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A PILOTED SIMULATOR EVALUATION OF A GROUND-BASED 4D DESCENT ADVISOR ALGORITHM

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ABSTRACT

A ground-based, four-dimensional (4D) descent-advisor algorithm has been developed that combines detailed aerodynamic, propulsive, and atmospheric models with an efficient numerical integration scheme to generate fuel-efficient descent advisories. This paper investigates the ability of the algorithm to provide advisories for controlling arrival time of aircraft not equipped with on-board 4D guidance systems. A piloted simulation was conducted to determine the precision with which the algorithm predicts the trajectories of typical straight-in descents flown by airline pilots under different wind conditions. The effects of errors in the estimation of winds and initial aircraft weight were also evaluated. A description of the algorithm as well as the results of the piloted simulation are presented.

INTRODUCTION

In the past several years, the United States' air traffic control (ATC) system has experienced a continual increase in the congestion of high-density terminal areas resulting in an increase in delays, fuel wastage, and controller workload. Research is currently underway at NASA Ames Research Center to investigate the potential for a time-based, automated air traffic management system to improve the traffic flow into high-density terminal areas. The success of a time-based air traffic management system depends on its ability to handle aircraft equipped with various types of on-board equipment ranging from the basic to the advanced. For example, the near future will bring new commercial aircraft that will be equipped with flightpath management systems capable of generating and flying four-dimensional (4D) trajectories. Although these systems are the essential component of a time-based air traffic management system, there will be a long transition period when there will be a mix of equipped and unequipped aircraft. Thus, to achieve some of the benefits of a time-based air traffic management system during the transition period, a means of controlling the arrival times of unequipped aircraft as well as ATC procedures must also be developed. ATC procedures for controlling a mix of 4D-equipped and unequipped aircraft have already been investigated in a series of simulation studies.[1]

This paper describes the development and performance of a ground-based 4D descent-advisor algorithm for controlling the arrival times of unequipped aircraft.* For the purposes of this paper, the arrival time is assumed to be controlled to a position (time-control point) located 30 n. mi. from touchdown at an altitude of 10,000 ft. This position represents an intermediate point between cruise and touchdown where commercial jet traffic transitions from enroute descent to terminal area operation. The desired arrival time accuracy for unequipped aircraft at this position is ±20 sec.[2]

Previous work in on-board flightpath management algorithms has laid the foundation for ground-based algorithms. The problem of generating optimum trajectories that minimize direct operating cost for free terminal time was originally solved using an energy-state approximation.[3] Sorenson and Waters extended that work to include control of time of arrival.[4] However, practical use of these optimal flightpaths requires an on-board guidance system to display the guidance commands necessary for the pilot to fly the trajectory. Several flight test programs have addressed this problem and demonstrated the feasibility of controlling arrival time using on-board flightpath management systems.[5,6] In principle, optimum trajectories could also be calculated on the ground and then uplinked, but data links for sending complex trajectories to aircraft are not currently available in civil aviation. The alternative pursued in this paper is to compromise somewhat on optimality by defining trajectories that can be specified succinctly and flown manually using conventional instrumentation. This compromise resulted in the choice of constant Mach/constant calibrated airspeed (CAS) and idle thrust altitude profiles for the descent trajectories. Such trajectories achieve fuel efficiencies that lie within about 1% of the optimum.

The algorithm described here resides in a microprocessor-based workstation that is interfaced with and receives aircraft surveillance data from the National Airspace System Host Computer. As an unequipped aircraft enters the terminal area, the algorithm calculates the trajectory to meet a specified arrival time. Commands to fly the trajectory are presented to the controller in the form of a descent advisory which the controller issues to the pilot as a clearance. The calculations take into account aircraft type and weight, current atmospheric conditions, and airline operating procedures. Unlike the simple "rules of thumb" pilots currently use in flying descents, the algorithm uses detailed aircraft performance and wind information to determine the position for initiating an idle descent.

A piloted simulation was conducted on a 727 simulator to determine the precision with which airline pilots could fly advisor-assisted descents. In addition, the effect of errors in the estimation of wind

*A modified version of this paper was presented at the August 1987 AIAA Guidance, Navigation, and Control Conference (AIAA Paper 87-2522).

and aircraft weight were also studied. This paper presents a description of the 4D descent advisor algorithm as well as the results of the simulation studies.

ALGORITHM DESCRIPTION

The descent advisor algorithm synthesizes a 4D trajectory in the following way. First, it calculates a nominal descent trajectory based upon the aircraft's current speed. After comparing the nominal arrival time to the desired time, the algorithm then iterates on descent speed until it computes a 4D trajectory which meets the desired time. For each iteration step, a corresponding trajectory is calculated by integrating the aircraft's equations of motion backwards from the time control point to the aircraft's initial position. Finally, the algorithm translates the desired trajectory into an advisory consisting of a top-of-descent point and a descent speed.

1. Descent Procedure

The trajectories generated by the descent advisor algorithm are based upon models of fuel conservative descent procedures currently used in airline operations. These procedures employ a near-idle thrust descent with a constant Mach/constant CAS profile. In general, a descent proceeds in the following way. First, the pilot reduces the throttle to idle and pitches down to maintain the cruise Mach number. When the aircraft has accelerated to the descent CAS, he then changes attitude to track CAS. As the aircraft nears 10,000 ft, the pilot reduces the descent rate to decelerate to 250 knots calibrated airspeed (KCAS), as per Federal Aviation Administration (FAA) regulations, and then continues on down to touchdown. However, some situations require thrust management procedures other than idle throttle. For example, inclement weather may require a minimum thrust level for deicing or turbulence penetration. In addition, some of the older pressurization systems require a minimum thrust level for smooth operation.

2. Equations of Motion

For each speed profile selected in the iteration process, the corresponding descent trajectory is computed by integrating a set of point mass equations of motion. In deriving these equations, no limiting assumptions were made with regard to pilot procedures, aircraft performance, or atmospheric parameters. As a result, the algorithm requires detailed information to model: thrust management; aircraft lift, drag, and thrust performance; and the altitude dependence of winds and temperature. Although this method is computationally intensive, it is highly flexible and is more accurate than schemes which depend on analytical approximations or precomputed trajectories. An additional benefit of this method is the potential to incorporate the preferred operational procedures of individual airlines into the trajectory calculations.

The trajectory equations are derived with respect to an earth-fixed reference frame. It is assumed that the aircraft is flying along a known ground track, thereby simplifying the trajectory to an altitude profile along this track. The descent advisor algorithm incorporates the general case of a curvilinear ground track in the trajectory synthesis process. However, for the purposes of this paper, the ground track is assumed to be a straight line. Defining the variables s and h as distance along the flightpath and altitude, respectively, the equations of motion to be integrated are

$$u \equiv \frac{ds}{dt} = V_T \cos(\gamma_a) + U_{ws} \tag{1}$$

$$w \equiv \frac{dh}{dt} = V_T \sin(\gamma_a) \tag{2}$$

where u and w are defined as the components of inertial velocity in the direction of s and h, respectively, V_T is the true airspeed, γ_a is the aerodynamic flightpath angle, and U_{ws} is the effective wind speed in the flightpath direction. With the wind known as a function of s and h, Eqs. (1) and (2) may be solved once expressions for V_T and γ_a as functions of time are found.

During the constant Mach/CAS segments of the descent, straightforward algebraic expressions for V_T and γ_a may be found. For the constant Mach case, the definition of Mach leads directly to

$$V_T = Ma(h) \tag{3}$$

where a is the speed of sound as a function of altitude and M is Mach number. Making use of the small angle approximation, the corresponding expression for γ_a is

$$\gamma_{a_M} = \left(\frac{T - D}{m}\right)\left[V_T \frac{da}{dh} M + g + \frac{dU_{ws}}{dh} V_T\right]^{-1} \tag{4}$$

where T is thrust, D is drag, and g is the acceleration of gravity. For the case of constant CAS, a lengthy expression for V_T can be expressed in the form

$$V_T = V_T(V_{CAS}, h) \tag{5}$$

The corresponding expression for γ_a, analogous to Eq. (4), is

$$\gamma_{a_{CAS}} = \left(\frac{T - D}{m}\right)\left[V_T \frac{dV_T}{dh} + g - \frac{dU_{ws}}{dh} V_T\right]^{-1} \tag{6}$$

For the case of neither Mach nor CAS constant (i.e., acceleration at the top or bottom of descent), V_T must be found by integrating the expression for its time derivative

$$\frac{dV_T}{dt} = \left(\frac{T - D}{m}\right) - g \sin(\gamma_a) - \left(\frac{dU_{ws}}{dt}\right)\cos(\gamma_a) \tag{7}$$

while taking into account

$$mV_T\left(\frac{d\gamma_a}{dt}\right) = L - mg \cos(\gamma_a) \approx 0 \tag{8}$$

where L is lift. Equations (7) and (8) are coupled by the dependence of drag on lift. The approximation of lift equal to weight in Eq. (8) is based on the assumption that the acceleration normal to the flightpath is negligible for normal descent operations.

The evaluation of the T, D, and U_{ws} terms in Eqs. (4), (6), and (7) will be discussed in the following section. The algorithm adopted to integrate Eqs. (1), (2), and (7) is a fourth-order Runge-Kutta scheme, the details of which are discussed in Ref. 2.

3. Descent Advisor Implementation

The descent advisor algorithm has been implemented on a SUN 3 workstation using FORTRAN 77. The information required for the trajectory computations is input both interactively and in file form. For each run, the user is prompted for the aircraft's initial cruise condition (position, altitude, velocity, and weight) and the desired time of arrival. Eventually, the descent advisor will access the cruise state information directly from radar and flight plan data stored in the ATC host computer. In the meantime however, the ability to interactively input the aircraft's initial condition is valuable for research purposes. The information stored in file form includes the aircraft performance models, the thrust management model, the atmospheric data, and the arrival route waypoint structure.

Presently, the descent advisor algorithm models only one aircraft type, a Boeing 727-200. However, the software is structured to accommodate any number of different aircraft types. The performance model, which includes detailed propulsive and aerodynamic information, is used to evaluate the thrust and drag terms just discussed. The propulsive model represents thrust as a function of engine pressure ratio (EPR), Mach, temperature, and pressure. The thrust management model, which will be discussed shortly, defines either the EPR or thrust value required during the descent for a particular thrust management procedure. The Mach number is determined by the speed profile along with temperature, and the temperature and pressure are determined from the atmospheric data. The aerodynamic model represents the drag coefficient as a function of lift coefficient, Mach number, and control surface deflection (speed brake, flaps, and gear). Here, the lift coefficient is determined by employing the approximation that lift is equal to weight. The control surface deflection schedule is based upon speed and position. However, for the purposes of this paper, the aircraft is assumed to be in a clean configuration.

With regard to the modeling of thrust management during a descent, three cases have been identified. The first case is that of a constant thrust setting. The second and third cases involve the variation of thrust to maintain a constant rate of descent and constant inertial flightpath angle, respectively. The actual implementation of the algorithm allows for the assignment of any one of these cases to each distinct segment in a descent (e.g., constant Mach, constant CAS, and so on) along with the corresponding descent rate or flightpath angle for the latter cases. Although a pilot would not actually fly a constant inertial flightpath angle, the combination of the three cases allows for the greatest flexibility in modeling automatic and manual descent procedures.

The atmospheric conditions are modeled in terms of altitude profiles of wind vectors and temperature data. This structure was adopted to take advantage of the Wind Profiler, developed by the Wave Propagation Lab (National Oceanographic and Atmospheric Administration), which reports wind vectors and temperature as a function of altitude on an hourly basis. The accuracy of this system's wind measurement is reported to be within two knots.[7] Several profiler units have been installed in the Denver area for the purpose of evaluation. For this reason, the Denver Air Route Traffic Control Center is most likely to be the first site for an operational evaluation of the Descent Advisor.

Finally, the arrival route waypoint structure defines the desired aircraft ground track for each arrival route as a set of discrete positions defined in longitude and latitude. Any number of routes may be modeled at one time allowing the controller to select the desired route for each arrival aircraft.

For each aircraft handled, the descent advisor stores data detailing the synthesized 4D trajectory for later comparison with the aircraft's actual trajectory. This information is used to track time error (defined as the difference between the actual and desired schedules) which may grow during the descent. An examplé of a synthesized trajectory is given in Ref. 2.

WEIGHT SENSITIVITY

Initially, there was concern about the effect of errors in the estimation of aircraft parameters, especially aircraft weight. Therefore, a study was conducted to determine the sensitivity of an advisor-assisted descent trajectory to an error in the estimation of weight. This section briefly details an analytic investigation of the sensitivity.

It is easily shown that, for a fixed descent speed profile, the time to descend is a function of γ_a. Therefore, the sensitivity, S, of a descent trajectory to a variation in aircraft weight, W, can be defined in the following way:

$$S \equiv \frac{d\gamma_a}{dW} \tag{9}$$

Neglecting the thrust (for an idle descent) in comparison to the drag, it follows from Eq. (6) that

$$\gamma_a \propto \left(\frac{-D}{m}\right) \tag{10}$$

Ignoring compressibility effects, the drag coefficient, C_D, is closely approximated by a second-order polynomial function of the lift coefficient, C_L

$$C_D = aC_L^2 + b \tag{11}$$

where a and b are constants. Equations (9), (10), and (11) may be combined to yield

$$S \propto \frac{d(-C_D/C_L)}{dC_L} = \frac{b}{C_L^2} - a \tag{12}$$

where it is assumed, as in Eq. (8), that lift is equal to weight.

Equation (12) indicates that the sensitivity of γ_a to variations in weight depends inversely on C_L^2 and is zero when the aircraft is operating at maximum L/D. For a given nominal aircraft weight, the sensitivity is a function of descent speed. What remains to be determined is the range of speeds for which a variation in γ_a, caused by a variation in weight, is negligible (i.e., less than 1%). For a 727 aircraft, nominally weighing 140,000 lb, this range was determined by fast-time simulation to be between 250 and 280 KCAS.

It is also of interest to determine the actual variation in time, and therefore γ_a, that is due to a variation in weight for the most sensitive case (i.e., fastest speed profile or smallest C_L). This case was also studied by simulation, the results of which are discussed in the simulation results section.

SIMULATION DESCRIPTION

The ground-based 4D descent advisor was evaluated in a piloted simulation, of a 727-200 aircraft, conducted at the Ames Research Center's Man Vehicle System Research Facility. The simulator, which is FAA certified phase II, has a six-degree-of-freedom motion system and a night-dusk computer-generated-imagery visual system.

A total of 12 pilots were used as test subjects, all of whom were current 727 captains from major U.S. airlines. Before each descent run, the pilot was briefed on current wind and weather conditions. Two wind conditions were tested: a direct tailwind of 70 knots at 35,000 ft linearly decreasing to 0 knots at sea level and a direct headwind of 70 knots at 35,000 ft linearly decreasing to 0 knots at sea level. These two relatively extreme wind conditions were chosen to expose pilots to a fairly difficult flying task, that of minimizing powered flight at lower altitudes, if performed without an advisory. The headwind case forced the trajectory algorithm to keep the aircraft at cruise altitude for a longer time than for a zero wind case, thus requiring a higher descent rate, while the tailwind case caused the aircraft to start down sooner. For each simulation run, the aircraft's initial conditions were: DME range to San Francisco International Airport of 150 n. mi., 35,000 ft altitude, a cruise Mach of 0.8, and heading set for a straight-in approach to runway 28R at San Francisco.

To compare the performance of the 4D descent advisor algorithm with a baseline of current descent procedures, the pilot was initially asked to fly a descent using his airline's standard operating procedure. It turned out that all of the pilots flew a Mach 0.8/280 KCAS descent speed profile. After the baseline descent was completed, the pilot was briefed on the procedures to be used in flying advisor-assisted descents. Following the briefing, the pilot flew several descents, with the aid of advisories, at speeds spanning the envelope of the aircraft. The descent speeds flown included slow (230 KCAS), nominal (0.8/320), and fast (0.84/350) profiles.

The advisor-assisted descent procedures required that all decelerations be performed in level flight and that all accelerations be performed using cruise thrust (for the case of a descent Mach number greater than the cruise Mach number). In addition, a restriction was imposed on each pilot to limit his descent rate to 3,000 ft per minute (fpm). This was done to study the pilot's ability to follow such a trajectory restriction. The advisory for each descent, generated off-line by the computer algorithm just described, was issued only once at a position approximately 5 n. mi. prior to the top-of-descent. A typical advisory was as follows, "Begin descent procedure at 108 DME; fly a Mach 0.8/320 KCAS speed profile."

RESULTS

A total of 55 descents were flown, 43 of which were advisor assisted. Errors in arrival time, defined as the difference between the actual arrival time and the scheduled arrival time at the time control point (30 n. mi. from touchdown at 10,000 ft) were the major criteria used to evaluate the effectiveness of the 4D descent advisor. Aircraft trajectory data, including altitude, position, time, CAS, Mach number, vertical speed, EPR, and total thrust, were recorded for each descent. Finally, extensive discussions with the subject pilots were conducted in debriefing sessions following the simulation.

1. Arrival Time Accuracy

Figure 1 is a histogram of arrival time errors at the time control point for the 43 advisor-assisted descents flown under both wind conditions. This plot shows that the majority of aircraft arrived within ±10 sec of their scheduled time. The one-sigma standard deviation was ±13 sec around the mean value of +6.1 sec. This bias of 6.1 sec is considered small and does not degrade the effectiveness of the algorithm.

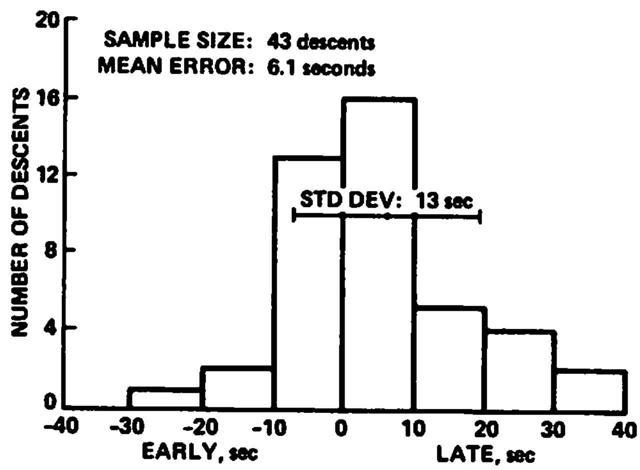

Fig. 1 Histogram of arrival time errors.

Table 1 lists the total variability in arrival time at the time control point, and Table 2 lists the one-sigma standard deviation in arrival time for all 55 descents (baseline and advisor assisted) for both wind conditions.

TABLE 1 TOTAL VARIABILITY OF ARRIVAL TIME IN SECONDS

	Baseline	Advisor assisted			
		Nominal	Slow	Fast	Fast-idle
Tailwind	195	42	12	21	
Headwind	88	24	13	55	22

Figures 2-6 are composite plots of altitude versus range for the baseline and advisor-assisted descents for the headwind case. These figures illustrate the trends which cause the time variability listed in Tables 1 and 2.

For the baseline descents, there were significant differences in arrival time at the time control point (88 and 195 sec for the headwind and tailwind conditions, respectively). The reason for this, a wide variation in the top-of-descent point, is illustrated in Fig. 2. Although each of the pilots used the glide ratio rule of thumb of 3 n. mi./1,000 ft, the correction they used for wind varied from pilot to

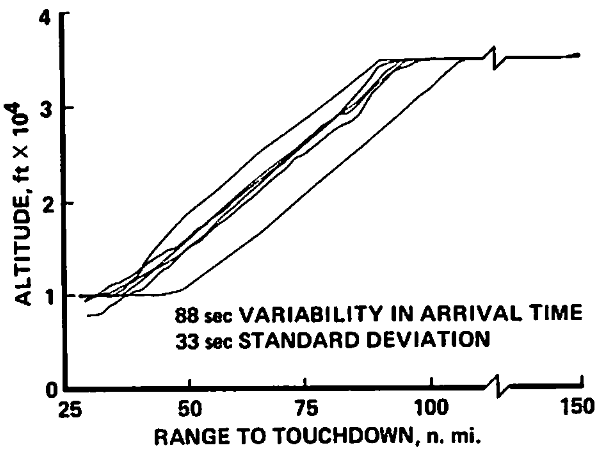

Fig. 2 Baseline descents.

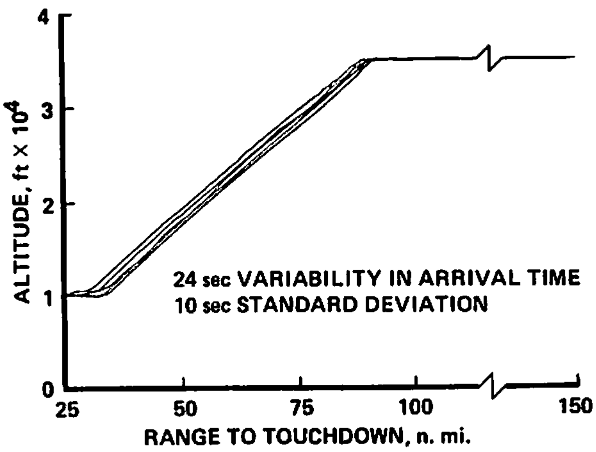

Fig. 3 Advisor assisted descents: nominal (0.80/320).

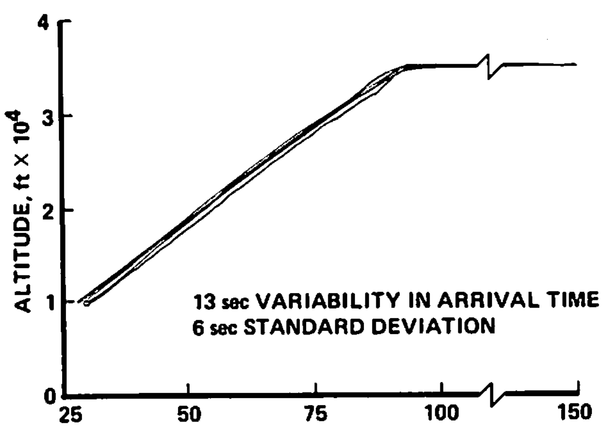

Fig. 4 Advisor assisted descents: slow (230).

pilot. The advisor-assisted descent using the nominal speed profile (0.8/320), the profile most similar to the baseline profile, resulted in a dramatic decrease in the arrival time variability. This is due to the consistent top-of-descent point used in the advisor assisted runs (Fig. 3). The slow profile (230 KCAS), which represents the low-speed boundary of the 727, yielded the lowest variability in arrival time. This profile (Fig. 4) was the simplest for the pilot to fly because he only tracked a single speed (CAS) throughout the entire descent; i.e., there was no constant Mach segment. Although there were good results for the fast (0.84/350) profile with the tailwind, the fast profile with the headwind presented problems for the pilots. The large variability for the headwind case (55 sec), which contrasts strongly with that for the tailwind case (21 sec), is due to the extremely difficult task of limiting the descent rate for this set of conditions. The maximum idle-thrust descent rate for the fast profile is approximately 6,000 fpm for the headwind case as opposed to 3,000 fpm for the tailwind case. The difficulty of

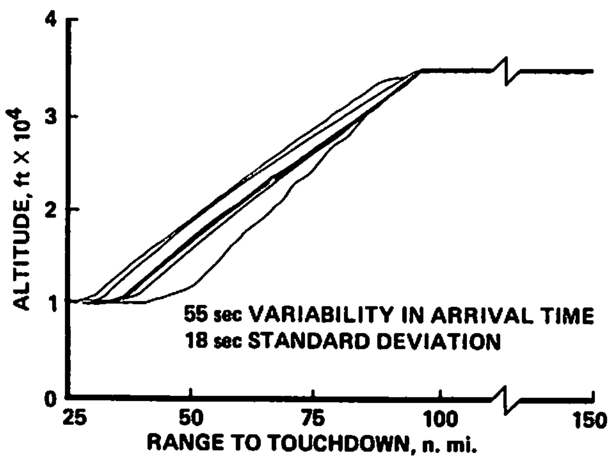

Fig. 5 Advisor assisted descents: fast (0.84/350).

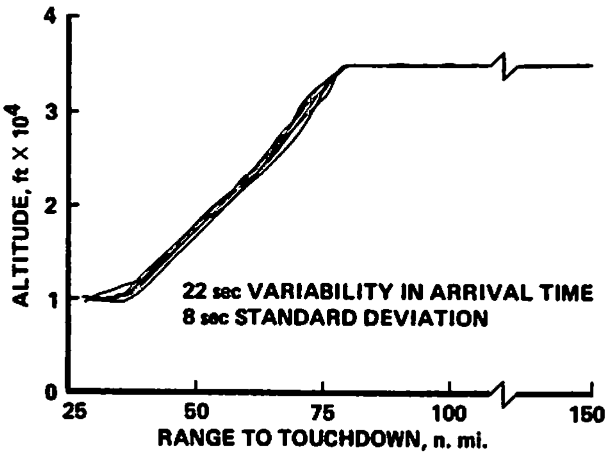

Fig. 6 Advisor assisted descents: fast-idle (0.84/350).

TABLE 2 ONE-SIGMA STANDARD DEVIATION OF ARRIVAL TIME IN SECONDS

	Baseline	Advisor assisted			
		Nominal	Slow	Fast	Fast-idle
Tailwind	±64	±16	±4	±10	
Headwind	±33	±10	±6	±18	±8

the descent rate limit task is due to two factors. First, the large difference between the idle thrust descent rate and the descent rate limit varies as a function of altitude. This forces the pilot to continually vary thrust to meet the limit. Second, there is a significant time lag in the vertical speed indicator and the thrust response of the aircraft is slow. As a result, there is a large variation in the altitude versus range profiles from pilot to pilot (Fig. 5). For the purposes of comparison, additional fast profile descents (with headwind) were flown without the descent rate limit (i.e., idle thrust). Figure 6 illustrates the relatively small variability in the altitude versus range trajectories for this case. These runs resulted in a 22-sec variability in arrival time which is very close to the result for the tailwind case.

The effect of the descent rate limit on time variability (as a function of speed profile) is best illustrated in Fig. 7. This figure plots the one-sigma standard deviation time versus range to touchdown for the advisor-assisted descents flown with the headwind condition. For the slow descent (230 KCAS), there is little variation in time over the trajectory because the aircraft never approaches the descent rate limit thus enabling the pilots to fly consistent trajectories. The same is partially true for the nominal profile (0.8/320) in that the idle-thrust rate of descent exceeds the limit only during the constant Mach segment of the descent. However, for the fast profile (0.84/350), the time variation is large because the idle thrust descent rate exceeds the 3,000-fpm limit over the entire trajectory.

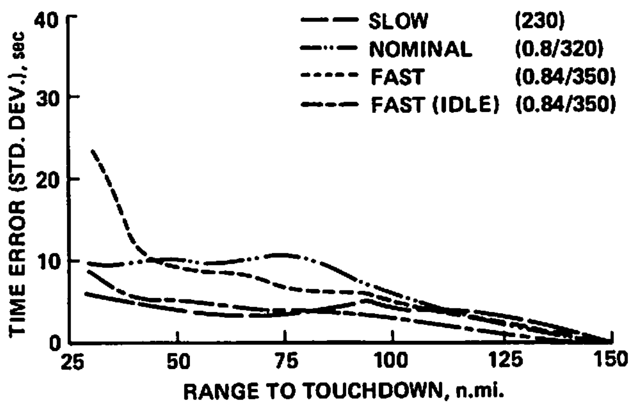

Fig. 7 Effect of descent rate limit on time variability.

A comparison of the plots for the nominal and fast profiles in Fig. 7 reveals an interesting phenomenon. Toward the end of the fast descent, within 45 n. mi. to touchdown, there is a noticeable increase in time variability. This is due entirely to the large variation in the flightpath angle, from one run to another, seen in Fig. 5. These variations in flightpath angle result in a wide range of positions at which the aircraft arrives at 10,000 ft (approximately 15 n. mi.). The large increase in time variability occurs inside 45 n. mi. because some aircraft are decelerating to 250 KCAS in level flight while others are still descending at 350 KCAS. Figure 7 also shows that when the descent rate limit is removed (fast-idle case), the time variability is dramatically improved. This improvement translates into a 56% reduction in the one-sigma standard deviation of arrival time. Therefore, to minimize errors in a descent advisory system, the procedures employed must avoid the necessity for large variations in thrust.

2. Effect of Wind Estimation Errors

Also studied was the effect of an error in the estimate of winds aloft on the time accuracy of an advisor-assisted descent. Five additional piloted descents were flown with descent advisories based upon an incorrect estimate of the wind. The initial conditions for this test were the same as just described. The descent advisory for each descent was Mach 0.8/320 KCAS with the top of descent based upon an estimated wind aloft of 70 knots at altitude linearly decreasing to 0 knots at sea level in the tailwind direction. However, the actual wind aloft programmed into the simulator was 90 knots at altitude linearly decreasing to 10 knots at sea level in the tailwind direction.

Figure 8 presents the time and altitude trajectories for the five piloted descents. The scheduled trajectory, synthesized by the descent advisor for the estimated wind condition, is superimposed on these figures. A 10- to 40-sec difference in descent duration exists between the piloted descents under the actual wind condition and the synthesized trajectory for the estimated wind condition. Although there were not enough runs performed for a reliable statistical analysis, two important trends may be observed. First, the variability in arrival time at 30 n. mi. for the piloted descents (30 sec) is within that found for the pilot performance studies just discussed. More importantly, the arrival time error (the difference between the actual and scheduled arrival times) exceeds the desired time accuracy of ±20 sec. These results tend to indicate the need for a "mid-descent" correction procedure which would allow a controller to correct a descent trajectory for any significant errors that may develop. However, it is important to note that the error in wind estimate studied is large compared to the ±2-knot accuracy of the Wind Profiler.

3. Effect of Weight Estimation Errors

The descent advisor algorithm was used to simulate the 4D trajectories resulting from a variation in aircraft weight. The initial conditions were the same as for the piloted simulation just described, except that the wind was set to zero. The trajectories were simulated to the time control point, for a variety of descent speeds spanning the aircraft's speed envelope. The baseline run incorporated a descent profile (at idle thrust) which would deliver a 140,000-lb aircraft to the final position at 10,000-ft altitude and decelerated to 250 KCAS. The same descent profile was also simulated for aircraft weights 10,000 lb above and below the baseline weight. This difference in weight represents a 10% error in the estimation of the aircraft's actual useful load (fuel plus payload) for a typical medium range flight. A survey of airline pilots showed that their airlines' estimates of enroute weight are accurate to within at least 5%.

The results of the fast-time simulation confirmed the earlier analysis that the sensitivity of flightpath angle to variations in weight is highly dependent on descent speed. For the descent speeds between 250 and 280 KCAS, there was no appreciable difference in flightpath angle for the various weights tested. However, for greater speeds, there were distinct differences in flightpath angle for the various weights. Figure 9 illustrates the variation in the altitude-versus-range trajectory for the worst case (highest descent speed profile, Mach 0.84/350 KCAS). The lighter aircraft arrived 12 sec later than the baseline while the heavier aircraft arrived 9 sec early. Although the lighter aircraft was able to meet

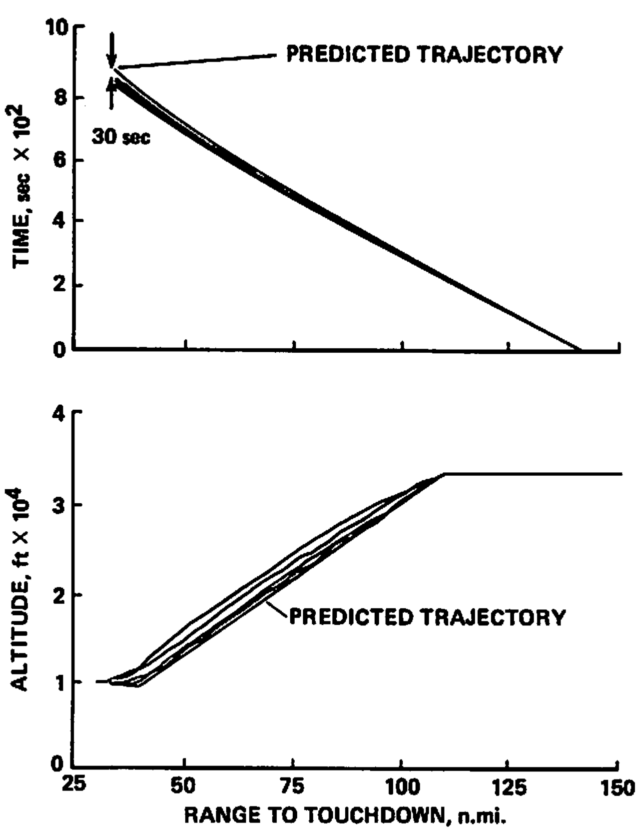

Fig. 8 Effect of errors in wind estimation.

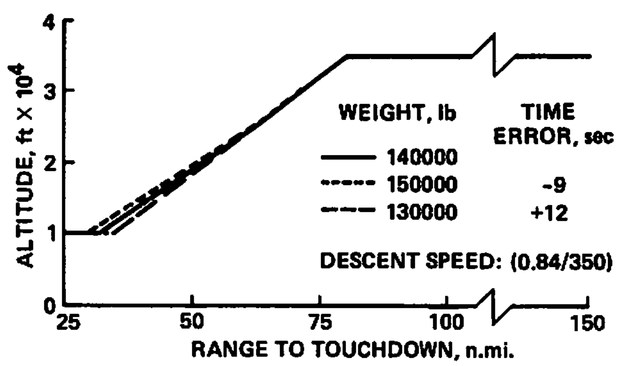

Fig. 9 Effect of errors in weight estimation.

the desired final condition of 250 KCAS at the time control point, the heavier aircraft was still decelerating through 280 KCAS at this point. This difference in final condition translates directly into an additional time error of 2 sec. It is interesting to note that nearly all of the time error, for both the lighter and heavier aircraft, occurs after the level-off at 10,000 ft. The difference in γ_a, between the baseline and off-weight cases, has little effect on the true airspeed profile for a given descent Mach/CAS. Once the aircraft reach the level-off altitude though, the variation in γ_a translates directly into a stretched or shortened level flight segment to the 30 n. mi. point.

4. Pilot Debriefing

Pilots were pleased that the procedures used in flying the descents were the same as they are currently using to fly unassisted descents. They felt that most line pilots would not resist following descent advisories issued by a controller if the advisories would lessen the chance of delays. All of the pilots were supportive of the descent advisor concept as a method for saving fuel and reducing delays.

CONCLUDING REMARKS

A ground-based 4D descent advisor algorithm has been developed and tested in a piloted simulation. The algorithm has significant potential for accurately controlling arrival times of aircraft not equipped with on-board 4D flightpath management systems. An accuracy at the time control point of ±20 sec, which is necessary for a time-based ATC system to be effective, appears attainable with the descent advisor. It was determined that to minimize time error, the descent procedures employed must avoid the necessity for large variations in thrust over the descent. It was also found that errors in the estimation of weight do not have a significant effect on the algorithm's performance. However, wind errors of 20 knots or more do have a significant effect and will require a mid-descent correction procedure if encountered. Subject pilots who participated in the simulation were able to fly the advisor-assisted descents without prior training and were enthusiastic about the potential use of the descent advisor. Current plans call for a more extensive evaluation of the algorithm to study its performance in handling descents with turns. In addition, a series of ATC simulations will be performed (in conjunction with piloted simulations) to evaluate the descent advisor's effectiveness as a controller tool. If these tests are successful, the FAA and NASA plan to conduct an operational evaluation of the descent advisor at an enroute traffic control center.

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