reduced the pilot's workload, no cockpit calculations were required to determine the top of descent point, and guidance presented to the pilot made it easy to maintain good time control. Computer inputs prior to descent were direct and simple.

Video tape recordings of the ATC controller's radar scope have shown that the test airplane operated compatibly with other traffic. The TCV airplane merged with, and remained in, a queue of other airplanes bound for the metering fix. This compatibility resulted due to the Mach/airspeed descent schedule and resulting time profile calculated with the descent management algorithm based on the assigned metering fix time. This assigned metering fix time was based upon the position and metering fix time assigned to the airplanes landing prior to the TCV airplane. Proper spacing between these airplanes and the test airplane would result if the time profile was followed.

Fuel Savings

Total fuel savings are accomplished on both a fleet-wide basis and an individual airplane basis. Time-based metering procedures produce fleet-wide fuel savings by reducing extra vectoring and holding of aircraft at low altitude for sequencing into an approach queue. Profile descent procedures produce individual airplane fuel savings by allowing the pilot to plan for a fuel efficient descent to the metering fix.

No attempt was made to quantify the increased fleet-wide fuel savings due to the reduction of time dispersion crossing the metering fix since the TCV vehicle was the only airplane that utilized onboard generated 4-D guidance during these tests. It is apparent, however, that a reduction in time dispersion between airplanes merged into an approach queue can produce an increase in fuel savings by a reduction of the extra maneuvering for longitudinal spacing and can produce an increase in runway utilization by narrowing larger than required time gaps between airplanes.

Fuel savings at the Denver airport as a result of profile descent operations have been estimated to be as high as three and a quarter million dollars per year (ref. 5). Additional fuel savings as a result of the airborne algorithms were quantified through an analytical comparison of a descent calculated by the flight management descent algorithm and a conventional descent typical of those airplanes observed on the ARTCC radar display. Fuel usage for each descent was based on fuel flow for a Boeing 737 airplane.

Figure 8 shows the vertical profile of both the calculated and conventional descents. Identical initial and final boundary conditions (location, altitude, speeds, and time) were used for both descents so that a valid comparison of fuel usage could be made. Both descents begin at the entry fix, 76 n.mi. from the metering fix, at an altitude of 10668 m (35000 ft), and at a cruise Mach of 0.78. The descents end at the metering fix at an altitude of 5944 m (19500 ft) and at a calibrated airspeed of 250 knots. Flying time for both descents is 11.7 min.

The conventional descent is based on idle thrust at a Mach of 0.78 with a transition to 340 knots airspeed. The descent from cruise altitude is started at a point 60 n.mi. from the metering fix which is consistent with various pilot rules-of-thumb for descent planning. At the bottom of descent, the airplane is slowed until reaching an airspeed of 250 knots. Thrust is then added as required to maintain the 250 knots airspeed.

The descent calculated by the flight management descent algorithm is based upon an 11.7 min time constraint. The calculated Mach/airspeed descent schedule for this profile is 0.62/250 knots. Thrust is set to flight idle approximately 7 n.mi. prior to the descent so that the airplane may slow from the cruise to the descent Mach. A constant 0.62 Mach descent segment is started 40.6 n.mi. from the metering fix with a transition to a constant 250 KCAS airspeed descent segment to the metering fix.

Both descents, by definition of the comparison, require the same length of time to fly between the entry fix and the metering fix. This time objective is achieved with similar ground speeds on both descents. Even though the calculated descent is flown at a slower indicated Mach/airspeed descent schedule, similar ground speeds result since the airplane stays at altitudes higher than on the conventional descent.

Fuel usage on these two descents is substantially different, however. The descent calculated by the flight management descent algorithm required approximately 28 percent less fuel to fly between the entry fix and the metering fix (2989 N (672 lb) on the conventional descent and 2148 N (483 lb) on the calculated descent). Approximately two-thirds of this fuel savings was attributed to the lower indicated airspeeds and one-third to flight at higher altitudes.

CONCLUSIONS

An airborne flight management descent algorithm designed to define a flight profile subject to the constraints of using idle-thrust, a clean airplane configuration (landing gear up, flaps zero, and speed brakes retracted), and fixed time end conditions was developed and flight tested in the NASA TCV Boeing 737 research airplane. The research test flights, conducted in the Denver ARTCC automated time-based metering LFM/PD ATC environment, demonstrated that time guidance and control in the cockpit was acceptable to the pilots and ATC controllers and resulted in delivery of the airplane over the metering fix with standard deviations of 6.5 knots of airspeed error, 23.7 m (77.8 ft) of altitude error, and 12 sec of arrival time accuracy. Fuel savings may be obtained on a fleet-wide basis through a reduction of the time error dispersions at the metering fix and on a single airplane basis by presenting the pilot guidance for a fuel efficient descent. Pilot workload was reduced by automating those processes that required use of rule-of-thumb and/or extensive experience to achieve a solution to a complex 4-D navigation problem and through steering guidance for 4-D path following. ATC controller workload was reduced through a reduction of required ground-to-air communications and through the transfer of time navigation responsibilities to the cockpit.

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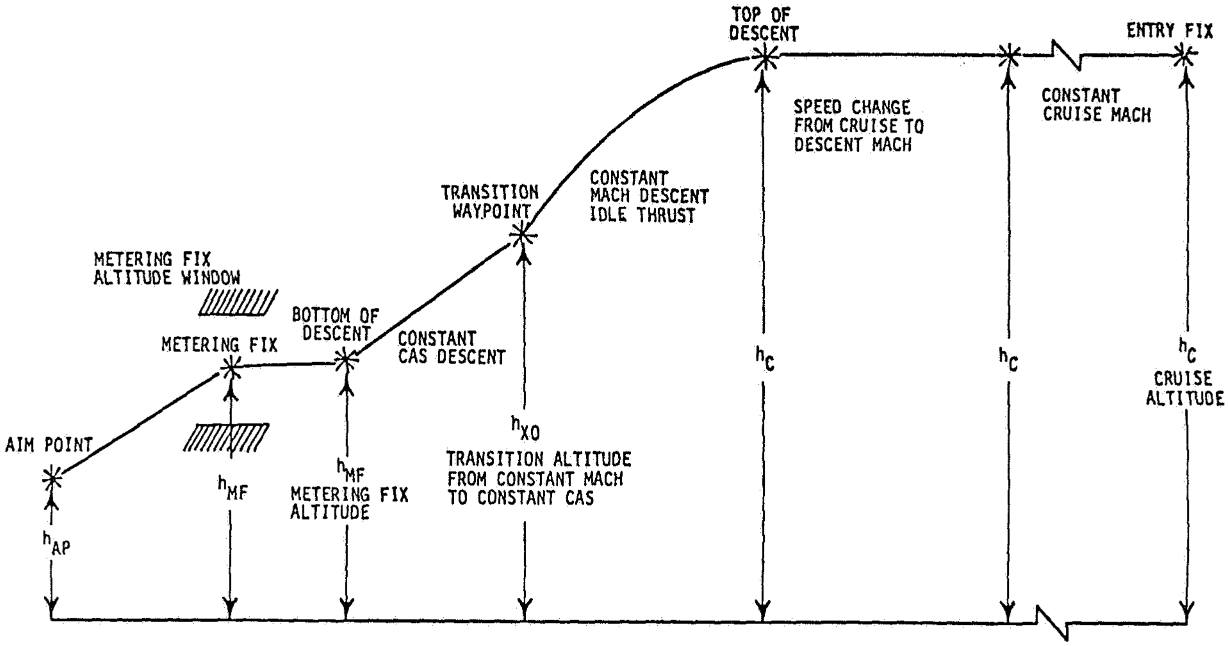
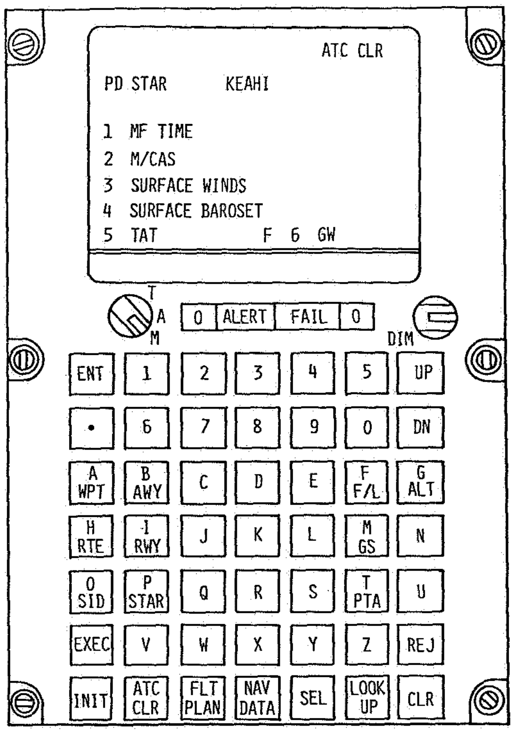


Figure 1.- Vertical plane geometry associated with LFM/PD algorithms.


ATC CLR

PD STAR KEAHI

1 MF TIME
2 M/CAS
3 SURFACE WINDS
4 SURFACE BAROSET
5 TAT F 6 GW

Figure 2.- Profile descent display format on the NCDU.

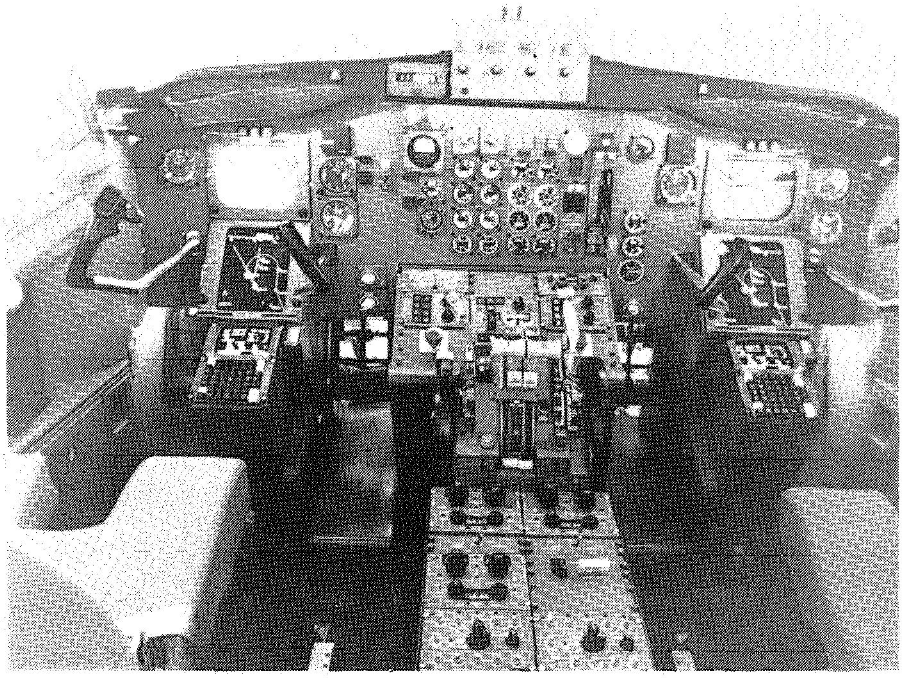


Figure 3.- Research flight deck instrument panel.

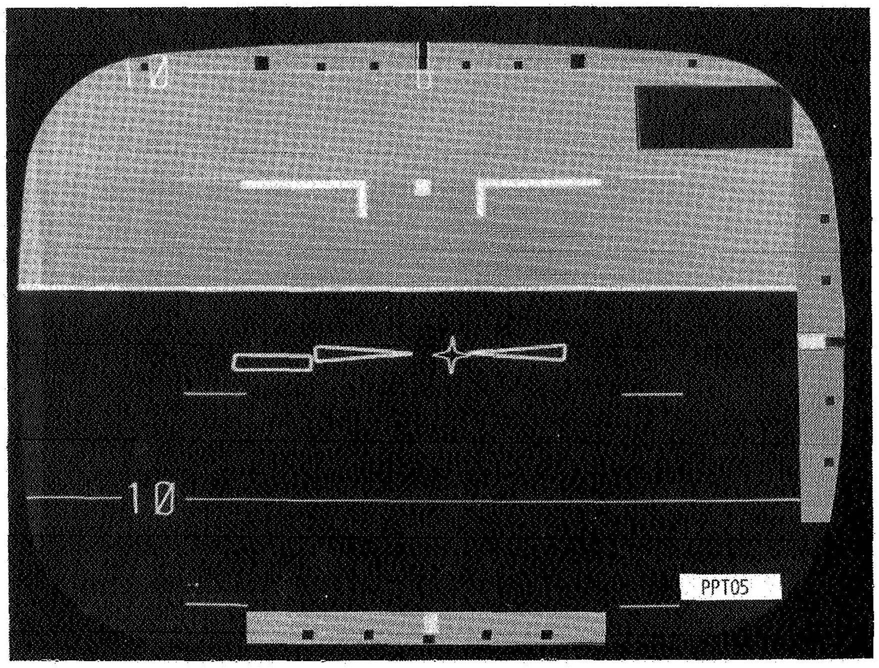


Figure 4.- EADI display with the course deviation indicators and the star and wedges guidance symbology.

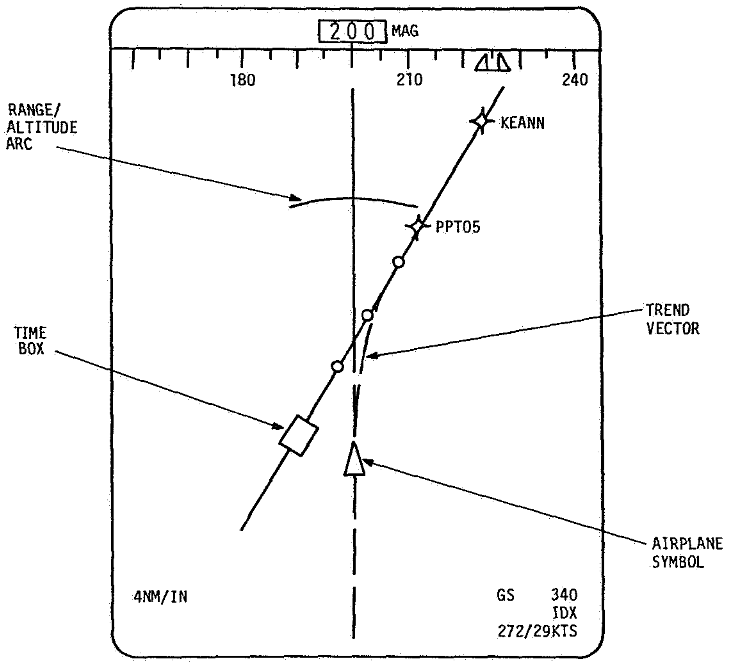


Figure 5.- EHSI display with the trend vector, range/altitude arc, and time guidance symbology. (Note: 1 in. = 2.54 cm.)

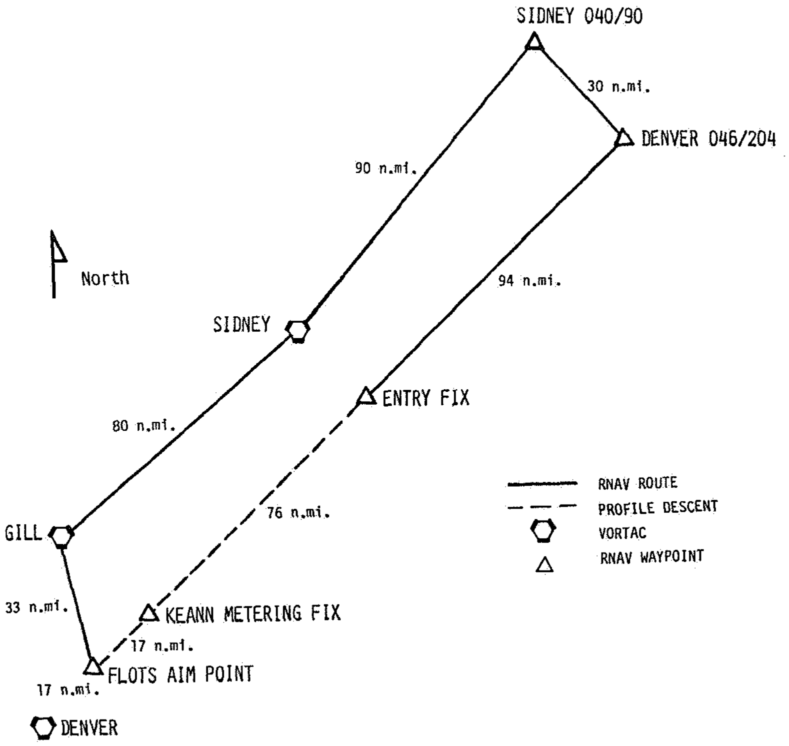


Figure 6.- LFM/PD flight test path.

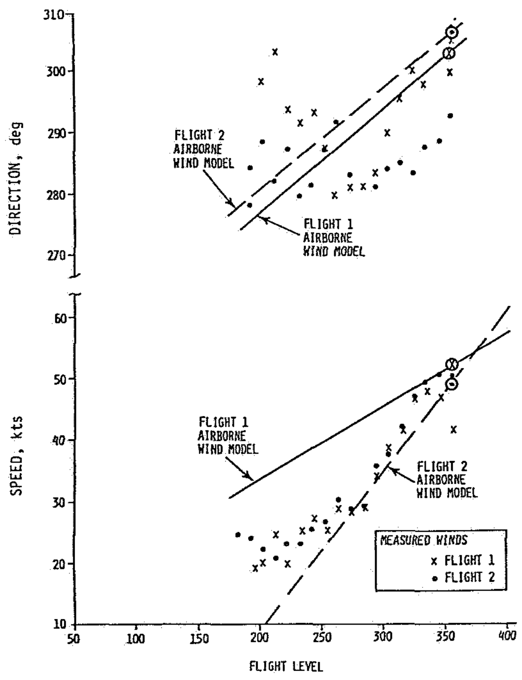
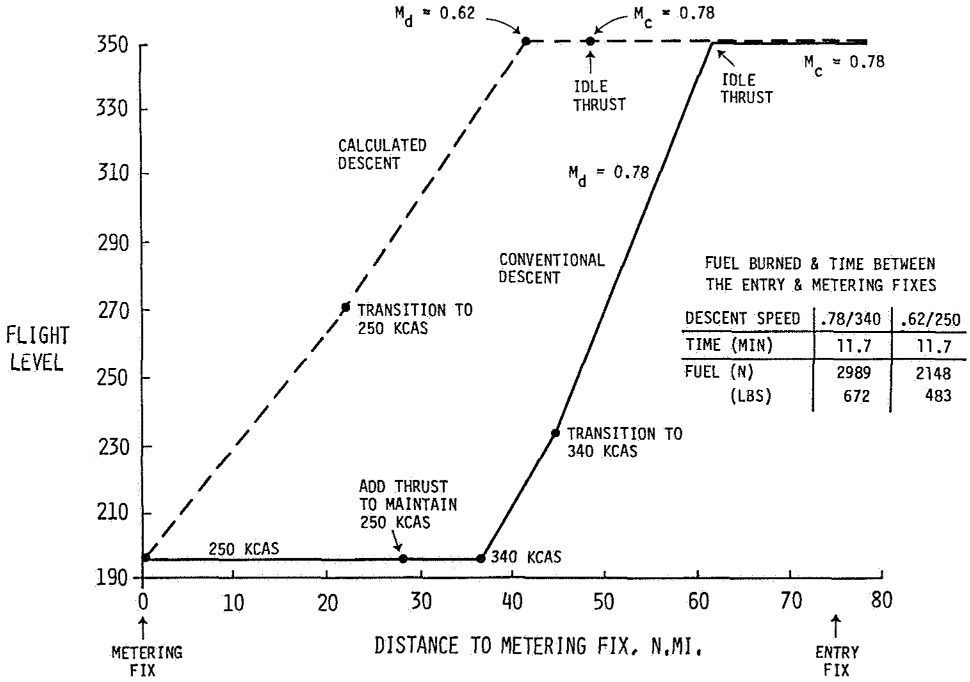


Figure 7.- Modelled and measured wind speed and direction (relative to magnetic north) for two flights.



FUEL BURNED & TIME BETWEEN THE ENTRY & METERING FIXES

DESCENT SPEED	.78/340	.62/250
TIME (MIN)	11.7	11.7
FUEL (N)	2989	2148
(LBS)	672	483

Figure 8.- A comparison of a conventional descent profile typically flown and a descent profile calculated by the flight management descent algorithm.