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Mixing Four-Dimensional Equipped and Unequipped Aircraft in the Terminal Area

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The problem of mixing four-dimensional (4-D) equipped aircraft (aircraft equipped with onboard guidance systems that can predict and control the touchdown time of an aircraft to an accuracy of a few seconds throughout the descent) with unequipped aircraft in the terminal area has been investigated via a real-time air traffic control simulation study. The objective of this study was to develop scheduling algorithms and operational procedures for various traffic mixes that ranged from 25 to 75% 4-D equipped aircraft. Results indicate substantial reduction in controller workload and an increase in orderliness when more than 25% of the aircraft are 4-D equipped. Moreover, this is accomplished without increasing the workload or adding delays for the unequipped aircraft.

Introduction

ONBOARD guidance systems that can predict and control the touchdown time of an aircraft to an accuracy of a few seconds throughout the descent have been proposed as an element of a future air traffic control (ATC) system.[1,2] The feasibility and performance of such systems, also known as four-dimensional (4-D) guidance systems, has been demonstrated in several flight test programs in recent years.[3,4]

A crucial problem in the application of 4-D guidance is the development of ATC procedures which can exploit the onboard time-control capability. The use of a time-based scheduling system in the terminal area when all aircraft are 4-D equipped was investigated in an earlier real-time simulation study.[5] That study demonstrated that if all aircraft in the system are 4-D equipped, then operational procedures and scheduling techniques could be developed which would reduce delays and increase capacity for the time-based system compared with a standard vectoring mode.

However, in planning for a future system in which all aircraft might be 4-D equipped, it is necessary to confront the transition situation in which some percentage of traffic must still be handled by conventional means. The basic difficulty is that the 4-D concept involves a separation of aircraft by time, whereas in the conventional vectoring mode, the controllers provide distance-separation. Developing techniques to handle both types of aircraft effectively is a complicated task. A simple, though inefficient, way to handle both types of scheduling techniques is as follows: 1) to time-schedule the 4-D equipped aircraft using methods developed earlier; and 2) for each vectored aircraft, assign a very large time slot (e.g., 10 min) so that a controller can deliver the aircraft to the scheduling point within the allotted slot. The difficulty with this method is that these large time slots can reduce capacity so that operating in the mixed mode is less efficient than operating in a pure vector mode; thus, a limiting factor in the development of the mixed mode is that it must not result in decreased capacity for the total system.

Another constraint is that the advantages achieved by the 4-D equipped aircraft must not be achieved at the expense of the vectored aircraft; that is, vectored aircraft still must be given a reasonable number of vectors, and they must not be more delayed than would be the case when all aircraft are being vectored.

Hence, the objective of this study was to develop efficient algorithms and operational procedures for time-scheduling a mix of 4-D equipped and unequipped aircraft in the terminal area. To accomplish this, a real-time ATC simulation study was conducted. First, as background, the onboard 4-D system will be described, and the problems associated with time-scheduling a mix of 4-D equipped and unequipped aircraft will be discussed. This will be followed by a description of the simulation facility, scenario, and test conditions. Results of the simulation study will then be given.

Onboard 4-D System

Overview

The capabilities and critical algorithms of the time-controlled (4-D) guidance system simulated in this study are summarized here. A complete 4-D guidance system is a complex entity involving interaction between numerous guidance, control, and navigation subsystems in an aircraft. The integrated collection of these subsystems augmented with special algorithms to provide fuel efficient time-control, essentially constitutes the 4-D flight-management system of an equipped aircraft.

For a number of years NASA has designed and flight-tested research systems incorporating various types of time-control methods for both STOL and conventional aircraft. These tests have demonstrated the ability to predict and control arrival time accurately under varied operational conditions, achieving arrival time accuracies of ± 10 (Refs. 3 and 4).

The system simulated in this study comprises algorithms and techniques previously flight tested[6] as well as new techniques developed specifically for this study. The discussion here centers primarily on those techniques unique to this study.

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The onboard calculation of a 4-D trajectory is carried out at the time the aircraft departs the feeder fix, located at approximately 120 n.mi. from touchdown, and at a cruise altitude of about 33,000 ft. Calculation is initiated when the simulated onboard system receives specification of touchdown time and approach route. If the flight/performance envelope of the aircraft permits it, the system will generate in fast time a time-controlled approach trajectory, starting at the current location of the aircraft and terminating at touchdown. Inability to meet the specified time causes the system to display an error message at the controller and/or pseudopilot stations.

The successfully synthesized trajectory comprises a vector function of time whose components are reference values of x and y positions, altitude, heading, and airspeed. Immediately after the trajectory has been synthesized in fast time, it is regenerated in real time, to provide continuous updated reference states. The simulated aircraft tracks the reference states by means of a closed-loop autopilot guidance law, thereby causing it to complete the approach trajectory at the assigned time.

The problem of synthesizing such trajectories is divided into three subproblems solved sequentially. First, the horizontal profile is constructed as a sequence of turns and straight lines passing through the set of waypoints that define the approach route.[7] Second, the vertical profile is synthesized as a sequence of level-flight and constant-descent-angle segments passing through specified altitude waypoints located on the horizontal profile. An alternative to the constant-descent-angle profiles are idle thrust descents, which can be more nearly fuel optimum. However, pilot preference is somewhat divided between these two strategies. Finally, the airspeed profile is synthesized to achieve the specified arrival time. Since the speed profile algorithm was developed specifically for this study, it is discussed in greater detail in the following section.

Speed Profile Synthesis

Three types of airspeed profiles typical of those used in the simulation are illustrated in Fig. 1. All three profiles start at waypoint 5 (WP5) at an altitude of 33,000 ft and at a true airspeed (TAS) of 460 knots, or 280 knots calibrated airspeed (CAS). Constant Mach segments are not shown in these example profiles. The profile labeled nominal starts with a brief segment of deceleration to a CAS or Mach number, computed by the speed selection algorithm. The computed CAS of 265 knots is held constant during the remainder of cruise and the greater portion of descent until the 10,000-ft altitude is reached at WP4. A descent at constant CAS produces the gradual deceleration seen in Fig. 1. This type of nominal speed profile is fairly typical in airline operation because it can be flown by a pilot using standard cockpit instruments. At 10,000 ft (WP4) the nominal trajectory decelerates to a maximum CAS of 250 knots, in accordance with ATC rules. The 250 knots CAS is held to a point at about 20 n mi. from touchdown (WP3) where a deceleration to 180 knots occurs. At 5 n.mi. from touchdown (WP2) deceleration to final approach speed occurs with flaps extended to landing configuration. The maximum speed profile shown in the example initially exceeds the speed limit of 250 KCAS below 10,000 ft. The algorithm allows the speed to be exceeded with prior approval of the flow controller.

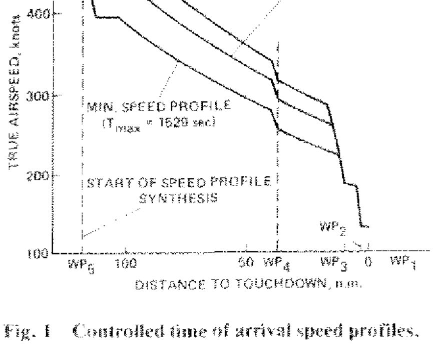


Fig. 1 Controlled time of arrival speed profiles.

The time to traverse the path and the points where speed changes begin and terminate are obtained by numerically integrating the following two equations along the known three-dimensional (3-D) profile.

$$\mathrm{d}V_a/\mathrm{d}t=(T-D)/W-g\sin\gamma \tag{1}$$

$$\mathrm{d}S/\mathrm{d}t=V_g \tag{2}$$

where V_a = true airspeed, T = total engine thrust, D = drag force, W = weight, g = acceleration of gravity, γ = flight-path angle, V_g = ground speed, and S = distance along flight-path. The integration computes the distance and time to fly the initial acceleration or deceleration segment and the constant CAS/Mach number descent in forward time. Starting at the touchdown point, it computes corresponding quantities for the deceleration segments at the end of the trajectory in backward time. The forward-backward integration scheme ensures that the initial and final speeds are achieved at specified speed waypoints along the horizontal profile. Furthermore, numerical integration of Eqs. (1) and (2) allows complete freedom in the choice of models for the thrust T, drag D, and the wind profile V_w. In the simulation thrust, drag and fuel flow models for a 727 class of aircraft were used. The wind profile can be given as a function of altitude and position along the horizontal path.

The value of thrust used in each integration step depends on the segment type. For acceleration the thrust is set to its maximum; for deceleration, it is set to idle. For constant CAS or constant Mach number segments in descent, the thrust computation is more involved; explicit relations for these cases are derived in Ref. 7. In general, the thrust will be close to the idle value for the 3 deg descent angle typically used here.

The algorithm for determining the speed profile starting at WP5 with specified time to fly begins with synthesis of three profiles flown at maximum, minimum, and nominal speeds, V_{max}, V_{min}, and V_{nom}, respectively (see Fig. 1). The nominal speed profile is one that the pilot would choose in the absence of any time constraints. By the backward-forward integration procedure described above, the corresponding times to fly, T_{min}, T_{max}, and T_{nom}, are obtained. Then a test is performed to determine if the specified time, T_d, falls within the range (T_{min}, T_{max}). If such is the case, a polynomial approximation

$$V=C_1/T+C_2/T^2+C_3/T^3 \tag{3}$$

of the exact but unknown relation between descent speed and time to fly is computed. A simple proportional formula also allows Eq. (3) to determine the speed between WP4 and WP3. The details of this procedure are given in Ref. 7. The coefficients C_1, C_2, and C_3 are obtained by substituting in Eq. (3) the three pairs of numbers (T_{min}, V_{max}), (T_{max}, V_{min}), and (T_{nom}, V_{nom}), and solving the resulting three simultaneous linear equations.

The desired time to fly, T_d, can now be substituted into Eq. (3) to obtain an estimate of the correct descent speed. Next, the actual time to fly corresponding to the estimated descent speed is calculated by the forward-backward synthesis method.

Experience with this algorithm has shown that for a 120-n.mi.-long trajectory with a nominal flight time of 1,300 s, the descent speed estimate obtained from Eq. (3) will achieve an actual arrival time within ±5 s of the desired time in most cases. This accuracy is adequate for terminal area time scheduling. Thus if the initial speed estimate using Eq. (3) gives insufficient time accuracy, one can iterate a second time by using the results of the first trial to update the polynomial coefficients.

The range of arrival time for the example in Fig. 1 is 220 s. If needed, a larger range can be obtained by route modifications, such as path stretching maneuvers.

Time Scheduling in the Mixed Environment

The 4-D equipped aircraft described in the previous section have the capability of meeting a touchdown-time assignment to an accuracy of a few seconds. It is now desired to use this capability to formulate efficient operational procedures for the time scheduling of all aircraft in the terminal area. This will be developed in two parts: 1) determination of the interarrival time separations for two consecutive aircraft to be used in aircraft scheduling; and 2) development of a scheduling algorithm for assigning landing times. They are generated by the ground computer automatically, but can be altered per controller requirements.

Time Separation Requirements

The present ATC system uses radar vectors and speed control to space aircraft so that the minimum separation distance rules are not violated. The minimum separation distance rules depend on aircraft-weight category, and are summarized in Table 1. For example, if a large aircraft lands first and is followed by a small aircraft, these aircraft are to be no closer than 4 n.mi. apart for the entire common path length.

These minimum separation distances can be converted to minimum separation times using speed profile data. Suppose that a large aircraft and a small aircraft use the same runway. The large aircraft is traveling at 180 knots, and at the outer marker (located 3.11 n.mi. from touchdown) begins its deceleration (at 2 ft/s^2) to a final speed of 135 knots. The final speed for the low speed aircraft is 110 knots, and the common path length is 5.09 n.mi. This information is summarized in Fig. 2. If the large aircraft lands first, the minimum distance separation occurs at the beginning of the common path. Using this information, the minimum separation time at touchdown can be computed to be 138 s. With this separation time, the minimum separation distance requirements will not be violated at any point along the common path. In this fashion, assuming the speed profile for the heavy aircraft is the same as that shown for the large aircraft, the minimum time separation matrix can be determined to be

$$T = (t_{ij}) = \begin{pmatrix} 98 & 74 & 74 \\ 138 & 74 & 74 \\ 167 & 114 & 94 \end{pmatrix} \tag{4}$$

where t_{ij} is the separation time at touchdown when a type "i" aircraft lands first, and is directly followed by a type "j" aircraft, and where types 1, 2, and 3 designate small, large, and heavy aircraft, respectively.

Table 1 Minimum separation distance

		Trailing A/C		
		Small	Large	Heavy
First to land	Small	3	3	3
	Large	4	3	3
	Heavy	6	5	4

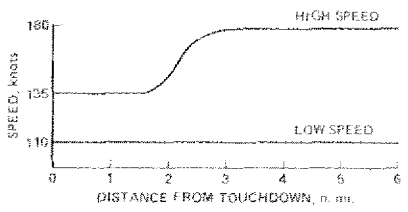


Fig. 2 Speed profiles.

It is assumed that, if two consecutive aircraft are 4-D equipped, the interarrival times given by T can be used for scheduling purposes. However, unequipped aircraft will need additional time buffers to prevent separation distance violations. If the probability density function of an unequipped aircraft meeting an assigned time via controller vectoring is known (this can be determined in the specific experimental context), then time buffers can be determined to keep the probability of separation distance violation below a desired level. The technique for obtaining these buffers is discussed in Ref. 8. For the purposes of this study, it was assumed that if one of the two consecutive aircraft was unequipped, a 10-s buffer was added to the separation time. If both aircraft are unequipped, a 20-s buffer is added.

Scheduling Algorithms

The previous discussion established the time separation matrix at touchdown shown as a function of weight category, and whether or not aircraft are 4-D equipped. It is assumed that the feeder fix time for each aircraft is known. Based on this time and on the desired time to traverse the route, a desired touchdown time for each aircraft can be determined. Using this first come, first served (FCFS) order and the time separation matrix, the time schedule at touchdown is obtained. It is possible to increase capacity by altering the FCFS order; thus, future studies will incorporate time-slot shifting algorithms to take advantage of bunching of speed classes. However, for purposes of this initial study of operational procedures, the FCFS order is adequate.

In addition to setting up an initial schedule, algorithms are required to revise the schedule. Missed approaches must be accommodated. Also, the controller may need to change the aircraft arrival rate. He also may be required to block out specific time periods from the computer schedule to accommodate a missed approach or a priority landing. In addition, he may require that a few aircraft be scheduled in a specified order.

This schedule manipulation will be illustrated using the halt problem as an example. Suppose that an initial schedule has been established for those aircraft that have departed the feeder fix (denoted active aircraft) and those which have not yet departed the feeder fix (denoted inactive aircraft). Controllers may need to halt the inactive aircraft for a time t_h. This may be necessary to accommodate a missed approach. A rescheduling algorithm is required which leaves the time assignments for the active aircraft unaltered, but which revises the touchdown times of inactive aircraft by at least t_h. This procedure can lead to a reordering of the schedule. Table 2 illustrates a typical revision. For illustrative purposes, aircraft are assumed to be scheduled 2 min apart. The effect of the missed approach is to leave active aircraft untouched and to revise the inactive aircraft schedule by 2-4 min.

Simulation Facility

The simulation was conducted using the NASA Ames ATC Simulation Facility. It includes two air traffic controller positions, each having its own color computer graphics

Table 2 Sample scheduling revision

Initial schedule (* = active A/C)		Event	Revised schedule (* = active A/C)	
Aircraft ID	Scheduled touchdown time (h:min)	A1 executes a missed approach.	Aircraft ID	Scheduled touchdown time (h:min)
A1*	9:06	Controller issues	B1*	9:08
B1*	9:08		C1*	9:10
C1*	9:10	halt for	D1*	9:12
D1*	9:12		A1*	9:14
E1	9:14	$T_h = 2$ min.	F1*	9:16
F1*	9:16		E1	9:18
G1	9:18		G1	9:20

display. In this study, one was designated arrival control, the other final control. In proximity to the color displays, there was a keyboard with which the ATC display related requests that were entered into the controller displays and the simulation computer. Such inputs included changing the position of an aircraft identification tag, transferring an aircraft between control sectors, or stopping and restarting the flow of traffic at the feeder fixes.

Each keyboard pilot station can control up to ten computer-generated aircraft simultaneously. The clearance vocabulary includes standard heading, speed, and altitude clearances as well as special clearances for 4-D equipped aircraft. In this study, three keyboard stations were used: one was responsible for all aircraft in the arrival sector, while the other two divided responsibility for aircraft in the final control sector. No piloted simulator was used. It is planned to include an airline quality simulator in future studies of the mixed environment.

Scenario and Test Conditions

The simulated terminal area is based on the John F. Kennedy (JFK) International Airport, New York. The route structure and runway configuration investigated are shown in Fig. 3. It is assumed that instrument flight rule (IFR) conditions prevail, and that all aircraft use runway 4R; furthermore, no departures, winds, or navigation errors are simulated. Two routes, Ellis, from the north, and Sates, from the south, are high-altitude routes flown by large or heavy jet transport type aircraft. Aircraft on these routes fly profile descent procedures, but may be either 4-D equipped or unequipped. Hence, there is a mix of 4-D equipped and unequipped aircraft of the same speed class along the same route. In addition, low-speed aircraft were considered which flew the Deerpark route from the east, but shared a 5 n.mi. common path length and used the same runway as the jet traffic. The Deerpark traffic was unequipped, and always constituted 25% of the traffic mix.

For the purposes of the study, an extended terminal area is considered. Aircraft enter the extended terminal area at the feeder fix departure points, and are at cruise. The total distance to be flown along each of the jet routes is about 120 n.mi. Two air traffic controller positions were established, an arrival control and a final control. The arrival controller handles arrivals from all three feeder fixes and transfers traffic to the final controller at approximately 20 n.mi. from touchdown.

Control procedures differ for equipped and unequipped aircraft. Controllers were instructed to monitor the progress of 4-D equipped aircraft after the time assignment has been established, and to override the ground computer scheduling system only if necessary for ATC purposes. Any 4-D aircraft could also be vectored and subsequently treated as unequipped. Alternatively, a vectored 4-D aircraft could be given a waypoint to capture a 4-D route and receive a revised runway time. Unequipped aircraft were considered to be navigating in the conventional manner via very-high-frequency omni-directional radar (VOR) procedures, with altitude clearances, radar vectors, and speed control.

To assist the controller in integrating the 4-D equipped and unequipped traffic, a flight data table (FDT) was provided on each controller display. A typical arrival control display is shown in Fig. 4. The map portion of the display provides a horizontal display of traffic in the terminal area. Each aircraft position is shown by a triangular symbol. The block of data next to each aircraft indicates the aircraft identification, status, altitude, and speed. The FDT in the upper left portion of the display provides schedule information for all aircraft in the approach control sector. At the top of the table, the time is shown in hours, minutes, and seconds. The first column shows the aircraft identification, such as "R1." The second column provides status (STA) which includes 1) weight category: small (S), large (blank), or heavy (H); and 2) 4-D status, equipped (4) or unequipped (U). The third column provides the assigned route (RT). Also shown is the scheduled touchdown time (ETA) at the runway in minutes and seconds. Thus, R1 will touch down at 13:37:00. Note that touch down times are shown for all aircraft, equipped or unequipped. This is the time the equipped aircraft has been assigned by ground control to touchdown. No time assignment is given to the unequipped aircraft; rather, the controller is to use this information and the positions of the 4-D equipped aircraft as they traverse their routes to generate appropriate vectors to the unequipped aircraft so that they touch down at the time indicated. The last column is the delay (DY), where the expected delay at touchdown is in seconds. For purposes of this initial study, it was assumed that all aircraft depart the feeder fix at their scheduled departure times. This assumes the existence of an advanced en route metering system. In the absence of such a system, large feeder fix departure errors may occur for unequipped aircraft. The issues of what magnitude departure errors can be tolerated as well as the means to provide ground computer assists to null departure errors will be the subject of a separate study. However, as the unequipped aircraft traverses its route in the terminal area, it will deviate from its scheduled touchdown time. It is this deviation that is shown in the "DY" column. Finally, aircraft below the dotted line are aircraft which will depart the feeder fix within the next 5 min (shown in the furthest right column), indicated by the feeder fix departure time in minutes and seconds.

The main test variable was the mix of traffic. Three mix cases were run: 25, 50, and 75% 4-D equipped. In addition, baseline data were obtained for the 0% 4-D equipped case, i.e., when all aircraft are vectored. For the case of 50% 4-D equipped, two formats were used for FDT information. The first is the standard display format discussed previously in the second condition, and no time information is displayed in the FDT for the unequipped aircraft. Unequipped aircraft were merely listed in departure order beneath the time ordered list of 4-D aircraft.

The aircraft arrival rate into the terminal area was assumed to be high enough so that a full schedule with no gaps is generated. The arrival rate for the baseline model was 30 aircraft/h and varied up to 34 aircraft/h for the 75% case. The lower "full schedule" arrival rate for the 0% 4-D case is due to the time separation buffers added for the unequipped aircraft.

No departure traffic was simulated, nor were winds or navigation errors considered. These will be included in future investigations. However, they are not expected to alter the general procedures discussed here significantly.

In addition to the main test cases, some special runs were conducted to get a minimum amount of data on other issues of interest. Due to the time constraints of real-time testing, these could not be considered as main variables. These issues included: 1) handling of traffic after a breakdown occurs in the 4-D scheduling computer; 2) rescheduling aircraft if a scheduled conflict occurs; 3) handling deviations from feeder fix departure times; and 4) operating at higher arrival rates for the vectoring mode.

Thirty data runs were made in November 1982, each 80 min long. Three research air traffic controller subjects from the FAA Technical Center participated in this study.

Controller Evaluations

Qualitative data were obtained from controller verbal evaluations recorded after each data run, and from controller written evaluations obtained after the completion of all data runs. Controllers were asked to compare operations under the traffic mix conditions. The 25% equipped case was rated the condition with the heaviest workload. The main difficulty seemed to be that the controllers were establishing distance spacing of the majority of the traffic. They felt that by not altering the flight path of the 4-D equipped aircraft, they were occasionally losing some slot time. They were, however, quite pleased with the 50% equipped case, which allowed for easy handling of the unequipped aircraft. One controller commented that it was the best ratio. He could "work without being overtaxed." The 75% 4-D equipped case was rated most orderly by all the controllers, but when so many aircraft were 4-D equipped (the only unequipped aircraft were the Deerpark arrivals which always constituted 25% of the traffic sample), there was "basically nothing to do." The human factors issues associated with a high level of ATC automation are major topics which cannot be dealt with here because of the limits in realism of the controller work stations. The interested reader is referred to the comprehensive paper by Hopkin.[9] Finally, the baseline case when 0% of the aircraft were 4-D equipped was regarded as reasonable, but not because of lightened workload. Rather, it was the most familiar mode.

Table 3 Average number of clearances

	Average number of clearances/aircraft			
% Equipped[a]	Heading	Speed	Altitude	Total
0	2.7	1.3	1.2	5.2
25	2.2	1.2	1.1	4.5
50	1.3	0.7	0.7	2.7
75	1.2	0.6	0.6	2.4

[a] Percent of aircraft equipped with 4-D capability.

Table 4 Deerpark route: clearances and time in the system

	Average number of clearances/aircraft				
% Equipped[a]	Heading	Speed	Altitude	Total	Average time in system, min:s
1	3.3	1.8	1.8	6.9	19:16
25	2.9	1.8	1.8	6.5	18:56
50	2.8	1.7	1.7	6.2	19:05
75	2.9	1.8	1.7	6.4	19:05

[a] Percent of aircraft equipped with 4-D capability.

The controllers were asked if there was any difficulty in handling the mix of speed cases, the slow traffic on Deerpark and the jet traffic on Ellis and Sates. They indicated that spacing behind the low-speed aircraft was sometimes a problem, since they had to allow for a large initial separation along the common path length. Also, one controller indicated that when handling a slow aircraft, he was reluctant to extend the downwind leg since this would result in a larger common path with the jet traffic. Hence, the airspace was somewhat confining for the slow traffic. No difficulties were indicted in spacing the high-speed equipped aircraft and high-speed unequipped aircraft along the same jet route.

The controllers were provided with time scheduling information in the FDT. The table was a time-ordered listing of traffic in each sector. Touchdown times and expected delays also were provided for each aircraft. The controllers indicated that the only information they used was the time-ordered listing from which the relative order of traffic in the downwind leg and the traffic from Sates were determined. By using this information, and not altering the 4-D equipped aircraft, the controllers were able to vector the unequipped aircraft to their assigned landing slots. However, the touchdown time and delay information were not used. Based on observations, standard vectoring techniques for the unequipped aircraft were adequate to fine-tune the spacing between aircraft. For the conditions of the experiment, there was not much need to alter initial schedules. If considerable interactive schedule manipulation is required, however, then it seems that a separate controller station for flow control and scheduling is needed. There is not sufficient time for the arrival and final controllers to monitor traffic visually and also to monitor numerical time scheduling information at the same time. The use of a flow control position is consistent with both the present- and near-term ATC systems which use flow controller positions for metering traffic.

Controller Workload

Controller workload will be measured by the clearances issued, and will be compared as a function of mix condition. Table 3 provides the average number of clearances/aircraft. The average number of heading, speed, and altitude clearances is shown, and the total number of these clearances is also provided. It can be seen that as more aircraft are 4-D equipped, the average number of clearances/aircraft decreases. This is fairly obvious in the experiment context described, since 4-D equipped aircraft were not vectored to as large an extent as possible. The concern is: does the average number of clearances for the *unequipped* increase as the percentage of equipped traffic increases? The answer to that question is provided in Table 4, which gives the average number of clearances/aircraft for the Deerpark route only. It should be recalled that the Deerpark traffic was always 25% of the traffic sample, and that all Deerpark traffic is unequipped aircraft. The table indicates that the average number of clearances given to the Deerpark unequipped aircraft is the same, independent of the mix condition. Also shown is the average time in the system (in minutes) for the Deerpark traffic, which also is seen to be independent of the mix condition. Similar results were obtained for Sates and Ellis unequipped traffic. Thus, the total workload reduction as the percentage of 4-D equipped aircraft increases (shown in Table 1) was not obtained by additional vectors and delays for the unequipped aircraft.

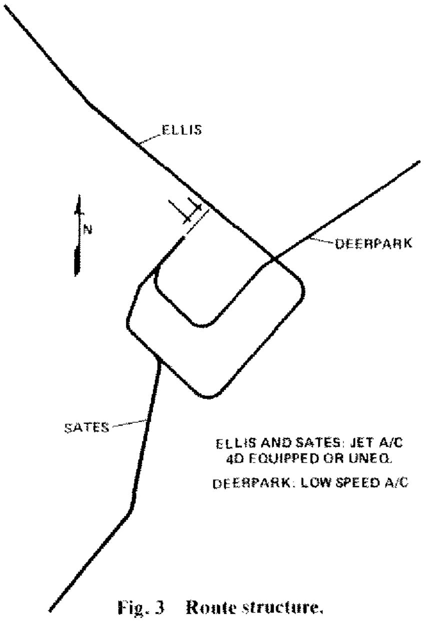


Fig. 3 Route structure.

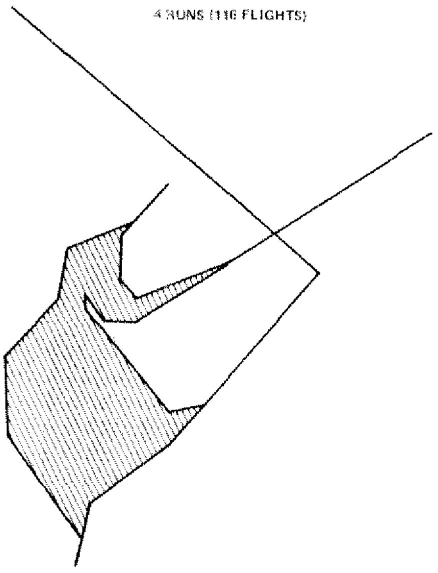
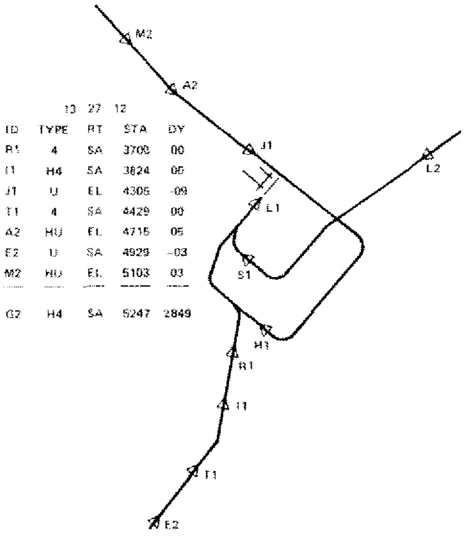


Fig. 5a Airspace used, 0% 4-D.



	13	27	12	
ID	TYPE	RT	STA	DY
R1	4	SA	3709	00
I1	H4	SA	3824	06
J1	U	EL	4306	-09
T1	4	SA	4429	00
A2	HU	EL	4715	05
E2	U	SA	4929	-03
M2	HU	EL	5103	03
G7	H4	SA	5247	2849

Fig. 4 Typical arrival control display.

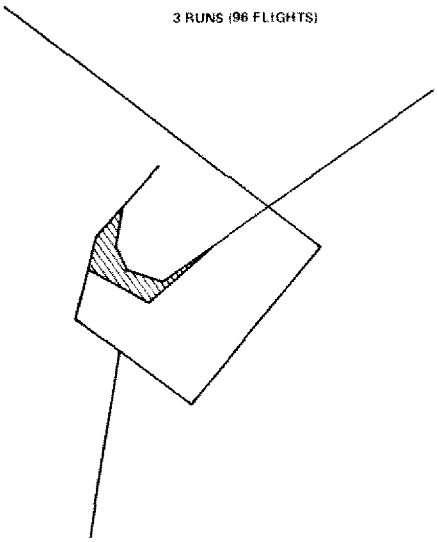


Fig. 5b Airspace used, 75% 4-D.

Airspace Used

A comparison was made of the airspace used in runs where all aircrafts are vectored, and runs in which 75% of the aircraft are 4-D equipped. Figure 5a is an envelope plot of all 116 flights flown in the four runs conducted in the baseline 0% 4-D equipped mode. For each aircraft, an x-y plot was drawn. The individual x-y plot shows the trajectory that the CTOL aircraft followed from feeder-fix entry until touchdown on the runway. Figure 5a is the envelope of these plots. Figure 5b is the corresponding plot for the 96 flights flown in the 75% 4-D equipped case. In the latter plot, the only region used for path stretching is the base leg of the Deerpark route. By contrast, the baseline mode requires a large region to perform vector operations. The 4-D operations permit the aircraft to fly more orderly, fuel-efficient routes, and to reduce the airspace required for each route considerably.

Special Case Runs

In addition to the main test case where the variable was the percentage of 4-D equipped aircraft, a minimum amount of data was taken (namely 1-2 runs each) for a variety of other test variables. These will now be briefly described.

Loss of 4-D

There was a desire to examine how traffic handling is disrupted if a breakdown of the 4-D scheduling computer should occur. To investigate this, the FDT was removed from the screen during a 75% 4-D equipped run so that the controllers no longer had a display of schedule times and order for aircraft in their sector. Furthermore, all feeder fix departures from then on had no 4-D time assignment, and would have to be vectored. The map display which showed aircraft positions was not removed. Initially, there was no change. The 4-D equipped aircraft already in the control sector could still be left alone, since they would continue to follow their previously assigned 4-D route. This is in contrast to a totally ground-based 4-D system where the ground system generates clearances for every aircraft. When that type of system fails, all aircraft are affected in a short time. The only difficulty experienced wih the system tested was that after the failure occurred, controllers continued to allow traffic to depart the feeder fixes at the higher arrival rate for the 75% equipped case, rather than adjust to the baseline vector arrival rate. If the flow-rate adjustment for new feeder-fix departures is made when the failure occurs, then it seems clear that the use of the onboard 4-D system provides a safe transition to the standard vector mode.

Uncoordinated Flow

In the main data runs, it was assumed that all aircraft depart the feeder fix without initial error. However, two special runs were conducted when the Deerpark traffic departed randomly. The Deerpark traffic still constituted 25% of the total traffic, but was not coordinated with the Sates and Ellis traffic flows. The mix condition was 50% 4-D equipped, which meant that some of the Ellis and Sates traffic was also unequipped. However, all Ellis and Sates traffic departed the feeder fix with no time errors, as before.

Time slots were allocated in the usual fashion for the equipped and for the Sates and Ellis unequipped. For the Deerpark traffic, time slots were allocated based on the Deerpark arrival flow rate; however, time slots did not correspond to the actual Deerpark departure times. Two display formats for the FDT were used; neither was the standard format. In the first case, no time or order information was available on the FDT for any unequipped aircraft. In the second case, the Ellis and Sates unequipped traffic was shown with time and order information, while the Deerpark traffic was listed only in departure order.

For the first format, the uncoordinated Deerpark flow resulted in heavy workload and reduced capacity. The addition of time and order information for Ellis and Sates in the second format improved both workload and capacity, but the mismatched flow was still a problem. It was felt that some kind of ground computer advisory at the time of departure from Deerpark would assist in establishing an efficient flow with respect to the time scheduled routes. A separate study is planned which would investigate the following issues: 1) what magnitude departure errors can be tolerated without causing a breakdown of the 4-D system; and 2) how to provide ground assists to null departure errors.

Real Time Rescheduling

This special case briefly evaluated the effect of large feeder fix departure time errors, and the feasibility of having the approach controller correct these errors by rescheduling the equipped aircraft.

In the special run, departure times were chosen such that aircraft departing from different feeder fixes would frequently be pairwise in conflict at the runway. These deliberately scheduled pairwise conflicts involved all types of aircraft, equipped, unequipped, large, heavy, and small. The conflicts were created by shifting the originally conflict-free landing times of certain aircraft by one landing time slot. Since the original schedule was full, this created conflicts. At the same time, it opened adjacent time slots which could be used to resolve the conflicts. A 50% 4-D equipped traffic mix was used. As in previous runs, predicted landing times were displayed in the flight data table, revealing the identity of aircraft in conflict as soon as they became active.

The problem for the controller was to detect the predicted conflict on the FDT as soon as an aircraft had departed the feeder fix and to reschedule the landing time of a 4-D equipped aircraft into an adjacent conflict-free time slot.

The rescheduling procedure depended on two special commands, one used by the controller and one used by the pseudopilot, that exploited the unique capabilities of the 4-D equipped aircraft. The use of these commands as aids in rescheduling is most easily explained by describing the controller procedure.

Assume the controller has selected a 4-D aircraft just departing the feeder fix to be delayed by some amount of time, typically 2 min. He first vectors the aircraft off the 4-D route at about a 45 deg angle. Then he enters in his keyboard the command known as Capture Predict (CP) along with the aircraft ID and the number of a capture waypoint on the original 4-D route. The 4-D algorithm calculates and displays the predicted landing time on the controller's display. This landing time is the time the aircraft would touch down if it flew directly from its present position to the capture waypoint and then followed the standard route. Since the landing time is dependent on aircraft position, it is updated every 30 s as long as the 4-D aircraft continues in the vector mode. The predicted landing time will gradually increase as long as the 4-D aircraft is heading away from the designated capture point. When the predicted landing time is within a few seconds of the desired rescheduling time, the controller issues the Capture Waypoint command to the pseudopilot. This will cause the aircraft to rejoin the 4-D route at the designated waypoint and achieve a landing time close to that predicted on the controller's display.

In general, the procedures described above allowed the controller to perform the rescheduling operation successfully. Since the approach control position had low workload to begin with, there was sufficient time to devote to this task, and after a brief learning period, the task became routine. By using the two commands in sequence, the controller was able to insert a 4-D aircraft between two occupied time slots with high accuracy, rarely missing the target time by more than 10 s.

Resolving predicted conflicts outside the final approach area has two well-known advantages, which were confirmed in this experiment. First, it is more fuel-efficient to absorb delays at high altitude, and second it reduces the workload of the final controller by reducing the frequency of spacing vectors.

The main difficulty with these procedures was that the data display format and the command entry language were not optimal for this mode of operation. Future research will try to improve the human interface for the rescheduling tasks.

Vector Operations and Capacity

In the vector mode, a time separation buffer of 20 s was assumed to be added to the minimum separation time for each pair of landing aircraft. This resulted in a capacity of about 30 aircraft per h. If all aircraft were 4-D equipped and no buffers added, the capacity would be 37 aircraft per h. In two special runs, the separation buffers were dropped to see if vector operations would be feasible at the higher arrival rate.

Data from these special runs indicated that it was necessary to delay feeder fix arrivals, and that more airspace was used for vectoring aircraft. It was determined that the landing rate was about the same as it was without the buffers. Thus, the limitation of the maximum arrival rate via the time buffers was reasonable, otherwise capacity would have to be reduced by the controllers via holding and path stretching delays. Thus, the addition of 4-D equipped aircraft reduces the buffers and increases capacity.

Conclusions

Algorithms were developed to obtain an initial time schedule and to provide for revisions for a mix of 4-D equipped and unequipped aircraft in the terminal area.

These algorithms were used to develop a candidate set of operational procedures for mixing 4-D equipped and unequipped jet aircraft along the same route, and for mixing different speed classes along merging routes. A basic rule established was not to alter the 4-D equipped aircraft once they were assigned a landing time. This procedure resulted in the controllers learning to use the 4-D aircraft positions to vector the unequipped aircraft to their assigned landing slot effectively. However, procedures were also demonstrated to vector the equipped aircraft and to reassign touchdown times. In addition, it was shown that a loss of the ground-based 4-D system results in a smooth transition to vector operations.

Controller evaluations indicated that the 25% equipped case was the most difficult to handle. Nevertheless, quantitative data actually showed a decrease in the number of controller clearances with respect to the 0% 4-D equipped case. Controllers felt that the procedure of not altering the 4-D aircraft when so few were equipped was workable, but a more complex task.

The controller workload as measured by the average number of clearances per aircraft decreased as the percentage of 4-D equipped aircraft increased. Moreover, this average decrease was not accomplished at the expense of the unequipped aircraft. The number of clearances for the unequipped aircraft as well as the time delays were independent of mix condition.

Additional studies are required to optimize the operational procedures and to develop procedures to handle aircraft deviations from assigned routes and times; however, this study established a basic set of algorithms and procedures which are reasonable and effective.

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