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# DEVELOPMENT AND EVALUATION OF A PROFILE NEGOTIATION PROCESS FOR INTEGRATING AIRCRAFT AND AIR TRAFFIC CONTROL AUTOMATION

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## SUMMARY

This report describes the development and evaluation of the profile negotiation process (PNP), an interactive process between an aircraft and air traffic control (ATC) that integrates airborne and ground-based automation capabilities to determine conflict-free trajectories that are as close to an aircraft's preference as possible. The PNP was evaluated in a real-time simulation experiment conducted jointly by NASA's Ames and Langley Research Centers. The Ames Center/TRACON Automation System (CTAS) was used to support the ATC environment, and the Langley Transport Systems Research Vehicle (TSRV) piloted cab was used to simulate a 4D Flight Management System (FMS) capable aircraft. Both systems were connected in real time by way of voice and data lines; digital datalink communications capability was developed and evaluated as a means of supporting the air/ground exchange of trajectory data. The controllers were able to consistently and effectively negotiate nominally conflict-free vertical profiles with the 4D-equipped aircraft. The actual profiles flown were substantially closer to the aircraft's preference than would have been possible without the PNP. However, there was a strong consensus among the pilots and controllers that the level of automation of the PNP should be increased to make the process more transparent. The experiment demonstrated the importance of an aircraft's ability to accurately execute a negotiated profile as well as the need for digital datalink to support advanced air/ground data communications. The concept of trajectory space is proposed as a comprehensive approach for coupling the processes of trajectory planning and tracking to allow maximum pilot discretion in meeting ATC constraints.

## INTRODUCTION

In the past, the development of airborne flight management systems (FMS) and ground-based air traffic control (ATC) systems has tended to focus on different objectives, with little consideration for operational integration. For example, the airborne FMS is designed to provide planning capability to optimize an individual aircraft's horizontal and vertical paths. Some newer systems even have limited time-based (four-dimensional (4D)) planning capability that enables the aircraft to meet prescribed arrival times. Comparatively, ATC has the objective to provide for a safe, orderly, and expeditious flow of traffic, the critical factor being the maintenance of separation between aircraft. Unfortunately, the objectives of individual flightpath optimization and traffic separation are often contrary in today's airspace system. Furthermore, controllers have no automation tools to predict separation 10 min or more into the future, let alone tools to assist in setting up nominally conflict-free descent trajectories. When arriving at high-density terminal areas, aircrews are often unable to take advantage of their FMS optimization capability because ATC instructions interrupt their FMS-planned trajectories. This barrier to FMS utilization not only reduces the fuel savings potential of FMS operations; it is also a major factor inhibiting the deployment of more advanced flight management systems, in particular those with 4D capability.

Successful integration of air and ground automation systems would realize several operational advantages. In addition to improving the operating efficiency of individual aircraft, the airborne FMS offers significant potential to enhance ATC operations. If a time-based ATC system were able to plan conflict-free arrival times, as well as nominally conflict-free trajectories to meet those times, the airborne FMS would serve well as an instrument for executing that plan. An airborne 4D system is the most accurate means of meeting a prescribed arrival time; experimental studies have shown that airborne 4D systems can achieve arrival time accuracies on the order of 5 sec (ref. 1). Furthermore, the FMS could provide the most accurate means of tracking a desired trajectory.

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FMS-equipped aircraft could also serve as flow markers for surrounding traffic of less capability. If ATC took advantage of the FMS to improve its prediction and control of aircraft trajectories, separation standards could be relaxed for the same level of safety. This, in turn, would provide greater flexibility for the FMS to perform optimum trajectory planning for individual aircraft.

The key technical challenge is the creation of an integrated air/ground environment whereby ATC can fulfill its objective efficiently and yet allow pilots maximum freedom to take advantage of the unique capabilities of their aircraft. This environment requires the development of compatible airborne and ground-based (ATC) automation systems as well as procedures designed to complement FMS operations (4D in particular).

A joint program between NASA's Ames Research Center (Ames) and Langley Research Center (Langley) is under way to investigate the issues of, and develop systems for, the integration of ATC and airborne automation systems. Ames has developed the Center/TRACON Automation System (CTAS), a ground-based 4D ATC automation system designed to assist controllers in the efficient handling of traffic of all types and capabilities. This system, recently selected by the Federal Aviation Administration for field test implementation, can accurately predict aircraft trajectories and determine effective advisories to help the controller manage traffic. CTAS provides a minimum 4D capability for all aircraft while simultaneously adapting the trajectory information to meet the needs of the controller. Langley has been conducting and sponsoring research on flight operations of advanced transport aircraft for many years. In this research, operational issues have been a primary concern, including the practical implementation of 4D flight-management concepts to permit fuel efficient operations in a time-based ATC environment.

The Ames/Langley joint program is in its second phase, the focus of which is the development and evaluation of the profile negotiation process (PNP). The PNP is an interactive process between an aircraft and ATC that combines airborne and ground-based automation capabilities to determine conflict-free trajectories that are as close to an aircraft's preference as possible.

This paper presents the PNP concept as it is applied to the management of arrival traffic within the extended terminal area up to, but not including, Terminal Radar Approach Control (TRACON) airspace. Although the emphasis is on 4D capability, much of the discussion may be applied to FMS operations in general. The paper begins with a background discussion on several pertinent air/ground system integration issues, including results from the first phase of the Ames/Langley program. A functional description of the PNP is presented, followed by a description of its laboratory implementation. The evaluation of the PNP in a real-time ATC simulation is presented next. An example scenario is used to illustrate how the PNP was executed during the evaluation, and preliminary results are presented along with experimenter observations. The concept of Trajectory Space is introduced as a comprehensive approach to address the issues of trajectory planning and tracking.

The primary focus of this paper is the description and evaluation of the PNP from the ATC perspective. Airborne related issues and results of the PNP evaluation are addressed in reference 2. The design and evaluation of the data link communication system used to support the PNP is presented in reference 3.


## BACKGROUND

### Arrival Operations and the FMS

At least two conditions are required to effectively use the FMS for flightpath optimization: (1) the FMS must be able to incorporate ATC instructions in its trajectory planning, and (2) ATC interruptions to the planned trajectory must be minimized. With regard to the first condition, today's flight management systems are able to handle most ATC instructions, including the crossing restriction. This ATC instruction requires an aircraft to meet altitude and speed restrictions at a fix and is useful for the separation of crossing traffic as well as the merging of arrival flows. With regard to the second condition, few interruptions occur during periods of light traffic. However, during periods of moderate to heavy traffic, interruptions to planned trajectories occur often as controllers work to maintain separation and expedite the flow. If the interruptions are such that the flight management system cannot adapt to them or that the aircrew cannot reprogram the FMS to handle them, the effectiveness of FMS flightpath optimization is significantly reduced. A major goal of air/ground system integration is to minimize the number of these interruptions as well as their individual effect on flightpath efficiency.

Interruptions to FMS-planned flightpaths are mostly due to the methods currently used by Air Route Traffic Control Center (Center) controllers for managing arrival traffic. The two primary methods for handling moderate to heavy arrival traffic at major terminal areas are intrail

spacing and metering. While both methods must provide for the minimum legal separation between aircraft, each method attempts to regulate the arrival flow differently. These methods will be described briefly here; a more detailed description of the methods and their use at the Denver Center may be found in reference 4.

The spacing method adjusts intrail separation (above minimum legal standards) to handle the compression and merging of arrival flows. General intrail spacing requirements are determined by prior agreement within and/or between ATC facilities. Spacing requirements are adjusted, as needed, based on the traffic conditions (e.g., 10, 15, or 20 n. mi. intrail). For a given spacing requirement, controllers adjust the aircraft's speed, altitude, and horizontal path to achieve the desired spacing. These adjustments lead to the interruption of FMS-planned trajectories.

The metering method is used at some major hub terminals, such as Denver and Dallas/Ft. Worth. This method, supported today by the Arrival Sequencing Program (ASP), is an early form of time-based traffic management. ASP is a continuation of enroute metering (ERM), which attempts to control the traffic flow through the assignment of metering fix (MF) arrival times. For the most part, the metering process is transparent to the pilot (i.e., the pilot is not given responsibility for meeting the MF time). ATC typically issues MF crossing restrictions and then adjusts each aircraft's speed, altitude, and horizontal path prior to the MF to maintain minimum separation and meet metering requirements. Like the spacing method, these adjustments also lead to interruptions that reduce the effectiveness of FMS flightpath optimization.

One expectation associated with time-based operations is that aircraft will be able to effectively use their 4D FMS capability. In an ideal world, arriving 4D-equipped aircraft would receive an assigned MF crossing time while still at cruise and then plan their speed and descent to meet the MF time and to minimize fuel burn. Unfortunately, this expectation has not been fully realized. For the most part, 4D operations do not occur today, even with ASP. There are at least two major reasons for this. To begin with, there are no 4D ATC procedures that exist today; many controllers are not even aware of this capability or of the aircraft that are equipped for it. The second, and more significant, barrier to current 4D operations is the poor precision of MF arrival times. 4D-equipped aircraft must receive a precise MF arrival time assignment, prior to descent, that is conflict-free at least at the MF. Under ASP, it is possible for two aircraft to be scheduled at the MF at the same time (MF arrival times are rounded to the minute on the controller's display). In

addition, the ASP sequence often does not correspond to the sequence set up by the controller. As a result, controllers use the MF times as only a secondary goal and give first priority to relative spacing. The controller sets the sequence, maintains separation, and tries to feed one aircraft through the MF for each ASP time slot. Furthermore, today's controller has no automation assistance to help unequipped aircraft meet their MF arrival times. The typical MF arrival time accuracy for unequipped aircraft is on the order of 2 min. Given today's ATC environment, and traffic of mixed capability (4D equipped and unequipped), it is all but impossible to determine precise MF arrival times for 4D-equipped aircraft and to ensure separation at the MF.

Recent developments in ATC automation have the potential to resolve these problems. The ability to schedule conflict-free arrival times based on variable traffic conditions and controller preferences has been demonstrated using CTAS (ref. 5). More importantly, automation tools have been developed to assist the controller in achieving arrival time accuracies, for unequipped aircraft, on the order of 10 and 20 sec in the TRACON and Center, respectively (refs. 6–8). These capabilities are the foundation for any ATC automation system that attempts air/ground integration for time-based ATC operations.

One additional issue concerns the ability of 4D-equipped aircraft to accurately track a 4D trajectory. Commercial 4D systems flying today can generate trajectories based on cost index (a ratio of time and fuel costs). These systems meet an arrival time constraint by iterating on cost index until a trajectory solution is obtained that satisfies the arrival time constraint. Closed-loop guidance to achieve the desired arrival time is accomplished by recomputing the vertical trajectory when time error exceeds a predefined level. There are no provisions to constrain the cruise and/or descent speeds chosen to achieve the desired arrival time. As a result, the aircraft may fly a substantially different vertical trajectory from the one originally planned to meet the time. The airspace that would be required to maintain separation for one 4D-equipped aircraft using this guidance method could easily prohibit a sequentially neighboring aircraft from exercising the same capability. For practical airborne 4D operations in a high-density terminal area, the capability to accurately track a given trajectory in four dimensions is probably as important as, if not more important than, the capability of an FMS to generate optimum trajectory plans. Research conducted and sponsored at Langley not only is investigating 4D trajectory-generation techniques, but also is developing guidance concepts for piloted and automatic trajectory tracking (refs. 9–11).

## Ames/Langley Joint Program

The Ames/Langley program was created in 1989 to develop and evaluate airborne and ATC automation systems for air/ground system integration. The program began with a baseline technology that combined the individual automation systems developed at Ames and Langley up to that time: ATC automation (CTAS) from Ames, and airborne flight management systems from Langley. The capabilities of this baseline technology addressed most of the major obstacles, mentioned earlier, to current-day airborne 4D operations. In particular, CTAS would provide conflict-free arrival time scheduling as well as controller advisories to help unequipped aircraft meet that schedule. On the airborne side, 4D guidance automation would assist the pilots of 4D-equipped aircraft both in planning a 4D trajectory to meet an assigned MF time and in accurately tracking that 4D trajectory plan.

The purpose of the program's first phase was to evaluate the baseline technology by introducing a 4D-equipped aircraft into a time-based ATC environment and exploring the resulting situations and problems. The associated experimental study (4D Aircraft/ATC Operations Study, July 1989) focused on the compatibility of airborne and ATC systems when dissimilar 4D strategies were used. Dissimilarity in 4D strategies refers to differences in the speed profiles (combinations of cruise and descent speed) chosen by the ATC and airborne automation to meet an assigned arrival time for a given routing. In the case of CTAS, trajectory solutions are fuel conservative in that they minimize level flight at lower altitudes; speed profiles are chosen to meet controller constraints. Dissimilarity occurs because airborne systems are designed to find the fuel-optimal speed profile for a fixed time. Candidate procedures for handling 4D-equipped aircraft were developed, and traffic scenarios were devised to create specific air traffic problems and delays. The study was conducted through 30 hr of real-time simulation using active controllers and airline flight crews as test subjects. A brief summary of results will be given here; more detailed descriptions of the experiment, from the airborne and ground-based perspectives, are presented in references 12 and 13.

In general, the 4D procedures were well received by the controllers and pilots. The controllers responded favorably to the CTAS tools and were effective in meeting the CTAS sequence and schedule; the pilots of the 4D aircraft achieved an arrival time accuracy indicated by a negligible mean time error with a standard deviation of 2.9 sec. Under conditions of medium delay (delays requiring vectoring, but not necessarily holding), the 4D FMS demonstrated an operational benefit. For the scenarios tested, pilots were able to consistently fly ATC vectors to absorb the delay while using the FMS to find the optimum point to return to an arrival routing.

However, under conditions of small delay (delays which could be absorbed using speed control only), dissimilar speed strategies often lead to a loss of minimum separation prior to the metering fix. To maintain separation, controllers interrupted the descents of one or more aircraft, usually including the 4D-equipped aircraft. For the cases studied, the 4D aircraft's minimum-fuel solution had the potential to save 39 lb (2.2%) more fuel per flight than did the basic uninterrupted ATC (CTAS) solution. However, ATC interruptions to the 4D aircraft's optimal trajectory plan caused the actual fuel burn to average 111 lb (6.3%) more per flight than did the basic uninterrupted ATC solution. Controllers found it very difficult to predict, let alone resolve, these conflicts prior to issuing a metering-fix arrival time clearance. The increase in fuel burn and added workload associated with the interrupted profiles negated the potential gains from the 4D aircraft's flying its own fuel-optimal trajectory. The experiment also investigated offset routing to allow sequentially scheduled aircraft to maintain separation while flying substantially different speed profiles. Results indicated that, for the geometry studied, it was more efficient for a 4D aircraft to adopt the ATC system's (CTAS) speed strategy than to attempt to use dissimilar speeds.

In summary, the July 1989 study fostered new insight into the minimum system requirements necessary to support 4D FMS operations. The ATC automation must do more than schedule conflict-free arrival times and provide controller advisories for unequipped aircraft. Specifically, the ATC automation must also probe the airspace for potential conflicts (loss of minimum separation) while incorporating FMS solutions in the analysis. If a potential conflict is predicted, the ATC automation must work with the controller to determine acceptable 4D trajectory solutions that are nominally free of conflict and still meet the assigned arrival time. 4D-equipped aircraft must then be able to follow an ATC-derived 4D solution while using the FMS for accurate tracking. Digital datalink technology would be ideally suited for the task of exchanging trajectory data between airborne and ATC automation systems. However, the minimum data required to adequately define 4D trajectory solutions must still be determined. In addition, the ATC automation should provide the controller with delay advisories in the horizontal plane (pathstretching) to complement speed and descent advisories in the vertical plane.

The purpose of the second phase of the program was to develop systems and procedures to address the issues

described above. ATC automation development focused on conflict prediction, conflict resolution, pathstretching, and the analysis of trajectory information downlinked from a 4D-equipped aircraft. An air/ground digital data-link communications capability was also developed to enable the two-way exchange of trajectory data. Airborne automation development included the addition of a 4D trajectory-generation mode that adapts to ATC 4D trajectory constraints, incorporation of automatic 4D path-stretching for trajectory planning, and integration of FMS trajectory information into the digital datalink system. The main emphasis of phase two is the implementation of the profile negotiation process. The PNP concept is presented next, followed by a description of the ground-based aspects of its implementation into a laboratory research system.

## PROFILE NEGOTIATION PROCESS

Profile negotiation is a simplification of the more general process of trajectory negotiation. The purpose of trajectory negotiation is to determine a "valid" trajectory that is as close to the aircraft's preference as possible. A valid trajectory is one that satisfies all ATC constraints, particularly separation. The aircraft's preferred trajectory may be determined by the pilot, company procedure, or FMS optimization. Trajectory negotiation is "strategic" in that it defines a future, or planned, trajectory to be followed under expected conditions (e.g., traffic, weather). Tactical deviations may occur, or a new strategic plan may be formed, to meet unexpected conditions. However, the better the strategic planning and the better a plan can be executed (through accurate trajectory tracking by aircraft), the greater the likelihood that a negotiated trajectory may be followed without significant interruption.

The negotiation process assumes the standard roles for the pilot and ATC. The pilot, acting as the final authority concerning the operation of the aircraft, may request or negotiate ATC clearances at any time. However, since ATC is responsible for maintaining separation between traffic (under instrument flight rules), ATC must assume the role of arbiter and strike a compromise between the preferences of conflicting aircraft. The concept of trajectory negotiation formalizes this compromise into an objective process that is ideally suited for automation as well as optimization (e.g., minimization of fleet fuel consumption). This study does not address optimization directly, but instead focuses on the realization of the negotiation process itself.

4D trajectories are uniquely characterized by three profiles: the horizontal path, or ground track; the altitude profile along the horizontal path; and the speed profile. For convenience, a vertical profile is defined as the composite of the altitude and speed profiles along the horizontal path. For the purposes of ATC, an aircraft's horizontal path is constrained by its assigned routing, which is typically determined by the controller independently of the vertical profile. This simplifies the process of synthesizing a 4D trajectory to that of synthesizing a vertical profile.

Given a predetermined routing, the PNP attempts to find a valid vertical profile that is as close to the aircraft's preference as possible. The PNP complements current-generation FMS optimization methods, which also search for a vertical profile solution for a predetermined routing. The PNP may also be applied to cases of partially determined routing. An example of partially determined routing occurs when a controller vectors an aircraft, to absorb a delay, with the intention of returning the aircraft to a predetermined routing. This method for absorbing delay is referred to here as pathstretching. The undefined portion of the aircraft's routing is directly related to the vertical profile in that the length of the delay vector is directly related to the speeds chosen. The PNP may be applied to any combination of flight segments: climb, cruise, and descent. This paper focuses on the final cruise segment and descent to a terminal-area metering fix.

The PNP is best described in terms of the air/ground interaction that would occur during a typical arrival scenario into an advanced time-based ATC environment (fig. 1). An advanced time-based ATC environment (e.g., CTAS) is one that employs automation that not only determines conflict-free arrival times but also determines conflict-free 4D trajectories to meet those times. As the aircraft enters the extended terminal area (approximately 200 n. mi. or 40 min from touchdown), it enters a scheduling process. The scheduling process (fig. 2) defines the arrival time constraint for the PNP. In the most general case, ATC would query the pilot of a 4D-equipped aircraft for the desired time of arrival, and the pilot would respond with the FMS solution. ATC records the pilot's proposal and compares it to the desired arrival times of the other arrival traffic to determine the best overall sequence and arrival schedule. Once scheduled, the aircraft enters the profile negotiation process to determine a 4D trajectory solution that is free of conflict, meets the arrival time, and is as close to the aircraft's preferred vertical profile as possible. This trajectory solution is transformed into a clearance for the pilot to execute, using the FMS for precise tracking.

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The profile negotiation process is illustrated in figure 3. The PNP begins when the controller requests a vertical profile proposal from the pilot. This request contains a list of all known ATC constraints, including the assigned arrival time and any additional items determined by the controller (e.g., routing). The controller always decides the amount of freedom each profile request will allow the pilot for generating a profile proposal. In the case of a delay requiring pathstretching, the controller may allow the aircraft some flexibility on the length of the delay vector based on the aircraft's preferred speeds. This process assumes the same procedures, in use today, for the issuance and acceptance of ATC clearances: the pilot may negotiate with the controller to modify unacceptable constraints as needed.

After receiving the profile request, the pilot uses the FMS to compute a preferred vertical-profile solution. This airborne solution must meet all ATC constraints and may also reflect additional constraints determined by the pilot. The resulting vertical profile is then transmitted to the controller for consideration, and entered into the ATC computer when convenient. In considering the pilot's proposal, the controller uses the ATC automation to check for potential conflicts with other aircraft all the way to the metering fix. If no conflicts are predicted, the controller issues a 4D clearance based on the aircraft's preferred vertical profile. The pilot then uses the FMS to execute the clearance and track the 4D trajectory.

If a conflict is predicted, the controller uses the ATC automation to determine the minimum modification to the aircraft's proposed vertical profile that is necessary to avoid any predicted conflicts. The resulting 4D trajectory solution may be implemented in one of two ways. One option is for the controller to issue the entire 4D solution as an arrival clearance for the aircraft to execute. This is useful when there is little time for fine adjustments (e.g., when the aircraft is near its top of descent, or the controller's workload is heavy). The second option is to issue "tactical" instructions (speed, heading, and/or altitude assignments) to implement the first portion of the controller's trajectory solution, and leave the rest of the clearance to be issued later. The advantage of this second option is that it allows the controller to make a gross correction to the aircraft's profile quickly and fine tune the final 4D solution later. This technique is useful for balancing workload between sectors when multiple sectors work together to sequence arrivals in a "high/low" configuration.

The PNP is performed by the controller only as the workload permits. It may be simultaneously applied to any number of aircraft capable of supporting the negotiation process. The word negotiation is used to emphasize the role of the pilot and FMS in determining a valid trajectory solution that would not necessarily be the first choice of ATC, but nevertheless would be acceptable. In general, the PNP is initiated by the controller following the scheduling process. However, pilots may also request the controller to consider an unsolicited vertical-profile proposal. The controller may discontinue negotiation at any time and handle the traffic in a conventional manner. Even if discontinued, profile negotiation offers the advantage of having reduced the number of potential conflicts that must be resolved in the future.

The PNP incorporates the major advantages of airborne and ATC automation in a complementary fashion. The FMS performs two tasks in support of the PNP: trajectory optimization, which is of primary concern to the aircraft operator, and trajectory tracking, of primary concern to ATC. The ATC automation performs the critical task of analyzing the airborne proposal and ensuring a nominally conflict-free solution (separation being the primary responsibility of ATC). Of the two tasks performed by the FMS, the paramount importance of accurate 4D trajectory tracking cannot be overstated. If an aircraft cannot accurately track a negotiated trajectory, the risk of ATC interruption to its negotiated trajectory as well as to the planned trajectories of sequentially neighboring aircraft is increased. Since interruptions may significantly reduce the potential benefit of trajectory optimization, there is little purpose in attempting trajectory optimization without adequate tracking capability. The definition of what constitutes adequate trajectory tracking has yet to be determined; the definition of minimum 4D tracking requirements is an important area for future research. The technical issue of interest here is the development and evaluation of the automation tools necessary to assist the pilot and controller in performing the PNP simply and effectively.

## PNP IMPLEMENTATION

The major elements necessary to implement the PNP include the airborne automation systems (FMS), the ATC automation tools, and a communications medium that enables the airborne and ATC systems to exchange trajectory data. This paper concentrates on the ground-based aspects of the PNP implementation, specifically with regard to using CTAS as the foundation for the ATC automation.

## Center/TRACON Automation System (CTAS)

CTAS is an integrated set of automation tools designed to assist controllers in the efficient management and control of arrival traffic. It has been implemented in the laboratory on a series of workstations connected by a local area network. CTAS is composed of three major toolboxes: the Traffic Management Advisor (TMA), the Descent Advisor (DA), and the Final Approach Spacing Tool (FAST). The TMA assists traffic managers in the Center and TRACON with the sequencing and scheduling of traffic; the DA assists Center controllers in efficiently meeting the TMA's schedule while maintaining separation; FAST assists TRACON controllers in fine-tuning the arrival flow. Implementation of the PNP primarily involves the DA, which will be described in more detail. Additional information on the TMA is provided in reference 5, and a thorough description of the design and evaluation of FAST is provided in references 6 and 14.

## Descent Advisor (DA)

The DA is designed to assist the Center controller in accurately and efficiently delivering arrival traffic to the TRACON feeder gates in accordance with the TMA's schedule. The heart of the DA is a generic 4D trajectory-generation algorithm that is adaptable to different types of aircraft. It contains detailed models of aircraft performance and operational characteristics, and takes advantage of all real-time inputs of atmospheric data available in its area of operation. The DA continuously resynthesizes 4D trajectory solutions for all arrivals, based on controller inputs, aircraft state (from radar tracking), and the TMA schedule. The DA translates these trajectory solutions into controller advisories, which include speeds for cruise and descent, top of descent, and heading. The DA monitors the traffic, including overflights, and compares the trajectories it predicted for each aircraft. The controller is advised of any potential conflicts up to 20 min, or more, in advance. The DA also provides continuous feedback on whether or not subsequent controller actions resolve the predicted conflicts. In effect, potential conflicts are resolved far earlier than a controller would have detected them without assistance from the DA.

The DA's functions are interfaced with a mouse-based, menu-driven controller display. The display features include those available on current Center plan-view displays (PVD), as well as color, timeline, and other advanced graphical features. A "mouse" or trackball pointer is used by the controller to select display objects, including aircraft symbols, tags, and fixes; the controller invokes the DA's functions via on-screen "buttons" or keyboard inputs. Additional information on the development and evaluation of the DA, its functions, and the controller interface, may be found in references 4 and 5.

Modifications to the DA in support of the PNP included the addition of two functions: Trajectory Re-Creation; and Conflict Resolution. Trajectory Re-Creation allows the DA to re-create an airborne trajectory solution based on the data transmitted by the pilot either by voice or datalink. This allows the DA to analyze airborne solutions for potential conflicts. Conflict Resolution determines a nominally conflict-free trajectory solution for an aircraft when its original solution is predicted to be in conflict with the trajectories of other aircraft. The development of these modifications followed the same guidelines for ATC automation development outlined for CTAS in reference 5. Among others things, these guidelines advise not to automate complex or poorly understood tasks; to apply automation to complement controllers' skills; and to involve controllers in the selection and design of automation tasks from the start. The application of these guidelines is described next.

The task of planning descent trajectories that are free from conflict far into the future (20 min or more) is a complex problem that is dependent on controller technique and preference. Controllers are highly skilled at solving tactical traffic problems given today's graphical displays. On the other hand, computers are well suited for the high-speed computation necessary for longer range strategic planning, which depends on accurate modeling of aircraft performance and atmospheric characteristics. For these reasons, the Trajectory Re-Creation and Conflict Resolution functions were developed with a low level of automation. While this allowed the controller maximum adaptability, it also required active controller participation. For example, the Trajectory Re-Creation function was designed to be invoked manually by the controller because it was not clear when, and under what circumstances, the function should be invoked automatically. This way, the controller decides when airborne trajectory solutions are to be analyzed. The Conflict Resolution function was also designed to be invoked manually. There are few tasks, if any, that are more challenging than "strategic" conflict resolution. Predicted conflicts within moderate- to heavy-density traffic usually require modification to more than one aircraft, and, typically, many "valid" solutions exist. The controller selects which aircraft to modify as well as the type of modification (speed, altitude, or routing). Until this problem is better understood, controller inputs are required to constrain the computer to solutions that follow the controller's preferences. The DA's display and interface were designed, following the guidelines listed above, to allow the controller to solve

problems graphically while the computer calculates the precise solutions. Once controller preferences and techniques for planning conflict-free 4D trajectories are better understood, the task of profile negotiation will be simpler to automate at a higher level.


## PNP EVALUATION

The PNP was evaluated in a real-time ATC simulation (4D Aircraft/ATC Integration Study, May 1991). The ATC environment was simulated at Ames using CTAS for 4D traffic management, while the 4D-equipped aircraft was simulated at Langley using the Transport Systems Research Vehicle (TSRV) 737 piloted cab. The TSRV cab was connected to the Ames simulation via voice and data communications lines. The remainder of the traffic was simulated at Ames using a pseudopilot aircraft simulation (ref. 4). Air/ground communications, for conventional as well as PNP (trajectory exchange) purposes, were supported by both voice and digital datalink media (ref. 3). Three teams of active Center controllers (two on each team) and three crews of line pilots (two in each crew) participated as test subjects in 30 hr of simulation.

Prototype ATC clearances, and procedures for their use, were developed to support the PNP as it was implemented for this study. The pilots and controllers who participated in the study were provided with a written description of each clearance and associated procedure. Parallel procedures were developed for operations in both a data link and voice-only communications environment. These written descriptions, including example usage, are presented in the appendix.

The simulation airspace was based in part on the Denver area. Arrival traffic for the Denver Stapleton airport was simulated from two directions: northeast (NE) and northwest (NW), and was scheduled for a coordinated feed into the TRACON. NW traffic was light and was handled automatically; NE traffic was of moderate density (36 arrivals per hour plus overflights) with delays of 3 to 8 min, and was handled by one controller team for each run. The NE airspace was divided into a High/Low configuration, with one controller handling the High sector (approximately 100–200 n. mi. from Denver) and the other controller handling the Low sector (approximately 30–100 n. mi. from Denver). The traffic scenarios ended at the TRACON handoff.

The controllers were tasked with meeting the TMA's arrival schedule at the metering fix while maintaining

separation. For each traffic scenario, the TSRV was injected into the arrival flow at a predetermined time to create a specific traffic problem for the controller team with regard to handling a 4D-equipped aircraft. Equivalent traffic scenarios were repeated by each controller and pilot team with and without digital datalink communications. A standard atmosphere with calm winds was used with no modeling errors (i.e., no differences between the actual atmospheric conditions used and the conditions modeled by the airborne and ground-based automation). A typical conflict problem will be presented here, along with one of the actual PNP solutions executed by the controller and pilot test subjects.


### PNP Scenario Example

The following example will serve to illustrate the practical application of the PNP. Figure 4 illustrates a set of traffic conditions that leads to a potential conflict during one traffic scenario. Three sequentially scheduled aircraft are shown, with the surrounding aircraft removed for clarity. The aircraft enter the airspace from the northeast; initial cruise conditions are tabulated in figure 4. The aircraft in the middle of the sequence is the 4D-equipped TSRV piloted cab. The aircraft sequenced in front and behind, referred to as the LEAD and TRAIL aircraft, respectively, are unequipped.

Before the PNP begins, the aircraft are scheduled by the TMA based on their desired times of arrival and the traffic load. For this case, the 4D aircraft's desired time of arrival at the metering fix is 29 min after the hour. The desired times of arrival for the LEAD and TRAIL aircraft are 31 sec earlier and 85 sec later, respectively. The DA computes the desired times of arrival for the unequipped aircraft based on the aircraft's state as it enters the scheduling process and on a predicted descent to the MF at the aircraft's preferred descent speed (a data base of preferred descent speeds as a function of airline and aircraft type is contained within the DA). All three aircraft are scheduled by the TMA to be free of conflict at the metering fix, with small delays due to capacity limits.

The controller must consider the 4D trajectory solutions necessary to meet the schedule. The DA computes a solution for each aircraft, based on the aircraft's state as well as constraints input by the controller (e.g., routing), and translates the solution into controller advisories for speed and descent. The original DA vertical-profile solutions for the LEAD and TRAIL aircraft are tabulated in figure 4 and are based on each aircraft's initial cruise conditions. For the LEAD aircraft, the DA advises a cruise speed reduction to 250 knots indicated airspeed

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(KIAS) followed by a descent at 280 KIAS; and for the TRAIL aircraft, the DA advises a cruise speed reduction to 250 KIAS followed by a descent at 230 KIAS. The corresponding tops of descent are shown by clear symbols on the plan view. Although the DA also computes a solution for the 4D aircraft, it is not shown since the solution of interest is that proposed by the 4D aircraft.

When workload permits, the controller initiates the PNP by requesting a profile proposal from the pilot of the 4D aircraft for the scheduled arrival time. The pilot enters all applicable constraints into the FMS. The FMS, like the DA, computes a 4D trajectory solution based on the aircraft's state. The 4D aircraft's profile proposal represents the FMS minimum-fuel solution for the 4D aircraft at the time of the request. The profile proposal tabulated in figure 4 is based on the initial cruise conditions listed. This proposal calls for a reduction in cruise speed to Mach 0.68 (250 KIAS) followed by a descent at 230 KIAS. The corresponding top of descent is marked by a clear diamond symbol.

In considering profile solutions, the controller uses the DA to predict any potential conflicts. Figure 5(a) depicts the predicted horizontal and vertical separation for the 4D aircraft based on the 4D aircraft's profile proposal and the original vertical profile solutions for the neighboring aircraft. This figure shows the predicted compression of the LEAD and TRAIL aircraft onto the 4D aircraft as all three converge on the metering fix. The separation trajectories for each aircraft pair (e.g., LEAD vs. 4D) are shown starting when the horizontal separation of each aircraft pair is within 40 n. mi., and ending when the metering fix is crossed. A conflict occurs when the minimum separation boundary is penetrated.

Figure 5(a) shows the TRAIL aircraft starting out 4000 ft above the 4D aircraft in cruise. Although the original profile solutions for the TRAIL and 4D aircraft maintain a significant cruise groundspeed difference (27 knots), the corresponding trajectories are predicted to be nominally free of conflict. This is not the case for the LEAD and 4D aircraft. The LEAD aircraft is initially 2000 ft above the 4D aircraft. The DA's original profile solution for the LEAD aircraft calls for a cruise speed reduction to 250 KIAS (Mach 0.75), followed by a descent at Mach 0.75 to 280 KIAS. This represents the DA's attempt to find a profile solution for an unequipped aircraft that is as close to that aircraft's company-preferred descent speed as possible. In this case, the company-preferred descent speed for the LEAD aircraft was programmed to be 280 KIAS. Although the original profile for the LEAD aircraft and the 4D aircraft's profile proposal are predicted to be free of conflict near the

metering fix, their separation is predicted to fall below minimums during the descent. The inset in figure 4 illustrates the predicted conflict at the first point where minimum separation is predicted to be lost.

This separation analysis of the original profile solutions is performed by the DA nearly instantaneously. The DA graphically displays the situation to the controller by marking the point of predicted loss of separation on the controller's traffic display, changing the color of the aircraft tags for the aircraft involved, and listing the time to go before separation is predicted to be lost. In this case, the problem is predicted 21 min in advance, far earlier than any controller could detect the problem using today's systems.

To resolve the predicted conflict, the controller invokes the Conflict Resolution function to modify the 4D aircraft's proposal. The controller may also use the DA to simultaneously modify the profile solution for the LEAD aircraft to find a better overall compromise. In the simulation case presented here, the controller balanced the LEAD aircraft's cruise and descent speeds by decreasing the descent speed by 15 KIAS, to 265 KIAS. This allowed the DA to find a nominally conflict-free profile for the 4D aircraft that was within 10 KIAS of the pilot's proposal.

The controller issued clearances based on the conflict-free profiles tabulated in figure 4. The 4D aircraft received a 4D clearance, to be executed by the pilot using the FMS for tracking, whereas the LEAD and TRAIL aircraft received speed and descent instructions based on DA advisories for the profile solutions. The actual descent speed for the TRAIL aircraft (240 KIAS) differs slightly from the original DA solution (230 KIAS) because the controller decided to absorb more of the delay in cruise with a small amount of vectoring rather than descend the TRAIL aircraft at 230 KIAS. The resulting separation histories from simulation are plotted in figure 5(b). The 4D aircraft was able to execute its negotiated profile without interruption.

**Preliminary Results and Observations**

The controller teams were able to consistently and effectively negotiate nominally conflict-free vertical profiles with 4D-equipped aircraft. The negotiated profiles were substantially closer to the aircraft's preference than would have been possible without the PNP. However, the workload required to support the PNP (as implemented for this study) was significant. This was due in part to a short training period. The controller teams were given an

average of two days' training to become familiar with the PNP, 4D procedures, datalink, and the DA's functions and interface. Similarly, the pilot crew training period of one half day was also short. Although more training would have significantly reduced the test subjects' workload, a strong consensus among the pilot and controller teams indicated the need to increase the level of automation of the PNP tasks to make them more transparent to both the pilot and controller. This increased level of automation should consider and recommend conflict-free 4D solutions automatically, with the pilots and controllers only constraining and approving the process. In addition, all subjects strongly agreed that digital datalink is preferred over voice for PNP trajectory data exchange, and that datalink should be a minimum requirement to support profile negotiation.

The ability of the airborne 4D FMS to adapt to ATC-specified 4D trajectory constraints was found to be a requirement for successful execution of the PNP. The conventional method of cost-index iteration for obtaining the minimum-fuel 4D trajectory must be supplemented by a method that constrains the profile speeds to those desired by ATC. Without such a capability, the 4D-equipped aircraft cannot participate in the PNP beyond the initial profile-request stage. The controllers also indicated that the tracking ability of 4D-equipped aircraft was of concern to them; if a 4D-equipped aircraft could not precisely execute the negotiated profile, controllers would prefer not to spend precious time and energy accommodating a pilot's profile request.

**Trajectory Space**

It was stated earlier that effective use of the FMS for trajectory planning requires minimum ATC interruptions. ATC interruptions are often a result of traffic conflicts. The goal of the PNP, and the ATC trajectory planning process in general, is to find conflict-free trajectory plans that are as close to the user-preferred trajectories as possible. It is essential that conflict-free trajectory plans be followed accurately so that they remain conflict free and ATC interruptions are avoided.

The tracking accuracy required in order to maintain minimum separation depends on the type of ATC constraints involved. In particular, separation from other traffic and obstacles tends to be a localized "bottleneck" problem. An aircraft is only affected by separation requirements when it is near an obstacle. Although many obstacles (e.g., restricted airspace and terrain) are fixed in space and time, traffic obstacles tend to have significant interdependencies between space and time. A small devia-

tion in one aircraft's planned trajectory may result in significant changes in its separation from other aircraft. Localized bottlenecks occur between aircraft pairs at locations where the separation between their trajectories is minimal. The geometry and size of these bottlenecks are a function of the planned trajectories.

The tracking accuracy is most important at these trajectory bottlenecks where separation between conflict-free planned trajectories is a minimum. In fact, the separation between the planned trajectories at these bottlenecks must allow for the minimum standard plus a buffer which is inversely proportional to the tracking accuracy of the aircraft (i.e., the better the tracking accuracy, the smaller the buffer required). In areas away from the traffic bottlenecks, aircraft may deviate farther from the plan without loss of minimum separation. It may be possible for FMS-equipped aircraft to use this freedom to deviate from the planned trajectory in a way which would further optimize their path without interrupting another aircraft or triggering a new trajectory planning process for ATC.

The trajectory planning process presented here (i.e., PNP) generates a single conflict-free planned trajectory, for each aircraft, out of an entire set (space) of possible conflict-free trajectories. This work has led the authors to formulate the Trajectory Space concept. This concept combines the ATC trajectory planning process with aircraft navigation capability (i.e., trajectory tracking accuracy) to identify and exploit the entire conflict-free trajectory space and thus maximize the benefit that can be achieved by airborne and ground-based automation systems.

The process of determining an aircraft's trajectory space begins with the ATC trajectory planning process. This process (e.g., PNP) determines a baseline conflict-free planned trajectory for each aircraft while taking into account each aircraft's preferences where possible. These baseline trajectories are then compared, and any excess conflict-free airspace (outside of the bottleneck regions) is divided among the aircraft to define each aircraft's conflict-free trajectory space. ATC may then assign each appropriately equipped aircraft its own trajectory space within which the aircraft may operate at the pilot's discretion. This clearance would allow a pilot maximum discretion to use the FMS for trajectory optimization, within the cleared space, without ATC interruption.

In general, this concept shares many characteristics with the negotiation process defined in reference 15. Both concepts define a 4D space within which an aircraft is cleared to operate, and both concepts allow for the negotiation of a basic trajectory plan. The development of the

Trajectory Space concept will focus on the process which determines the ATC constraints that make optimum use of the airspace and aircraft navigational capabilities. Future research is required to better develop and evaluate the Trajectory Space concept, including required airborne and ground-based automation functions, human interface requirements, and procedures.

## CONCLUDING REMARKS

The development of airborne and ground-based automation must address the issues of air/ground integration to maximize the effectiveness of the overall system. In particular, airborne automation must consider the constraints and requirements of the ATC system or risk under-utilization. The effectiveness of airborne trajectory planning can be improved by reducing the net effect of interruptions to the planned trajectories. ATC interruptions can be minimized through (1) the use of strategic planning by ATC to determine nominally conflict-free trajectories and (2) accurate tracking of planned trajectories by the aircraft. ATC strategic planning should consider each aircraft's trajectory preference and determine the best compromise.

The PNP, a concept for integrating airborne and ground-based 4D automation capability to improve ATC strategic planning, was implemented in a laboratory environment. A real-time ATC simulation was conducted to evaluate the PNP and explore the issues related to 4D aircraft operations in a 4D ATC environment. The PNP established an effective dialogue between the aircraft and ATC in support of 4D aircraft operations. Controller subjects indicated a strong preference for datalink over voice communications in support of the PNP. Controllers also stated their concern that 4D-equipped aircraft must be capable of accurately tracking a 4D trajectory solution to make worthwhile the controller's time and effort required to negotiate a solution. The Trajectory Space concept was introduced as a comprehensive approach to addressing the issues of trajectory planning and tracking from both the ATC and aircraft perspectives. Further development of the PNP must address workload; controller and pilot test subjects indicated the need to automate the process further without significantly reducing their ability or authority to constrain the process. However, the controllers found the DA tools to be very effective for strategic planning and tactical control, particularly when dealing with aircraft that were not 4D equipped.

Additional research is needed to develop and evaluate the Trajectory Space concept. This work must determine individual and overall system requirements necessary to support 4D ATC operations, including minimum standards for 4D trajectory tracking. In addition, this work must consider the relative effect of various aircraft navigational capabilities (ranging from unequipped to 4D-FMS-equipped), and traffic ratios thereof, on the overall system. Another important issue concerns the modeling of aircraft performance and atmospheric characteristics; the overall system must be sufficiently robust to handle real-world modeling errors. Future work should also investigate alternative methods for representing the aircraft's preference in the ATC strategic planning process. If the aircraft's preferred trajectory is to be generated by airborne automation in support of air/ground negotiation, the specifications for trajectory data exchange must be defined. Alternatively, the generation of preferred trajectories could be performed equally well on the ground, given that critical performance data and constraints are known. Such ground-based generation of aircraft trajectory preferences could provide the additional benefit of trajectory-optimization capability for unequipped aircraft.

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# APPENDIX

# ATC CLEARANCES/PROCEDURES

The purpose of this experiment is to study the issues of integrating FMS equipped aircraft into a time-based (4D) ATC system. Specifically, this study will focus on how ATC and 4D FMS equipped aircraft can work together to improve the efficiency of traffic flow under moderate delay conditions (3 to 8 minutes; 200 n.mi. from touchdown).

The clearances and procedures described in this document are designed to take advantage of the unique capabilities of both the airborne and ground based automation systems to be used in this simulation. These procedures were originally developed for a previous 4D experiment in July 1989 (ref. 12), and have been refined for this study. The procedures for this study are experimental, and should be considered a basis for further development.

The cornerstone of this experiment is the profile negotiation process. This process will assist the controller and pilot of a 4D FMS equipped aircraft in finding a "conflict-free" arrival trajectory that is as close to the aircraft's optimum as possible. The resulting trajectory is then translated into an ARRIVAL CLEARANCE for the pilot to fly. The arrival clearance and associated procedures are described below. Additional information on the negotiation process may be found in a related document entitled AIR/GROUND 4D INTERACTION.

## CLEARANCE CATEGORIES

The clearances to be used in this simulation have been divided into three major categories:

    STRATEGIC
        ARRIVAL CLEARANCE
    NAVIGATION (flightplan re-routing)
        ROUTE INTERCEPT, DIRECT TO WAYPOINT
    TACTICAL (vectors)
        HEADING, ALTITUDE, SPEED

The strategic arrival clearance is used to deliver the aircraft to a metering fix on time and conflict free. The strategic arrival clearance is based upon an arrival routing (through to the metering fix) and profile (altitude and speeds over the arrival path). Tactical clearances are used primarily for immediate separation and for setting up strategic clearances. The navigational clearances are used to modify the flight plan routing (through to the metering fix), and generally precede a revised strategic arrival clearance.

The three clearance categories have a definite hierarchy of precedence; from top to bottom the precedence is: TACTICAL, NAVIGATION, STRATEGIC.

For example:

   **Navigation clearances cancel any previously issued strategic (arrival) clearance.** If the flightplan routing is modified after an arrival clearance has been issued, the arrival clearance (particularly the vertical profile) is invalid, and new arrival instructions must be issued by ATC.

   **Tactical clearances cancel any previously issued strategic (arrival) clearances.** If ATC issues a heading, altitude, or speed, any previously issued arrival clearance is invalid, and new arrival instructions must be issued.

   **Tactical clearances, involving heading, cancel any previously issued navigation and strategic (arrival) clearances.** If ATC issues a heading, any previous navigational clearance through to the metering fix is invalid, and new routing instructions must be issued by ATC.

## CLEARANCE DESCRIPTIONS

The clearances described below apply to all aircraft, conventional and 4D FMS equipped. Some exceptional cases are detailed for the 4D aircraft. Each clearance is outlined in terms of its definition, purpose, context, and use. The example phraseology represents the minimum information which must be communicated verbally, or via datalink, to complete each clearance.

Throughout this document, the call sign NASA515 will be used for examples involving 4D FMS equipped aircraft.

The most important (and complex) procedure is that associated with the STRATEGIC ARRIVAL CLEARANCE. One third of this document is devoted to its description. Mastery of the details of this clearance is essential to the effective use of both the airborne and ground-based systems.

# ARRIVAL CLEARANCE

Definition: An arrival clearance is based on a procedure which includes "published" metering fix crossing restrictions (e.g. cross SWEET at 11,000 MSL and 210 KIAS). In addition, ATC may issue additional restrictions and/or constraints with the arrival clearance. For example, "UNITED 123, cleared for the SWEET Arrival, begin descent 80 DME DEN, descend at Mach 0.80 / 280 KIAS." 4D FMS equipped aircraft may be issued a metering fix crossing time, e.g. "NASA 515, cleared for the SWEET Arrival, cross SWEET at 1523 (15 minutes, 23 seconds after the GMT hour)."

Purpose: The purpose of the arrival clearance is to deliver the aircraft to themetering fix on time and "conflict-free."

For all aircraft (conventional and 4D FMS equipped), CTAS will assist the controller in determining a "conflict-free" trajectory that will meet the CTAS scheduled arrival time. For 4D equipped aircraft, the arrival clearance follows a "profile negotiation process." This process involves a two-way exchange of information; the downlinking of a profile proposal by the pilot, and the uplinking of an arrival clearance with modifications to the proposal to make it "conflict-free." It is within this negotiation process that the pilot may use the FMS to optimize the arrival profile and then downlink a proposal to ATC for consideration. The uplinked arrival clearance from ATC then allows the pilot to use the FMS to track the cleared profile, given the ATC imposed constraints (published or issued).

Context: In general, the arrival clearance is issued by ATC prior to the top of descent. It is advantageous for a 4D FMS equipped aircraft to receive the

arrival constraints as early as possible. This allows the aircraft to plan the most efficient descent possible while giving ATC more time to consider the pilot's profile proposal and come up with a "conflict-free" strategic plan. However, the 4D "negotiation process" is on a "workload permitting" basis only. **At any time, ATC may discontinue 4D negotiation and issue an arrival clearance.**

Use: The arrival clearance may be issued any time after the aircraft's scheduled time of arrival (STA) has frozen. The clearance may also be amended at any time, however, the number of amendments should bekept to a minimum. The pilot should query ATC any time the clearance or situation is not clear.

Before the arrival clearance may be issued, the aircraft must be "established" on a path which eventually connects the aircraft's current position to the metering fix. This path may be defined by a combination of a DIRECT TO a WAYPOINT or vectors to ROUTE INTERCEPT, and Jet airways. For this simulation, the following will apply:

## 4D FMS Equipped Aircraft (NASA515)

### Datalink communications:

An arrival clearance must be preceded by a valid routingclearance to the metering fix. If it is necessary to issue a new routing clearance for an arrival, an arrival routing clearance message will automatically be sent as a part of the arrival clearance message sequence (i.e. transparent to the controller, CTAS datalink software will automatically send the appropriatearrival routing clearance whenever the controller sends an arrival clearance). In addition, the clearance will also specify the altitude and speed profile along the route.

### Voice communications:

A verbal arrival clearance must be preceded by a valid routing clearance to the metering fix. As with the datalink, the arrival clearance must also include all necessary altitude and speed information (e.g. cruise speed, top of descent, and descent speed profile).

### Pseudo Aircraft

The arrival clearance (also called a "DA" descent clearance) must also be preceded by a valid arrival routing clearance to the metering fix (via datalink or voice).

For both datalink and voice, the arrival clearance must also include all necessary altitude and speed information (e.g. cruise speed, top of descent, and descent speed profile).

## Arrival Clearance Cancellation

In the event of a cancellation of an arrival clearance, the following definitions apply:

If the aircraft has not begun the descent portion of the arrival clearance,

and

if ATC has not issued a new altitude assignment, *the aircraft's assigned altitude is the aircraft's current altitude*,

and

if ATC has not issued a new speed assignment, *the aircraft's assigned speed is the current cruise speed*;

or, if the aircraft has begun the descent portion of the arrival clearance,

and

if ATC has not issued a new altitude assignment, *the aircraft's assigned altitude is based on the previously issued arrival clearance altitude constraints (e.g. 11,000 at SWEET)*,

and

if ATC has not issued a new descent speed assignment, *the aircraft's assigned speed is the descent speed profile assigned in the previously issued arrival clearance*.

**Any Tactical or Navigation clearance cancels any previously issued arrival clearance.**

If an arrival clearance is cancelled, the aircraft must proceed according to its last assigned altitude and speed according to the definitions above. ATC must then re-issue arrival instructions, or in the event of lost communications, FAR Part 91.185 must be observed.

The following are examples of ATC clearances which cancel a previously issued arrival clearance (e.g. "United 123, cleared for the SWEET Arrival...").

**Aircraft still in cruise:**

1) "United 123, reduce speed to Mach 0.70 (250 KIAS) for spacing, expect new SWEET Arrival in five minutes;"

2) "United 123, fly heading 270 for spacing, vectors to SMITY, expect new SWEET Arrival in five minutes;"

3) "United 123, descend and maintain Flight Level 280, expect new SWEET Arrival in five minutes;"

**Aircraft already in descent:**

4) "United 123, turn right heading 260 for spacing, vectors to SMITY, descend and maintain FL210, reduce speed to 260 KIAS, expectnew SWEET Arrival in two minutes;"

5) "United 123, turn left heading 180 for spacing, vectors to KEANN, reduce speed to 250 KIAS, expect new SWEET Arrival in two minutes."

For each of the five cases, United 123 must maintain its last assigned altitude and speed until either the expect further clearance time (EFC) or until ATC issues a new arrival clearance, whichever comes first. In examples 1 and 2, the aircraft must maintain its current cruise altitude. In examples 3 and 4, the aircraft must descend and maintain a new assigned altitude, whereas in example 5, the aircraft must continue its descent to the altitude appropriate to the previously issued arrival clearance (11,000 at SWEET in this case).

Before the EFC time, ATC should come back with a new arrival:

"United 123, cleared for the SWEET Arrival, begin descent at 50 DME DEN, descend at 250 KIAS."

4D-equipped aircraft will be handled in the same way. However, for the purposes of this simulation, it is expected that the 4D aircraft will have the capability to monitor its progress along the arrival. In the case of an interrupted arrival descent procedure, the pilot of the 4D aircraft is expected to use that monitoring capability to get "back on time" in the event that ATC re-clears the aircraft for the same original metering fix crossing time.

### Arrival Clearance Restrictions/Constraints

The arrival clearance may be issued with additional restrictions and/or constraints in addition to the published ones (e.g. top of descent, speed profile, or 4D trajectory).

All ATC heading, speed, and altitude restrictions and/or constraints must be observed in an arrival clearance. However, if the pilot determines that the metering fix crossing restrictions cannot be met, the pilot must comply with all "current" ATC issued heading, speeds, and altitudes, and notify ATC, as soon as practical, which metering fix constraints cannot be met. ATC will then re-issue appropriate arrival instructions.

The pilot of the 4D aircraft will use the FMS to fly the arrival descent giving priority to the tracking of metering fix time first, altitude profile second, and descent speed profile third.

### ROUTE INTERCEPT CLEARANCE

Definition:   The ROUTE INTERCEPT clearance defines a route from the aircraft's current position to a clearance fix, via a Jet (or Victor) Airway. The aircraft must fly its assigned heading to intercept the route and then proceed along the route to the clearance fix. This clearance differs from the "DIRECT TO WAYPOINT" in two ways: it does not define the intercept point on the new route; and it does not involve an initial turn to intercept.

Purpose:   The ROUTE INTERCEPT clearance allows the controller to direct an aircraft onto a defined route (Jet Airway) using conventional navigation. It is one way to modify an aircraft's flight plan route prior to the issuance of an ARRIVAL clearance. This type of clearance is generally used for path stretching to delay an aircraft.

Context:   This clearance is used primarily for aircraft that are not RNAV equipped. However, a controller may wish to exercise this type of clearance with the more sophisticated aircraft to set up particular traffic flows where RNAV equipped aircraft are mixed with conventionally equipped aircraft.

Use:   The ROUTE INTERCEPT clearance may be issued anytime after the aircraft's scheduled arrival time has been frozen. The clearance generally follows the issuance of a vector heading to set up the

intercept, and should only be issued if the aircraft will be able to readily accomplish the interception.

This clearance will cancel a previously issued ARRIVAL. However, it is likely that a vector would have preceded this type of clearance, and the vector would have cancelled the ARRIVAL. If an ARRIVAL clearance is cancelled, the aircraft must maintain its last assigned altitude and speed.

For example, if an aircraft were established on J-114 (magnetic course 226), and the controller planned to take the aircraft off route to intercept

J-157 (magnetic course 180) for the SWEET ARRIVAL, the controller would issue:

"United 123, turn right heading 260 for sequencing, vectors to J-157,"

followed later by

"United 123, maintain present heading, intercept J157, cleared for the SWEET ARRIVAL ..."

### DIRECT TO WAYPOINT CLEARANCE

Definition:   The DIRECT TO WAYPOINT (or WAYPOINT CAPTURE) clearance defines a route from the aircraft's current position to a waypoint. The waypoint to be captured is not necessarily on a published route. The aircraft must turn to a heading for waypoint interception, and then proceed direct to the waypoint. This clearance differs from the "ROUTE INTERCEPT" in two ways: it defines a specific capture waypoint; and it involves an aircraft initiated turn to intercept the waypoint.

Purpose:   The DIRECT TO WAYPOINT clearance allows the controller to create a direct path from the aircraft's present position to a waypoint. It is one way to modify an aircraft's flight plan route prior to the issuance of an ARRIVAL clearance. This is the most precise procedure for stretching or shortening an aircraft's path; and it may also be helpful in resolving a potential conflict between a pair of aircraft while trying to meet the scheduled arrival times.

Context:    For the majority of cases, this clearance is used once an aircraft is off of a route (Jet or Victor Airway) and is being cleared back onto a route.

Use:    The DIRECT TO WAYPOINT clearance may be issued anytime after the aircraft's scheduled arrival time has been frozen. This clearance should not be issued unless the aircraft can readily accomplish the capture. If the direction of turn is in question, the controller should issue a turn to a heading and then follow up with the DIRECT TO WAYPOINT when the aircraft has clearly established itself in the desired direction.

This clearance will cancel a previously issued ARRIVAL. However, it is likely that a vector would have preceded this type of clearance, and the vector would have cancelled the ARRIVAL. If an ARRIVAL clearance is cancelled, the aircraft must maintain its last assigned altitude and speed.

For example, if an aircraft were on a magnetic course of 260 which would bring the aircraft North of SMITY intersection (the desired capture waypoint, on a relative magnetic bearing of 190 from the aircraft), and the controller planned to bring the aircraft through SMITY and then on for the SWEET ARRIVAL, the controller would issue:

"United 123, proceed direct SMITY, cleared for the SWEET ARRIVAL..."

or

"United 123, turn left heading 190, when able, proceed direct SMITY, cleared for the SWEET ARRIVAL..."

# HEADING ASSIGNMENT

Definition:    The HEADING ASSIGNMENT is a VECTOR heading.

Purpose:    Vectors are used to change the aircraft's current course to either avoid a potential conflict or to delay the aircraft more than that possible with speed control only.

Context:    In general, this clearance may be issued at any time. It is to the aircraft's advantage to minimize pathdistance to touchdown. It is advantageous

to the 4D aircraft to establish its arrival path as early as possible to plan the most efficient descent.

Use:    Vectors should only be issued after an aircraft's scheduled arrival time has been frozen, or if the aircraft has an immediate potential for a conflict.

Vectors cancel any previously issued strategic (arrival) or navigation (routing) clearances. Following a vector, a new routing clearance must be issued before an arrival clearance may be issued. However, a routing clearance does not necessarily cancel a previously issued vector (i.e. ROUTE INTERCEPTS maintain the vector heading until the route is intercepted; DIRECT TO WAYPOINTS change the heading from that assigned to that needed by the aircraft to follow a path directly to the specified waypoint). For example, if an aircraft has been cleared for the SWEET ARRIVAL along J-114 (magnetic course 226 degrees) and it receives:

"United 123, turn right heading 270 for separation, vectors to SMITY, expect new SWEET ARRIVAL in five minutes," then United 123 must fly the heading (its route/arrival clearance cancelled). If the aircraft had begun the arrival descent, it must continue descending to the last assigned altitude (although ATC should have assigned a new altitude); if the aircraft was still in cruise, then it must maintain its current cruise altitude.

Following the vector to 260, if ATC issues a ROUTE INTERCEPT to a route ahead, the aircraft must maintain a heading of 260 until intercepting the cleared Jet Route; if ATC issues a DIRECT TO SMITY intersection, the aircraft must immediately turn to a heading for an intercept course to SMITY. Following either navigational clearance, the aircraft can then be issued an ARRIVAL clearance.

# ALTITUDE ASSIGNMENT

Definition:    The ALTITUDE ASSIGNMENT constrains the aircraft to immediately climb/descend to and maintain the assigned altitude.

Purpose:    The ALTITUDE ASSIGNMENT is used to change the aircraft's current altitude to either avoid a potential conflict or to delay the aircraft more than that possible with speed control only.

Context: In general, this clearance may be issued at any time. It is to the aircraft's advantage to stay at cruising altitude as long as possible without over-shooting any crossing restrictions. It is advantageous to the 4D aircraft to establish its final cruising altitude as early as possible to plan the most efficient descent. An ALTITUDE clearance may be beneficial to a 4D aircraft if it is helpful in clearing the 4D aircraft's path of potential conflicts thus allowing the 4D aircraft the maximum flex-ibility in planning its descent.

Use: ALTITUDE ASSIGNMENTS should only be issued after an aircraft's scheduled arrival time has been frozen, or if the aircraft has an immediate potential for a conflict. ALTITUDE ASSIGN-MENTS cancel any previously issued arrival clear-ance. However, an arrival clearance does not cancel a previously issued altitude assignment. For example, if an aircraft in cruise (e.g. level at FL350) receives:

"United 123, descend and maintain FL310 for separation,"

followed by

"United 123, cleared for the SWEET ARRIVAL, begin descent at 80 DME DEN, descend at Mach 0.80 / 280 KIAS."

United 123 must immediately begin a descent from FL350 to FL310, and then at 80 DME DEN, initiate a descent as specified for the SWEET ARRIVAL. However, if the ARRIVAL CLEARANCE was issued first, followed by the ALTITUDE ASSIGN-MENT, the result would be totally different. At first, United 123 would just maintain FL350, and plan to begin a descent at 80 DME DEN. Then, after the ALTITUDE ASSIGNMENT was issued, United 123 would immediately descend to and maintain FL310. At this point, the ARRIVAL is cancelled, and ATC would have to issue a new ARRIVAL clearance.

If the aircraft began the arrival descent and then received the altitude assignment, the ARRIVAL is cancelled, and the aircraft must continue its descent to the assigned assigned.

## SPEED ASSIGNMENT

Definition: The SPEED ASSIGNMENT clearance con-strains the pilot to fly an ATC specified cruise or descent speed until otherwise advised by ATC.

Purpose: SPEED ASSIGNMENT clearances are gen-erally used for two purposes: meeting scheduled arrival times; and resolving potential conflicts. While in cruise, far from top of descent (e.g. 50 to 100 n.mi.), cruise speed can be an effective control in delaying an aircraft to meet a scheduled time. Cruise speed control can also be balanced with descent speed control to resolve potential conflicts between aircraft pairs in sequence. Once in descent, speed control may be used to adjust an arrival if the aircraft becomes significantly early or late, or if a potential conflict develops.

Context: In general, this clearance may be issued at any time. As part of the 4D profile negotiation pro-cess, ATC may use a SPEED ASSIGNMENT to constrain the 4D aircraft to follow the controller's traffic plan.

Use: SPEED ASSIGNMENTS should only be issued after an aircraft's scheduled arrival time has been frozen, or if the aircraft has an immediate potential for a conflict. SPEED ASSIGNMENTS cancel any previously issued arrival clearance. However, an arrival clearance, even with descent speed con-strained, does not cancel a previously issued cruise speed assignment. For example, if an aircraft in cruise (e.g. level at FL350 at Mach 0.80/271 KIAS) receives:

"United 123, reduce speed to 260 KIAS for sequencing,"

followed by

"United 123, cleared for the SWEET ARRIVAL, begin descent at 90 DME DEN, descend at 250 KIAS."

United 123 must immediately slow to 260 KIAS at FL350, and then at 90 DME DEN, decelerate to

250 KIAS and descend according to the SWEET
ARRIVAL. However, if the ARRIVAL CLEAR-
ANCE was issued first, followed by the SPEED
ASSIGNMENT, the result would be totally differ-
ent. At first, United 123 would just maintain its
cruise at Mach 0.80 at FL350, and plan to begin a
descent (and slow to 250 KIAS) at 90 DME DEN.
Then, after the SPEED ASSIGNMENT was issued,
United 123 would immediately decelerate to
260 KIAS, and would continue level at FL350 until
ATC issued a new descent or arrival clearance.

If the aircraft began the arrival descent and then
received the speed, the ARRIVAL is cancelled, but the
aircraft must continue its descent to the last assigned alti-
tude at the assigned speed.

## REFERENCES

1. Erzberger, Heinz; and Tobias, Leonard: A Time-
   Based Concept for Terminal-Area Traffic
   Management. NASA TM-88243,1986.

2. Williams, David H.; and Green, Steven M.: Piloted
   Simulation of an Air-Ground Profile Negotiation
   Process in a Time-Based Air Traffic Control
   Environment. NASA TM-107748, 1993.

3. den Braven, Wim: Design and Evaluation of an
   Advanced Air-Ground Data-Link System for Air
   Traffic Control. NASA TM-103899, 1992.

4. Tobias, Leonard; Volckers, Uwe; and Erzberger,
   Heinz: Controller Evaluations of the Descent
   Advisor Automation Aid. NASA TM-102197,
   1989.

5. Erzberger, Heinz; and Nedell, William: Design of an
   Automated System for Management of Arrival
   Traffic. NASA TM-102201, 1989.

6. Davis, Thomas J.; Erzberger, Heinz; and Green,
   Steven M.: Simulator Evaluation of the Final
   Approach Spacing Tool. NASA TM-102807,
   1990.

7. Green, Steven M.; Davis, Thomas J.; and Erzberger,
   Heinz: A Piloted Simulator Evaluation of a
   Ground-Based 4D Descent Advisor Algorithm.
   Proceedings of the 1987 AIAA Conference on
   Guidance, Navigation, and Control, Monterey,
   CA, Aug. 1987, pp. 1173–1180.

8. Davis, Thomas J.; and Green, Steven M.: Piloted
   Simulation of a Ground-Based Time-Control
   Concept for Air Traffic Control. AIAA
   Paper 89-3625, Aug. 1989.

9. Williams, David H.; and Knox, Charles E.: 4D
   Descent Trajectory Generation Techniques
   Under Realistic Operating Conditions. Aircraft
   Trajectories, Computations—Predictions—
   Control, Volume 2—Air Traffic Handling and
   Ground-Based Guidance of Aircraft, AGARD-
   AG-301, Vol. 2, May 1990, pp. 25-1–25-22.

10. Vicroy, Dan D.: Guidance Concepts for Time-Based
    Flight Operations. Aircraft Trajectories,
    Computations—Predictions—Control,
    Volume 2—Air Traffic Handling and Ground-
    Based Guidance of Aircraft, AGARD-AG-301,
    Vol. 2, May 1990, pp. 24-1–24-12.

11. Kaminer, I.; and O'Shaughnessy, P. R.: 4D-TECS
    Integration for NASA TSRV Airplane. NASA
    CR-4231, 1989.

12. Williams, David H.; and Green, Steven M.: Airborne
    Four-Dimensional Flight Management in a
    Time-Based Air Traffic Control Environment.
    NASA TM-4249, 1991.

13. Green, Steven M.: Time-Based Operations in an
    Advanced ATC Environment. Proceedings of
    the Aviation Safety/Automation Program
    Conference, October 1989, Virginia Beach, VA.
    NASA CP-3090, pp. 249–260.

14. Davis, Thomas J.; Erzberger, Heinz; and Bergeron,
    Hugh: Design of a Final Approach Spacing Tool
    for TRACON Air Traffic Control. NASA
    TM-102229, 1989.

15. Sylla, Babacar: Trajectory Negotiation Process User
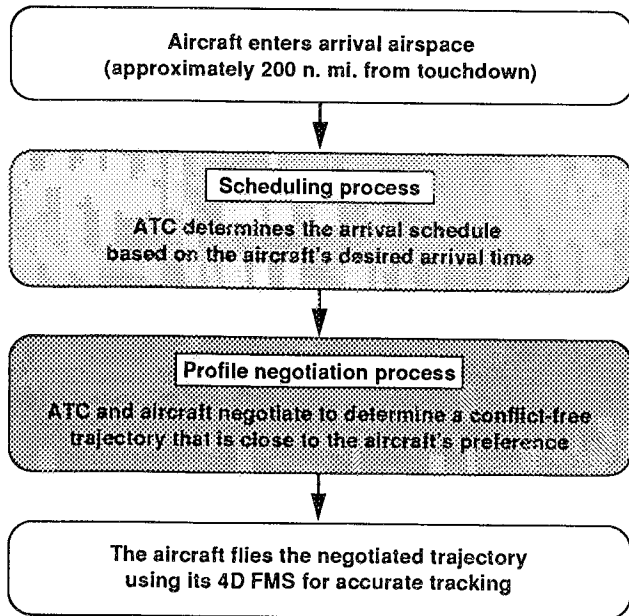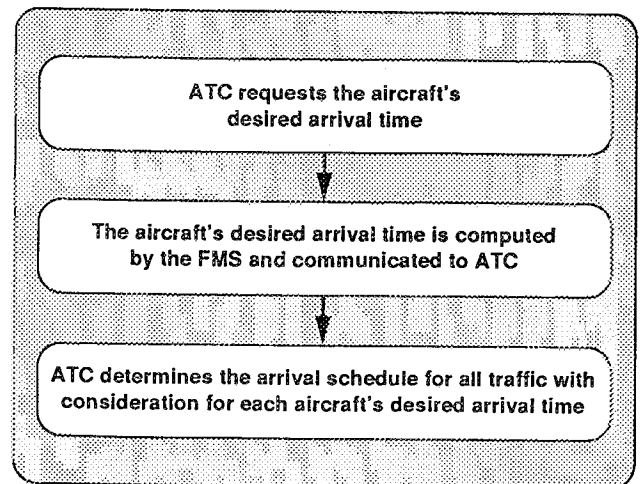    Requirements Document. CENA/R91-31, Oct.
    1991.

Aircraft enters arrival airspace
(approximately 200 n. mi. from touchdown)

Scheduling process

ATC determines the arrival schedule
based on the aircraft's desired arrival time

Profile negotiation process

ATC and aircraft negotiate to determine a conflict-free
trajectory that is close to the aircraft's preference

The aircraft flies the negotiated trajectory
using its 4D FMS for accurate tracking

Figure 1. Air/ground 4D interaction.

ATC requests the aircraft's
desired arrival time

The aircraft's desired arrival time is computed
by the FMS and communicated to ATC

ATC determines the arrival schedule for all traffic with
consideration for each aircraft's desired arrival time

Figure 2. Scheduling process.

ATC uplinks
profile request

Airborne side

Aircraft uses FMS
to track the profile

Aircraft computes and
downlinks vertical
profile proposal

Aircraft adjusts to
meet constraints

ATC issues arrival
clearance based on
aircraft-preferred
vertical profile

Conflict
predicted

No

Yes

ATC issues arrival
clearance based on
ground-computed
vertical profile

Far from top
of descent

No

Yes

ATC issues tactical
clearance based on
strategic conflict
resolution

Figure 3. Profile negotiation process.

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| Initial cruise conditions | | | | | | MF arrival times Reference (00:00:00) | |
|---|---|---|---|---|---|---|---|
| Aircraft | Type | Alt | Mach | Ground speed (knots) | Flying distance to MF (n. mi.) | Desired | Scheduled (Delay (min)) |
| LEAD | B727 | FL330 | 0.80 | 465 | 207 | 00:28:29 | 00:30:29 (2:00) |
| 4D | B737 | FL310 | 0.72 | 423 | 195 | 00:29:00 | 00:32:00 (3:00) |
| TRAIL | B727 | FL350 | 0.76 | 438 | 200 | 00:30:25 | 00:33:25 (3:00) |



Inset: conflict predicted at 00:21:13 based on the original vertical profile for LEAD and the profile proposal for 4D.

5 n. mi. range ring

0          50

Scale, n. mi.

Metering Fix (MF): 14 n. mi. from Denver (cross at 11,000 ft, 210 knots indicated airspeed)

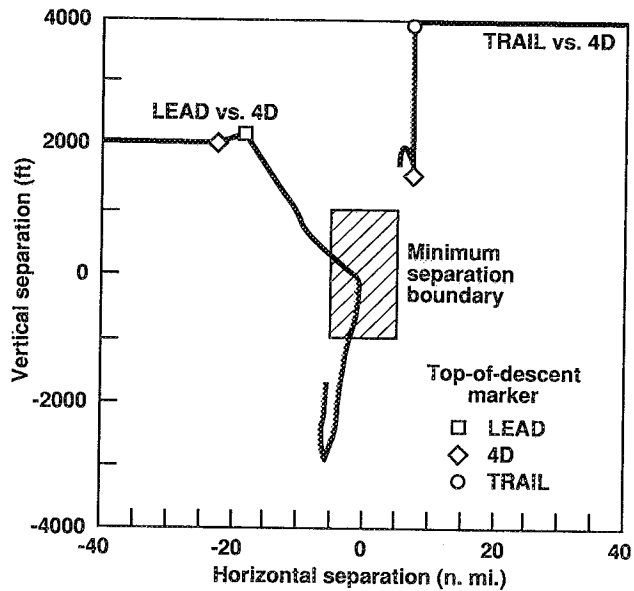| Original vertical profiles (conflict predicted) | | | | |
|---|---|---|---|---|
| Aircraft | Speed profiles (knots) | | | Top-of-descent marker (descent distance to metering fix, n. mi.) |
| | Cruise | | Descent | |
| | Indicated | Ground | Indicated | |
| LEAD | 250 | 413 | 280 | □ (66) |
| 4D (proposal) | 250 | 400 | 230 | ◇ (63) |
| TRAIL | 250 | 427 | 230 | ○ (77) |
| Controller-issued profiles (conflict free) | | | | |
| LEAD | 265 | 436 | 265 | ▨ (69) |
| 4D | 240 | 384 | 240 | ◈ (62) |
| TRAIL | 250 | 427 | 240 | ◎ (78) |

Figure 4. Example arrival scenario.

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(a) Predicted loss of separation based on original
vertical profiles (including 4D proposal)
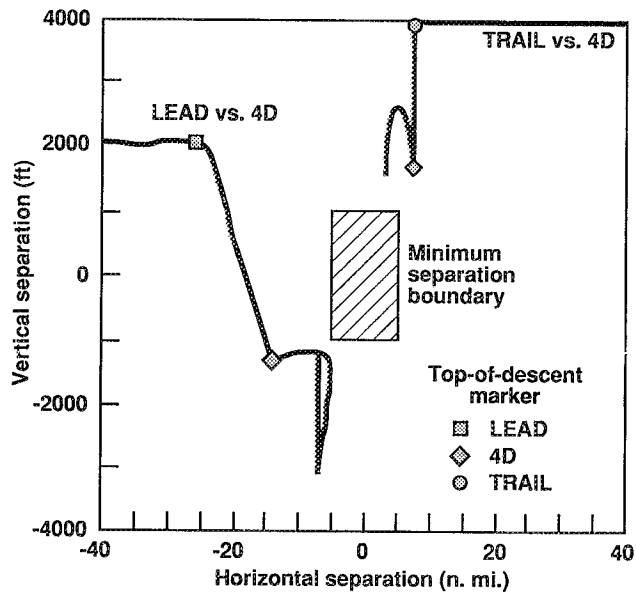


(b) Resulting separation based on profiles actually
flown in simulation

Figure 5. Separation of the LEAD and TRAIL aircraft from the 4D aircraft for the example illustrated in figure 4.

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**13. ABSTRACT (Maximum 200 words)**

This report describes the development and evaluation of the profile negotiation process (PNP), an interactive process between an aircraft and air traffic control (ATC) that integrates airborne and ground-based automation capabilities to determine conflict-free trajectories that are as close to an aircraft's preference as possible. The PNP was evaluated in a real-time simulation experiment conducted jointly by NASA's Ames and Langley Research Centers. The Ames Center/TRACON Automation System (CTAS) was used to support the ATC environment, and the Langley Transport Systems Research Vehicle (TSRV) piloted cab was used to simulate a 4D Flight Management System (FMS) capable aircraft. Both systems were connected in real time by way of voice and data lines; digital datalink communications capability was developed and evaluated as a means of supporting the air/ground exchange of trajectory data. The controllers were able to consistently and effectively negotiate nominally conflict-free vertical profiles with the 4D-equipped aircraft. The actual profiles flown were substantially closer to the aircraft's preference than would have been possible without the PNP. However, there was a strong consensus among the pilots and controllers that the level of automation of the PNP should be increased to make the process more trans-parent. The experiment demonstrated the importance of an aircraft's ability to accurately execute a negotiated profile as well as the need for digital datalink to support advanced air/ground data communications. The concept of trajectory space is proposed as a comprehensive approach for coupling the processes of trajectory planning and tracking to allow maximum pilot discretion in meeting ATC constraints.

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