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Piloted Simulation of an Air-Ground Profile Negotiation Process in a Time-Based Air Traffic Control Environment

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Summary

Historically, 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. A joint program, between NASA's Ames Research Center (Ames) and Langley Research Center (Langley), is underway to investigate the issues of, and develop systems for, the integration of ATC and airborne automation systems. A simulation study was conducted to evaluate a profile negotiation process (PNP) between a time-based air traffic control (ATC) system and an aircraft equipped with a four-dimensional flight management system (4D FMS). Prototype procedures were developed to support the functional implementation of this process. The PNP was designed to provide an arrival trajectory solution which satisfies the separation requirements of ATC while remaining as close as possible to the aircraft's preferred trajectory.

The Langley Transport Systems Research Vehicle (TSRV) cockpit simulator was linked in real-time to the Ames Center/Tracon Automation System (CTAS) for the experiment. Approximately 30 hours of simulation testing were conducted over a three week period. Three crews of active airline pilots (each 2 pilot crew from a different major airline) participated as test subjects at Langley and three teams of active Center controllers (2 each) participated at Ames.

Results from the experiment indicate the potential for successful incorporation of aircraft preferred arrival trajectories in the CTAS automation environment. Fuel savings on the order of 2 percent to 8 percent, compared to fuel required for the baseline CTAS arrival speed strategy, were achieved in the test scenarios. The data link procedures and clearances developed for this experiment, while providing the necessary functionality, were found to be operationally unacceptable to the pilots. In particular, additional pilot control and understanding of the proposed aircraft-preferred trajectory, and a simplified clearance procedure were cited as necessary for operational implementation of the concept.

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 (4D) planning capability which enables the aircraft to meet prescribed arrival times. Comparatively, ATC has the objective of providing a safe, orderly, and expeditious flow of traffic; the critical factor being the maintenance of separation between aircraft. Unfortunately, the objectives of individual aircraft flight path optimization and traffic separation are often contrary in today's airspace system. Furthermore, controllers have no direct tools to predict separation more than a few minutes ahead, let alone tools to assist in setting up nominally conflict-free descent trajectories. When arriving at high density terminal areas, air crews 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.

A joint program, between NASA's Ames Research Center (Ames) and Langley Research Center (Langley), is underway 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 has the ability to accurately predict aircraft trajectories and determine effective advisories to assist the controller in managing traffic. Langley has been conducting and sponsoring research on flight operations of advanced transport aircraft for a number of years. During the course of 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 current experiment is a follow-on to an initial study conducted in 1989 (reference 1). In that experiment, procedures for conducting 4D enroute ATC operations involving 4D FMS aircraft were developed and evaluated. Results of that study indicated favorable interaction could be achieved between the airborne and ground-based 4D systems with potentially significant payoffs in terms of increased capacity and efficiency of terminal-area arrival operations. Potential problems involving dissimilar speed strategies and lengthy clearances were also uncovered. The primary purpose of this study is to apply digital data link technology to relieve the problems encountered in the previous experiment and to further explore situations where airborne 4D FMS could enhance terminal area arrival operations in a time-based ATC system. In particular, a profile negotiation process (PNP), which combines the

features of airborne and ground-based automation to determine conflict-free trajectories that are as close to an aircraft's preference as possible, is developed and tested.

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 which is as close to the aircraft's preference as possible. A valid trajectory is one which 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 formed, to meet unexpected conditions. However, the better the strategic planning, and the better the plan can be executed (through accurate trajectory tracking by aircraft), the greater the likelihood that a negotiated trajectory may be followed without significant interruption. A detailed description of the Profile Negotiation Process is contained in reference 2. The following paragraphs present a brief overview of the process as implemented for this experiment.

The profile negotiation process is illustrated in Figure 1. 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 degree of freedom each profile request will allow the pilot for generating a profile proposal. In the case of a delay requiring path stretching, 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, used today, for the issuance and acceptance of ATC clearances: the pilot may negotiate with the controller to modify unacceptable constraints as required.

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. In considering the pilot's proposal, the controller uses the ATC automation to probe for potential conflicts with other aircraft all the way to the metering fix. If there are no conflicts 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 for the controller is to issue the entire 4D solution as an arrival clearance for the aircraft to execute. 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 PNP is performed by the controller on a workload permitting basis only. 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 which 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.

Research System

This study was conducted by using a piloted cockpit simulation in conjunction with an air traffic control simulation. The research system was designed to provide a realistic environment for pilot and controller interaction with 4D automation aids. A block diagram of the research system is shown in figure 2. The cockpit simulator at NASA Langley Research Center was connected via voice and data links to the ATC automation laboratory at NASA Ames Research Center. The data link provided two-way transmission of digital messages between the TSRV simulator and the Ames controller workstations. A voice link between the Langley Transport System Research Vehicle (TSRV) cockpit and the Ames controller stations permitted ATC voice communication. A second voice link between Langley and Ames research personnel was provided for coordination of the two simulations. This research system is the same as was used in the reference 1 experiment with the addition of the two-way data link communications.

Cockpit Simulator

The cockpit simulator utilized for this study was the fixed-base replica of the research cockpit in the NASA Transport Systems Research Vehicle airplane (ref. 3). This simulation included six-degree-of-freedom equations of motion with nonlinear mathematical models of the B-737-100 airplane aerodynamics and engine performance. The processing of the equations was performed in a Control Data Corporation (CDC) CYBER 175 digital computer at a 32-Hz iteration rate. Standard day atmospheric effects were included in the simulation with no winds.

The configuration of the TSRV cockpit simulator is shown in figure 3. Electronic primary and navigation displays were provided each pilot in an over-and-under arrangement. A control display unit (CDU) was located in front of the pilot just below the navigation display. Two center-mounted electronic displays provided data link and engine information. Manual flight control was handled by a two-axis sidestick located to the left of the pilots seat. A mode control panel on the center glare shield was used for selection of auto pilot control modes.

Air Traffic Control Simulation

The ATC simulation is comprised of both the ATC automation aids (controller stations) and the air traffic simulation. The communications manager, center block of figure 2, is the software connection between the ATC controller stations and the various sources of air traffic (simulated radar) data including the TSRV piloted cab and the Ames air traffic simulation. Sun Microsystems Inc. workstations were used for each controller and pseudo pilot station. A description of the air traffic simulation and pseudo pilot system may be found in reference 4.

The configuration of the controller stations is flexible and may include any combination and number of Air Route Traffic Control Center (ARTCC) or Terminal Radar Approach Control (TRACON) sectors. This experiment concentrated on ARTCC arrival operations with the primary ATC automation aid being the Descent Advisor (DA) along with its associated plan-view display and graphical interface (figure 4). The Traffic Management Advisor (TMA) was used in a secondary role to assist in the creation and control of the traffic scenarios. A detailed description of these automation aids may be found in reference 5. Modifications and additions to the controller interface incorporated to handle the data link message exchange are described in reference 6.

Experiment Design

Flight Management System

The TSRV simulator was equipped with a 4D navigation and guidance system during the mid 1970's in support of the Terminal Configured Vehicle (TCV) program (ref. 3). A schematic diagram of this system is shown in figure 5. The elements of this system consist of (1) central flight management computer, (2) airplane system inputs of air data, inertial reference and engine sensor parameters, (3) digital flight control computers, and (4) pilot interface consisting of electronic flight displays, mode control selection panel, and control display unit (CDU).

This baseline system was expanded for the simulation study of reference 1 to incorporate performance management features necessary for computation of vertical trajectories and generation of complete flight plans. For this study, the TSRV flight management system was further modified to accommodate the path generation capabilities needed for the profile negotiation process. The significant capabilities of the flight management are described in the following sections. Additional details of the profile generation algorithms may be found in reference 1.

Flight plan definition. Flight plans are entered into the flight management system using the one of the control display units located in front of each pilot. As shown in figure 6, each CDU consisted of a CRT display area with line select keys along the sides of the display, function and mode select keys below, and a complete alphanumeric keypad. Entry of a flight plan could be accomplished by entering a pre-stored company route or individually specifying jet routes and waypoints. Altitudes and speeds at each waypoint were not required as inputs to the flight plan. Departure and arrival waypoints had pre-specified speed and altitude constraints as part of the navigation data base. Enroute waypoints would have the crossing speeds, altitudes, and times computed by the vertical profile generation program based on a selected cruise altitude and cost index. Constraint values of speed and altitude could be entered at any waypoint to override the computed values and force a re-computation of the vertical profile using the constraint values. A complete or partial flight plan could also be loaded into the flight management system using the data link system.

The FMC in the TSRV simulator accomodated a single active flight plan or route. Entry of a new flight plan, or modifications to the active one, were handled in a separate buffer referred to as the provisional route.

Whenever a provisional route was present, the indication of MOD appeared at the top of the RTE and LEGS pages on the CDU and the EXECUTE button was lighted. Pressing the EXECUTE button would transfer the provisional route to the active route.

Required time of arrival. The first arrival waypoint in the flight plan could be assigned a required time of arrival or RTA. This was done either manually by the pilot entering the time as a constraint in the CDU or automatically via data link. In either case, the vertical profile generation algorithm would attempt to compute a vertical profile which would satisfy the arrival time requirement. Once an RTA had been selected, status information involving projected time of arrival error and maximum and minimum arrival times was presented on the PROGRESS page of the CDU (fig. 7). This information was the same as presented on the vertical situation display (VSD) used in the reference 1 experiment.

Two methods of computing an RTA-constrained vertical profile were available in the FMC. The default method was to iterate on cost index (CI) until a vertical profile was found which achieved the RTA. This method, as described in reference 1, would achieve the RTA with minimum fuel usage. The second method was to freeze cruise Mach number and iterate on descent calibrated airspeed until the RTA was satisfied. This method, similar to the descent bias mode of the CTAS Descent Advisor, was added as a result of the reference 1 experiment. That study indicated the need for cruise speed constraint to prevent traffic conflicts in the CTAS ATC environment. The pilot could select the RTA calculation mode using the PERF INIT page of the CDU, as illustrated in figure 8. CI MODE referred to the default cost index iteration and CRZ MODE referred to the fixed cruise speed with descent speed iteration. Procedures for selecting the RTA calculation mode are described in the *Airborne Procedures* section of this report.

Automatic path stretching. The vertical profile generation algorithm would attempt to compute a vertical profile satisfying the RTA without changing the horizontal route. Should the RTA be outside the time capability of the airplane, the vertical profile closest to the RTA (maximum speed or minimum speed) would be computed. When the RTA was later than the time possible using the minimum speed profile, a special path-stretching algorithm was utilized to increase the horizontal range by the amount required to achieve the RTA while flying near minimum speed.

The algorithm was designed as a result of the reference 1 experiment in which ATC controller path

stretching techniques were observed. When moderate time delays were necessary (less than 8 minutes for the test scenarios in reference 1), the controllers would send the aircraft on a heading to the side of the intended route in order to increase the flight distance and absorb the time delay without resorting to a holding pattern. The CTAS automation would provide guidance as to where the aircraft should be turned back to achieve the desired metering fix crossing time. The airborne implementation of this technique provided the flight crew with the ability to request a path stretch which was consistent with CTAS automation and would be minimum fuel for their airplane. The path stretching of the FMC generated path was automatic and enabled whenever the aircraft was flying on a heading which was more than 15 degrees and less than 90 degrees different than the heading of the programmed horizontal path. A path stretch waypoint would be automatically inserted along the current aircraft ground track with a turn back to the next waypoint on the path. The location of the path stretch waypoint was determined by the amount of distance needed at minimum fuel airspeed to absorb the time delay. The turn from the path stretch waypoint back to the next programmed waypoint was limited to a maximum of 100 degrees.

Airborne Data Link System

The data link system developed for the experiment in reference 7 was modified for use in this experiment. This system was designed for use as primary communication between the air and the ground for purposes of ATC, weather and company message exchanges. Only the ATC communication functions of the system were employed in the current experiment, with minor additions to accommodate the profile negotiation process. The following sections provide a brief overview of the data link system, a complete description of the system may be found in reference 7.

Display format. The pilot interface with the data link system was through a dedicated center panel display. The display format consisted of small, medium and large overlapping windows, arranged as shown in figure 9. The windows were drawn on three layers, with the large window on the bottom, medium overlaying the large, and small window on top. The large window was always on the display and provided menu selection options. The medium window was displayed when menu items were selected which allowed the pilot to compose information to be data linked to the ground or to view stored information. The small window was used to view messages uplinked from the ground. Each window had

touch sensitive areas which were used for pilot interaction and control of the display.

ATC messages. Communication with ATC consisted of pilot-initiated air-to-ground messages and controller-initiated ground-to-air messages. Appendix A provides a complete description of the data link message format and all ATC-related data link messages available in this experiment. Details of the CTAS formats for the data link messages may be found in reference 6.

The pilot could compose and send a message to ATC using the ATC request menu, selectable from the MAIN MENU (fig. 10). This was a medium-size window with ATC-specific options for downlink information (fig. 11). The ATC request menu functioned the same as in reference 7, however, the PROFILE button was activated for this study to accommodate the aircraft-preferred profile downlink to ATC. Selecting PROFILE from the ATC request menu brought up another medium-size window with the vertical profile information to be sent to ATC (fig. 12). This information was extracted from the provisional path in the FMC. The pilot could then SEND the message or CANCEL and return to the previous ATC request menu. Procedures for using this function are discussed in the *Airborne Procedures* section of this report.

ATC messages uplinked from the ground were handled using the time-critical small window. The message is displayed automatically when received, and an electronic digitized voice reads the message to the flight crew. The flight crew must respond to the message before any other message can be viewed or display page selected. An example of a time-critical ATC message is shown in figure 13. The pilots have the option of ROGER, ROGER/ENTER, or UNABLE as a response to the message. ROGER sends an affirmative acknowledgment to ATC, ROGER/ENTER sends the same acknowledgment to ATC and also automatically enters the appropriate information (heading of 270 degrees in figure 13) into the mode control panel and/or FMC, and UNABLE sends a negative response to ATC.

A summary of all messages received or sent by the data link system was stored and available for review at any time using the VIEW MESSAGES selection from the main menu. This page (fig. 14) listed the messages in time sequence, and included the type of response selected by the crew -- ROGER, ROGER/ENTER, or UNABLE. The message list could be scrolled up or down by touching the scroll buttons.

The current ATC clearance and assignments were available for review on the VIEW CLEARANCE page, which was selectable from the main menu. This page (fig. 15) showed the last clearance received from ATC at the top, and specific altitude, heading, speed, metering fix arrival time, and voice frequency assignments below. The addition to this menu for the current experiment was the metering fix arrival time with a real-time indication of arrival time error, shown as <ON TIME>, <EARLY XX>, or <LATE XX>, where XX is the number of seconds of time error. The clearance was also expanded to include the arrival clearance and vertical profile clearance, which are described in *Airborne Procedures* section of this report.

Flight Displays

The display system of the TSRV simulator consisted of a primary flight display (PFD), a navigation display (ND), an engine display, and the data link display. The arrangement of these displays is shown in figure 16. The flight displays were developed for use with the velocity-vector control-wheel steering mode (VCWS) of the simulator. References 8 and 9 describe the design and development history of the VCWS and primary flight display.

Primary flight display. The primary flight display for this experiment was a modified version of the display developed for the experiment of reference 7. The format of the display as used in this experiment is shown in figure 17. The significant modifications to the reference 7 display were the addition of flight director bars in the center of the display and the 4D energy bug on the left side next to the airspeed read out. The flight director provided guidance to follow the reference lateral and vertical path programmed in the FMC. The 4D energy bug was implemented the same as in the reference 1 experiment.

Navigation display. The track-up oriented moving map display used in the reference 1 experiment was again used as the navigation display for this experiment (fig. 18). A significant feature of this display was the graphical depiction of the active and provisional routes programmed into the FMC. The active route provided guidance and situation information for the pilots, while the provisional route was used extensively for review of proposed routing from ATC clearances, profile requests, or pilot-initiated route modifications. A time-box was also provided on the active route indicating the desired position of the airplane for tracking the 4D trajectory.

Air Traffic Scenario

The airspace used for this study was based on the Denver Air Route Traffic Control Center (ARTCC) northeast arrival sectors. Figure 19 illustrates the major arrival routes. All arrival traffic in this sector was

merged and controlled to cross the metering fix at a specified time. The arrival schedule was determined during the simulation, in real time, by the TMA. The sequence was based upon a first come first served (FCFS) rule applied at a constant time horizon from the airport.

Although the simulated air traffic entered the airspace at a variety of altitudes and speeds, the TSRV was initialized on the same route, and at the same altitude and speed for each flight. The initial conditions for the 4D equipped aircraft were handled in this way to facilitate the controlled insertion of the aircraft into a particular traffic scenario. Each TSRV flight was injected into an arrival "rush" with an average traffic load of 32 aircraft per hour (80% of single active runway capacity).

The most important characteristic of the traffic flow, for this experiment, is the delay. Delay is defined here as the difference between the aircraft's original estimated time of arrival (octa) and scheduled time of arrival (sta). Two levels of delay were studied: small, and moderate. Small delay is defined to be a delay which is absorbable with speed reduction alone, whereas moderate delay requires path stretching (off-route vectoring or holding) in addition to any speed or altitude changes. For the conditions of this experiment, the small delay was chosen to be three minutes and the moderate delay was chosen to be eight. The maximum delay absorbable with speed control alone, for the TSRV's test conditions, was approximately six minutes.

The FCFS rule allows for the control of delay during a real time simulation, even though the traffic flow in an ATC environment is chaotic. This allows for the generation of traffic lists (initial conditions) which appear random to the controller subjects yet maintains the significant test conditions. From the pilot's perspective however, the only known characteristic of the surrounding traffic was the delay which the pilot could determine from his clearance. Although the traffic was designed to result in the same delay for each TSRV flight (small or moderate), the time at which the ATC clearance (delay) was transmitted to the aircraft varied depending on the controller's response to the traffic situation. The random time of delivery of ATC clearances resulted in variations in the 4D trajectory solutions (speed profiles and path stretching) for the same delay.

Airborne Procedures

Prototype ATC clearances, and procedures for their use, were developed to handle the profile negotiation process developed for this experiment. The pilots and controllers who participated in the study were provided with written descriptions of each clearance. Appendix B

contains a complete description of these clearances, as provided the test subjects, with examples of their usage in the test scenarios. Parallel procedures were developed for operation both in a data link and voice-only communications environment. The information contained in the voice-only messages, however, was by necessity often less than that contained in similar data link messages. The following sections provide a summary of the airborne procedures and examples of the usage.

Profile negotiation. The cornerstone of the PNP was the profile request from ATC and a proposed vertical profile by the aircraft. The profile request contained the horizontal routing (data link only) and the required arrival time at a specified metering fix. The voice-only profile request would first establish the routing and arrival time and then request the desired vertical profile. The proposed vertical profile consisted of the desired cruise Mach and descent Mach/CAS speed schedule, and for data link only, the top of descent point, latitude and longitude of the next waypoint on the path, and a confirmation of metering fix name and time of arrival. This information was available for review by the pilot on the data link PROFILE TO ATC page (fig. 12) for the data link runs. The speed profile for the voice-only situation were obtained from the CDU.

Two methods for handling the profile request using data link were developed for this experiment. The first involved the automatic downlink of the profile following the pilot selection of ROGER to the profile request. The second method allowed the pilot the opportunity to review the profile information on the PROFILE TO ATC data link page prior to downlink. In both cases, the flight crew received a profile request data link message, as shown in figure 20. The crew had the option of agreeing to the request with a ROGER, or deciding not to negotiate the arrival profile with an UNABLE response. Typically, a crew would UNABLE the request only if their FMC contained a provisional route which they did not want to have erased by the profile request, a situation not expected in this experiment. A ROGER response resulted in the profile request being processed as the provisional route in the FMC. When the automatic response mode was being used, the profile information was packed into the downlink message and automatically sent to ATC. With the manual response mode, the pilot was required to select the PROFILE TO ATC data link page and press SEND to have the profile message sent to ATC. Prior to sending the profile in the manual mode, the pilot could review the profile information on the data link page and in the CDU. Changes could be made to the provisional route, such as changing from COST INDEX to CRUISE mode of profile calculation, as desired by the

6

pilot. Once the profile was sent, either automatically or manually, the provisional route was automatically erased from the FMC to prevent an inadvertent EXECUTE of the provisional route prior to receiving a clearance. The flight crew could then call up the VIEW MESSAGES data link page (fig. 14) to review the profile information sent to ATC.

4D Arrival Clearance. Once the profile negotiation was complete, or the aircraft was nearing top of descent, the controller would issue the 4D arrival clearance to the airplane. The clearance actually consisted of three elements; the route clearance, the arrival clearance itself, and vertical profile constraints. The route clearance was of the same format as standard ATC clearances which define the horizontal route of flight. The path stretching scenarios in this experiment dictated the need to issue the route clearance prior to the arrival clearance since actual routing was typically not fixed until the full profile, with path stretch, was computed by ATC. The arrival clearance was based on a standard procedure which would have published terminology and restrictions (similar to Standard Terminal Arrival Routes or STARs). For this experiment, one standard arrival was created, the SWEET ARRIVAL, which entailed crossing the SWEET waypoint at an altitude of 11,000 feet altitude at 210 knots indicated airspeed. The FMC navigation data base contained this information for use as constraints in computing the vertical profile. The arrival clearance would include the published procedure with additional restrictions imposed by ATC. The restrictions could include the arrival time at the metering fix (SWEET for these scenarios), the required top of descent point (in nautical miles from a reference navigation fix), and the speed profile to be used in the descent. A complete description of the arrival clearance, including the voice-only communication options, may be found in appendix B.

The data link implementation of the 4D arrival clearance in this experiment required the use of three distinct messages. While a single clearance message would have been preferred, this implementation was chosen in order to utilize the existing data link message types and software developed during the reference 7 experiment. Figures 21 through 23 illustrate the sequence of messages used for the 4D clearance delivery.

The first message received was the route clearance message (fig. 21). As soon as the message was received, the route was entered into the FMC as the provisional route. If a provisional route already existed in the FMC, the crew was prompted to erase or execute that provisional route before the route clearance could be viewed. The flight crew would then review the uplinked provisional route before responding to the route clearance

message. A ROGER response sent the affirmative response to ATC, updated the clearance information on the VIEW CLEARANCE data link page, and removed the uplinked provisional route from the FMC. The crew would then be required to manually enter the route into the FMC. A ROGER/ENTER response was the same as ROGER, however, the provisional route remained entered in the FMC.

Following an affirmative response to the route clearance, the ARRIVAL clearance message was received (fig. 22). The time assignment in the message (if applicable) was inserted as the RTA at the metering fix waypoint and a complete provisional path, with vertical profile and path stretching if authorized, was immediately computed. When the time assignment fell within the maximum and minimum possible arrival times at the metering fix, the message <ON TIME> was inserted next to the time assignment on the arrival clearance uplinked data link message. When the time assignment fell outside the time capability at the metering fix, an <EARLY XX> or <LATE XX> message was inserted next to the time assignment, with XX being the number of seconds the aircraft would be early or late at minimum or maximum speeds. The pilot would respond with UNABLE to the clearance if the time assignment did not indicate <ON TIME>. As with the route clearance, ROGER/ENTER retained the time assignment RTA in the FMC while ROGER simply updated the VIEW CLEARANCE data link page and removed the RTA from the FMC.

Following an affirmative response to the ARRIVAL clearance, the VERTICAL PROFILE message was received (fig. 23). This message contained the ATC expected top of descent point and descent speed schedule. There was no option to ENTER this information since the FMC in this experiment could not be programmed to compute a profile with RTA as well as constrained speeds and top of descent. The ROGER response would again update the VIEW CLEARANCE data link page with the appropriate information.

A comparison of the VIEW CLEARANCE page before and after a complete 4D arrival clearance is shown in figure 24.

Profile tracking. The pilots were provided sufficient information on the primary flight display to track the arrival trajectory. Principle guidance was the flight director and 4D energy bug. Supplemental information, necessary to assure adherence to ATC restrictions, was provided on the primary flight display, navigation display, data link display, and in the CDU. The pilots were provided with the following guidelines for tracking the arrival profile:

1. *Top of descent computed by the FMC must be within 2 nautical miles of ATC required top of descent.*
2. *Metering fix arrival time must be achieved to within 20 seconds.*
3. *Cruise/descent Mach number must stay within .02 of the ATC assignment.*
4. *Descent CAS must stay within 15 knots of the ATC assigned speed.*

The 15 knot airspeed tolerance was chosen to allow the pilots some margin for nulling the time errors. Current ATC requirements are for adherence to within 10 knots of an ATC speed assignment. The pilots were instructed to advise ATC if any of these conditions could not be achieved. The piloting task was therefore to fly the flight director and energy bug on the PFD as primary guidance. The flying and non-flying pilots would monitor the projected metering fix time error (shown on the data link VIEW CLEARANCE page and in the CDU) and the reference ATC speed bug on the PFD to assure compliance with the ATC assignments.

Test Conditions

A series of test conditions was devised which would exercise the profile negotiation process using both data link and voice communications. Table I shows the specific combinations of test conditions which were pertinent to the airborne evaluation.

Table I. Experiment Test Conditions

Condition number	Delay level	Communication mode with ATC
1	small	voice only
2	"	data link (manual)
3	"	data link (auto)
4	moderate	voice only
5	"	data link (manual)
6	"	data link (auto)

The delay level of the test condition refers to the traffic delay which the controller must handle based on the traffic situation created by the CTAS TMA. The small delay level was approximately 3 minutes, which could be absorbed by speed reduction along the nominal arrival route. The moderate delay was approximately 8 minutes, which required a path stretch off-route to absorb the delay. For evaluation of the controller performance, the small delay level situations were divided into three conflict geometry's: (a) aircraft from different routes merging during descent, (b) aircraft from different routes merging during cruise, and (c) aircraft along the same route. While significant to the controller evaluation, the geometry of the conflict was invisible to the flight crew and not included as a parameter in the test matrix for the airborne evaluation. References 2 and 6 contain further discussion of the test conditions for the controller evaluation.

Each traffic situation contained one or more aircraft which would conflict with the TSRV at some point during the arrival, even though conflict-free arrival times were generated by the TMA. These conflicts were either caused by different aircraft types flying different speed profiles for the same flight time, or the result of dissimilar speed strategies between CTAS and the airborne FMC, as in the reference 1 experiment.

Communication mode with ATC was divided into voice only and data link. The data link mode was further divided into manual and automatic, referring to the method in which the response to a profile request from ATC was handled. In the automatic mode, the vertical profile message was down linked to ATC automatically after the pilot had selected ROGER to the profile request message. In the manual mode, the vertical profile was computed after a ROGER to the request message, however, the pilot must then select the PROFILE menu on the ATC data link page and press the SEND button to downlink the profile.

Results and Discussion

Approximately 30 hours of simulation testing were conducted over a three week period during this experiment. Three crews of active airline pilots (each 2 pilot crew from a different major airline) participated as test subjects at Langley and three teams of active Center controllers (2 each) participated at Ames. All of the pilots had experience flying FMC-equipped aircraft with electronic flight displays. A total of 29 data runs were completed, with each crew flying all the test conditions at least once, except for condition 5 which was only flown by one crew.

Results from this study were obtained in the form of pilot opinions from questionnaires and debriefing sessions, quantitative measures of airplane state variables and fuel usage, and researcher observations of pilot and controller performance. The pilot rating was used primarily as a tool to prompt pilot thinking and discussion of the research issues, in particular regarding ATC procedures and 4D guidance. The quantitative data were used in the analysis of the trajectory tracking and metering fix arrival performance of the flight crew and comparisons of fuel usage.

The test subjects in this study were presented with a combination of new technology and procedures in a relatively unfamiliar cockpit environment. The training time allotted (approximately 4 hours) proved to be totally insufficient to achieve a consistent level of performance and understanding from the flight crews. In addition, the majority of the simulation time during the experiment (approximately 24 minutes of a 36 minute scenario) was spent during the long cruise portion of the flight, during which the flight crew had virtually no tasks to perform. These long scenarios were necessary to exercise the ATC aspects of the experiment and provide the air traffic controllers with realistic situations to handle.

Profile Negotiation

During 26 of the 29 data runs, the PNP resulted in the flight crew receiving a complete arrival clearance and then executing a 4D descent to the metering fix. The remaining 3 runs were completed without a 4D arrival clearance, with controllers issuing conventional altitude, speed and heading instructions. Data link runs accounted for 18 of the complete PNP runs and 2 of the incomplete runs. Voice only was used during 8 complete and 1 incomplete PNP run.

The principle reason for the incomplete PNP was the controller's attempt to accommodate the aircraft preferred trajectory, even though the aircraft was close to top of descent. The arrival clearance was then delivered too late for the aircraft to respond or the controller decided to abandon the process and manually descend the aircraft. This result is primarily an artifact of this experiment and the controllers lack of experience with the 4D clearance. Operational procedures and guidelines for issuing the 4D clearance must provide adequate lead time to prevent aircraft from reaching top of descent without a descent clearance. These procedures should include time buffers for the negotiation process as well as the clearance delivery itself.

Two important factors affected the performance of the PNP in terms of the number of cycles required to completed the process successfully. Successful completion is defined here to mean that the PNP resulted in a conflict-free 4D arrival clearance all the way down to the metering fix. The first factor was the design of the PNP itself; the second factor was the design of the traffic scenarios used to evaluate the PNP.

The PNP design implemented for this test was biased towards re-negotiation if and when an aircraft's profile request was found to create a conflict. Referring to figure 1, the flow chart shows that if a conflict occurs, the controller must either (A) issue a ground-based conflict-free 4D solution if close to the top of descent, or (B) issue a tactical correction to maintain separation followed by a

later cycle of negotiation initiated by a profile request. As a result, every conflict case required two or more cycles to complete the PNP successfully. This PNP design was chosen to increase the subject's experience and understanding of the negotiation process, as well as variations in trajectory solutions between the aircraft and ground, with the hope that it would inspire greater subject discussion during the debriefing. The alternative design would have given the controller the option at path (B) to either follow the re-negotiation path or issue a clearance based on a ground-based 4D solution without further negotiation. This alternative design would allow the controller to complete the process in one cycle, even when conflicts arise due to the profile proposal.

The second factor affecting PNP completion was the traffic scenarios. Each scenario had intentional conflicts designed to prevent the initial profile request from succeeding. As a result, every data run had at least two profile negotiation cycles in which the controller would issue profile requests. While this provides more opportunities for negotiation, it also tends to bias the overall results in terms of the number of PNP cycles required per run. Random traffic situations would yield fewer conflicts and the profile negotiation would frequently succeed on the first attempt. Clearances could then be issued much further from top of descent with a much greater likelihood for success. Figure 25 shows the range from top of descent at which the arrival clearances were issued for the data link runs in this experiment. As seen, more than two-thirds of the clearances were issued at a range less than 50 miles from top of descent. The high number of clearances issued close to top of descent were a direct result of the conflicts designed into the traffic scenarios.

A clear preference for data link communication for the profile negotiation was clearly stated by both pilot and controller test subjects. The voice-only runs revealed the process to be cumbersome and subject to error. Somewhat surprisingly, however, the voice procedures worked well and some of the pilots indicated no reservations to using the procedures in actual operations. The additional involvement of the pilot, manually entering arrival time and computing the preferred trajectory, especially during the low-workload cruise portion of the flight, was appealing to some of the pilots. The controllers, with a significantly higher workload at this point during the flight, generally preferred the data link negotiation.

Profile request. The initial stage of the PNP, the profile request, received a mixed response from the pilots. The overall consensus was favorable toward ATC soliciting the aircraft preferred profile, however, the desired level of pilot involvement in the process was

quite variable. Some of the test subjects wanted the FMC to handle the profile request; even the automated response mode required too much interaction by the pilot. Other pilots were quite concerned over the limited control they were given over the actual trajectory that was generated by the FMC; even the manual response mode to the request was not acceptable to these subjects. In particular, the choice of minimum speed by the FMC was considered to be too slow a speed by some pilots and was not controllable by the pilot. The other potential problem cited was possible routing through severe weather, which could not be modified by the pilot.

A compromise method for dealing with the profile request was considered and discussed with the pilots in this experiment. The procedure would let the FMC automatically deal with the profile request. The pilot would have control over the speed range usable by the FMC and could review the profile after it was sent to spot routing problems which could then be communicated to the controller prior to receiving a clearance change. This method was not tested in this experiment, but would seem to address the major concerns expressed by the test subjects.

ATC clearances. The pilots encountered numerous difficulties in handling the 4D clearances developed for this experiment. Most of the problems were related to the method in which the 4D clearances were delivered, i.e. through three separate data link messages. Other problems, however, revealed limitations in the FMC path generation capability as well as difficulty for the pilot to resolve the difference between the ATC clearance and the aircraft guidance. In addition, the timing of the clearance prior to top of descent proved to be a major concern.

The separation of the 4D clearance into three separate data link messages (route, arrival, and vertical profile) proved to be confusing to the pilots and disruptive to the PNP process. A single clearance message with the same information would have been preferable. Besides being a nuisance to the pilot, the possibility of responding with ROGER to the arrival and then UNABLE to the vertical profile clearance was an undesirable situation. Also, the time required to process each message separately could endanger the entire process if the clearances were issued near top of descent, as was encountered during several of the test runs.

Although the method of presenting the clearances as three messages was considered unacceptable, the contents of the messages were generally understandable to the pilots. The primary exception to this was the vertical profile clearance, which provided the ATC-required top of descent point and descent speed schedule. Typically there would be a slight discrepancy in the ATC clearance

values and the FMC-computed values. The pilots were instructed to use the FMC values for guidance as long as they were within 15 knots in speed and 2 nautical miles in top of descent range. While this was always the case for the successful negotiations, the pilots were uncomfortable having the guidance value of descent speed (or top of descent) different than the clearance value. A more preferable situation would be to insert the ATC values into the FMC and force calculation of a profile which agreed with ATC, even if small amounts of thrust or speed brake were required to actually fly the trajectory. This ability to constrain speeds, top of descent and arrival time is not available in any commercial FMC and was not programmed into the FMC path generation program used in the TSRV simulator.

The VIEW CLEARANCE page on the data link display was also the subject of some concern to the pilots. The intent of the page was to provide a concise summary of the current ATC clearances and tactical assignments for quick reference by the flight crew. The information on this page was updated whenever a pertinent data link clearance or tactical ATC instruction was acknowledged by the flight crew with a ROGER response. During several of the data link runs in this experiment, controllers issued voice instructions which effectively canceled or changed the information on the VIEW CLEARANCE page. These voice instructions were not reflected on the data link page, and the pilots were given no way of modifying the information on the data link page. This situation was deemed unacceptable by several pilots who cited the importance of consistent and accurate information display regarding ATC clearances and assignments.

Flight Guidance

The flight guidance used in this experiment was modified slightly over that developed for the reference 1 experiment. A flight director was added to provide guidance for tracking the FMC descent altitude profile. The vertical situation display (VSD) was eliminated, and time of arrival and time error were displayed on the data link VIEW CLEARANCE page as well as on the CDU. The 4D energy bug was enlarged on the primary flight display for better visibility. Evaluation of the flight guidance was a secondary objective of this experiment, and the test conditions were not designed to support a rigorous analysis. Pilot comments and performance, however, were reviewed to provide insight into the effectiveness of the flight guidance for conducting the 4D arrivals.

The pilots were asked to rate the usefulness of specific flight guidance elements for flying the descent trajectory at the conclusion of each simulation run. Figure 26

shows the results of these ratings for the 26 data runs which were flown with complete 4D arrival trajectories. The energy bug and flight director on the PFD consistently received the highest ratings. These ratings, coupled with pilot comments, reaffirmed the results obtained in the reference 1 experiment. Namely, the pilots preferred flight guidance which showed them what to do rather than only situational information. The concept of centering the flight director and energy bug to achieve the proper arrival condition was appealing to most of the pilots. The situational information, such as reference altitude and time box position were also of interest, however secondary to the flight director guidance.

The only significant flight guidance problems encountered by the pilots were the sometimes contradictory requirements encountered during tracking of the 4D arrival profile. These requirements included centering the energy bug and flight director while also staying within 15 knots of the reference airspeed. The idea of intentionally flying as much as 15 knots faster or slower than the reference airspeed in order to keep the energy bug centered was difficult for some of the pilots to accept. Most of the test subjects agreed that the best solution would be to remove the reference airspeed (and possibly reference altitude) from the PFD and incorporate the speed (and altitude) tolerance into the energy bug and flight director logic. The pilot would then be assured that following the flight director and energy bug guidance would not result in deviating from the expected airspeed and altitude profile.

Fuel Efficiency

The CTAS Descent Advisor is designed to provide for fuel-efficient descent trajectories. Fuel efficiency is achieved by generating trajectories for each aircraft which minimize flight at lower altitude, are based on near-idle descents, and are conflict free to avoid interruption. The current implementaton of the Descent Advisor, however, does not consider fuel burn in determining cruise and descent speed profiles. Speed selection is based on nominal schedules and constraints applied by the controllers.

A primary purpose of the profile negotiation process is to allow the aircraft to utilize the FMC profile generation capabilty, which includes fuel flow modeling, to achieve the most fuel-efficient arrival trajectory possible. Quantifying the fuel efficiency improvements afforded by the PNP is not a simple or straightforward task. Analysis of the fuel differences between CTAS-proposed trajectories and those computed by the aircraft in this experiment, however, can provide some measure of fuel savings which may be afforded by implementing a

PNP. Significant factors, such as performance modeling of the airplane and atmospheric modeling by CTAS and the aircraft FMC, are not included in this analysis.

The data link runs flown by the TSRV during the small time delay scenarios (conditions 1, 2, and 3) were analyzed to compare the initial CTAS-computed profile, the aircraft-preferred profile, and the actual profile flown by the aircraft. These scenarios all had a fixed range of 232 nautical miles with an average flight time of 36.9 minutes. The delay was such that speed adjustment alone was sufficient, and path stretching was not required. A total of 10 data link runs were completed using these scenarios. Table II summarizes the average descent speed and corresponding theoretical fuel required for initial CTAS, initial aircraft-preferred, and final clearance profiles for these 10 runs. The fuel numbers in the table were calculated using the FMC performance model using the descent CAS and whatever cruise Mach was required to achieve the 36.9 minute flight time. Actual fuel usage, measured in the 10 simulation runs, was an average of 2183 pounds with a standard deviation of 29 pounds. This agreed well with the 2188 pounds calculated using the FMC performance model.

Table II. Theoretical Fuel for Small Time Delay Scenarios.

	Initial CTAS Profile	Initial Aircraft Request	Final Clearance
Descent CAS	280 knots	231	237
Fuel required	2231 lbs (ref)	2180 (-2.3%)	2188 (-2.0%)

The initial CTAS profile, with a descent speed of 280 knots, would require a cruise Mach number of approximately .63 to achieve the required arrival time. The aircraft preferred profile, with an average descent speed selection of 231 knots, required a cruise Mach of approximately .69, with a fuel savings of approximately 2.3 percent for the same flight time. Conflicts in the aircraft-preferred trajectory prevented the controllers from issuing a clearance based on that profile. Rather than issue the less efficient CTAS profile, the controller(s) would manually slow the aircraft to a comfortable cruise Mach (typically between .63 and .69) and wait for another negotiation. On the second or third profile request, the aircraft-preferred profile (with a slightly greater descent speed) would result in a conflict-free trajectory, and the controller would issue the final clearance profile. The end result was a trajectory close

the original request, with a fuel savings of approximately 2 percent over the initial CTAS trajectory.

The fuel savings during the moderate time delay scenarios (conditions 4, 5 and 6) was more difficult to quantify. These scenarios involved path stretching to absorb part of the time delay. The technique used in the path stretch has a significant effect on the fuel usage, and the controllers in this study were free to choose their own technique. The CTAS automation was not programmed to prompt them in the most efficient technique to be used. The large amount of fuel savings (or waste) possible during path stretch delays warrants further discussion.

Figure 27 illustrates four possible path stretch techniques which the controllers could apply to the traffic in the moderate time delay scenarios. Method 1, holding pattern, would keep the aircraft at the initial cruise speed and then enter a holding pattern (at minimum fuel speed) to absorb the delay. This technique is common in today's ATC system, and is considered the baseline for this analysis. Method 2, path stretch at cruise speed, involves vectoring the aircraft off the normal route to increase the distance flown by the amount necessary to absorb the time delay. The aircraft speed profile is not changed. Method 3 and method 4 are fundamentally the same as method 2, in that the aircraft is vectored to increase path distance, however the speed profile is also changed. The nominal speed profile of method 3 uses speeds which a wide variety of aircraft could fly, while method 4 uses the speeds for minimum fuel usage for the specific aircraft. Table III provides a summary for the theoretical fuel usage of the four techniques for the specific moderate time delay scenarios in this experiment.

Table III. Theoretical Fuel for Moderate Delay Scenarios

Delay Method	Speed Profile	Fuel Required
1	.72/280 (220 hold)	2758 lbs (ref)
2	.72/280	2842 lbs (+3.0%)
3	.68/250	2570 lbs (-6.8%)
4	.61/220	2204 lbs (-20.0%)

Path stretching at cruise speed, delay method 2, was the default mode of operation for CTAS in this experiment. The system automatically computed the path stretch using aircraft current heading (once vectored off route) and did not change the speed schedule unless instructed by the controller. The controllers were encouraged to reduce speed during the path stretch, however, they were not prompted to do so by the automation. The aircraft FMC would default to delay method 4, and compute the minimum fuel path stretch. The difference in fuel usage could be significant, with

approximately 25 percent difference in fuel between the cruise speed path stretch and the minimum fuel stretch. The PNP in this experiment provided the controllers with the initiative to reduce the aircraft speed during a delay vector. The traffic conflicts designed into the scenarios, however, prevented the controllers from actually issuing minimum fuel delays. The average measured fuel usage of the TSRV simulator was approximately 2546 pounds, just slightly better than the theoretical fuel required for delay method 3.

The fuel savings potential of the PNP (between 2 and 8 percent in this experiment) must be considered in the context of the CTAS Descent Advisor implementation and the simulation environment in which it was tested. Modifications to the DA algorithms could achieve similar fuel savings without the necessity for profile negotiation. These modifications could include empirically-derived fuel-efficient speed strategies or even fuel flow modeling of the aircraft. The complexity and computational requirements of these modifications to the CTAS DA must be weighed against the data link communication loading and pilot/controller workload involved with the PNP. In addition, the operating environment, including real-world atmospheric variations and performance variations of different aircraft, must also be considered in simulation testing of fuel efficiency. The fuel savings achieved under benign, well-modeled conditions might change considerably under real-world conditions.

Finally, the system-wide fuel benefits of CTAS (i.e. reduced arrival time variation and full idle descents versus segmented descents for all aircraft) are not considered in the analysis presented in this paper. These benefits, while impossible to quantify until the system is actually implemented, should be greater than those presented here. The fuel savings afforded by the PNP (or modified CTAS DA algorithms), however, would add to the overall system benefits.

Concluding Remarks

A simulation study was conducted to evaluate a profile negotiation process (PNP) between a time-based air traffic control (ATC) system and an aircraft equipped with a four-dimensional flight management system (4D FMS). The following remarks are based on the results of this piloted simulation study.

The exchange of profile requests and trajectory information demonstrated the ability of the ATC automation to adapt to aircraft preferred arrival trajectories. Despite intentional traffic conflicts designed into each traffic scenario, the controllers were consistently able to adjust the CTAS-computed arrival trajectory to more closely match the desired trajectory of

the airplane. Resultant fuel savings of between 2 percent and 8 percent, compared to fuel required for the baseline CTAS arrival speed strategy, were estimated for the arrival scenarios in this experiment.

Data link was clearly preferred over voice-only communication for this profile negotiation by the air traffic controllers in this study. Pilots also preferred the data link, however, there was no strong objection to the voice-only situation. The low-workload environment (enroute cruise) in which the PNP occurred tended to bias some of the pilots toward a more active involvement in the profile negotiation process. From a system standpoint, however, it is highly unlikely that the PNP, as developed for this experiment, could be effectively incorporated without a digital data link for communication.

The experimental procedures used for the profile negotiation were found to be generally unacceptable to the pilot test subjects. Some pilots stated that their involvement in the profile request did not provide enough control over the FMC-generated trajectory. The inability to select minimum flight speed or to modify the route due to weather were cited as major problem areas. Other pilots, however, expressed the desire to not be involved in the process until time for the actual clearance delivery. The major objection was the nuisance of dealing with the profile request. They would prefer the aircraft and ATC automation to work out the details, within the constraints set by the pilot and controller, and tell them the results at the time of the clearance delivery.

The ATC clearance procedures using the data link were also found to be unacceptable to the majority of the pilots. The separation of the 4D clearance into three separate data link messages (route, arrival, and vertical profile) proved to be confusing to the pilots and disruptive to the PNP process. A single clearance message with the same information would have been preferable. In addition, the occasional slight discrepancy between ATC descent restrictions (top of descent and speed profile) and the profile computed by their FMC for the same arrival time, was disconcerting to several pilots. The ability to insert the uplinked ATC speed profile into the FMC may be necessary to provide an operationally acceptable procedure.

The airborne flight guidance proved effective in delivering the airplane to the metering fix at the assigned arrival time. The only significant guidance problem encountered by some of the pilots was the sometimes contradictory requirements of centering the energy bug and flight director while also staying within 15 knots of the reference airspeed. The pilots generally felt the tolerance on deviation from reference airspeed should be included in the flight director and energy bug logic and not displayed as a separate item. The pilots wanted

assurance that following their flight director and energy bug guidance would not result in deviations from their required airspeed and altitude profiles.

Appendix A

Data Link Messages

Format

The basic data link message is an ASCII string of up to 220 characters with the following format:

    TTTFFFYYY:X...X:HHMMSS:<CR>

where,

TTT	address field of recipient of message (to).
FFF	address field of sender of message (from).
YYY	message type.
X...X	message text.
HHMMSS	sequence number of message (hours, min, sec zulu time).
<CR>	message terminator is carriage return character (decimal 13).

Address fields

The address field is a 3 character identifier of the recipient or sender of a message. The identifiers for this experiment are:

ATC	Air traffic control (Ames CTAS)
515	TSRV simulator (NASA 515)

Message types

The 3 character field following the address fields indicates the type of message which is contained in the message text field. The format of the message text field is dependent on the message type. The following message types are used in this experiment:

TAC	tactical message from ATC to aircraft
ROU	route clearance message from ATC to aircraft
REQ	profile request message from ATC to aircraft
PRO	profile clearance from ATC to aircraft
INF	information message from aircraft or ATC
ROG	"roger" acknowledgment from aircraft or ATC
UNA	"unable" acknowledgment from aircraft or ATC
POS	position report from aircraft to ATC or ground
PRO	arrival profile report from aircraft to ATC
RDR	position data for simulated radar tracking from aircraft to ATC

Tactical ATC message (TAC)

1. Heading assignments (HE)

message text	meaning
HEXXX	MAINTAIN HEADING XXX
HETRXXX	TURN RIGHT XXX DEGREES
HETRTXXX	TURN RIGHT TO XXX
HETLXXX	TURN LEFT XXX DEGREES
HETLTXXX	TURN LEFT TO XXX
HERES	RESUME OWN NAVIGATION

14

example,

```
515ATCTAC:HETRT230:123456:
"NASA 515, TURN RIGHT TO 230"
```

2. Proceed direct to waypoint (PD).

PDXXX PROCEED DIRECT TO XXX
where XXX is a 3 to 5 char nav aid name

example,

```
515ATCTAC:PDPONNY:123456:
"NASA 515, PROCEED DIRECT TO PONNY"
```

3. Path stretch to waypoint (PS).

PSXXX PATH STRETCH TO XXX
where XXX is a 3 to 5 char nav aid name

aircraft is cleared to fly current heading until pilot discretion turn to specified waypoint.

example,

```
515ATCTAC:PSPONNY:123456:
"NASA 515, PATH STRETCH TO PONNY"
```

4. Route intercept (RI).

RIXXX INTERCEPT XXX
if XXX = JNNN, JET ROUTE NNN
= VNNN, VICTOR ROUTE NNN

5. Speed assignment (SP).

SPXXX MAINTAIN XXX
if XXX = NNN, NNN KNOTS
= .MM, MACH .MM

SPUNS SPEED UNRESTRICTED

example,

```
515ATCTAC:SP.68:123456:
"NASA 515, MAINTAIN MACH .68"
```

6. Altitude assignment (AL)

ALDXXX DESCEND AND MAINTAIN XXX
ALCXXX CLIMB AND MAINTAIN XXX
ALMXXX MAINTAIN XXX

if XXX = NNN,   NNN00
         = FLNNN,   FLIGHT LEVEL NN0

example,

515ATCTAC:ALD240:123456:
"NASA 515, DESCEND AND MAINTAIN 24000"

7. Tactical clearances (CL)

CLPXXX	CLEARED FOR PROFILE DESCENT INTO XXX
CLRXXX	CLEARED FOR XXX ARRIVAL
CLAXXX	CLEARED FOR XXX APPROACH
	(where XXX is 3 to 5 character name)

example,

515ATCTAC:CLPDEN:123456:
"NASA 515, CLEARED FOR PROFILE DESCENT INTO DENVER"

515ATCTAC:CLRKEANN:123456:
"NASA 515, CLEARED FOR KEANN ARRIVAL"

All tactical clearances are displayed under CURRENT CLEARANCES of the VIEW CLEARANCE page if the pilot presses ROGER of ROGER/ENTER. The clearances are displayed in parsed form without the leading CLEARED FOR.

8. Metering fix time assignment (MT).

MTHHMMSSXXX   CROSS XXX AT HH:MM:SS   *Y...Y*
                             where XXX is a 3 to 5 character nav aid name,
                             HHMMSS is hours, minutes, seconds ZULU time.

Y...Y is a message, inserted by the airborne system, indicating the ability of the aircraft to achieve the assigned time. It has the following possible entries:

<INVALID> if the XXX nav aid does not match the current metering fix name of the provisional
                flight plan.

<ON TIME> if the assigned time (T) is greater than or equal to the minimum arrival time
                (TMIN) and less than or equal to the maximum arrival time (TMAX).

<LATE SSS> if T < TMIN, where SSS = TMIN - T, sec.

<EARLY SSS> if T > TMAX, where SSS = T - TMAX, sec.

example,

515ATCTAC:MF172340KEANN:123456:
"NASA 515, CROSS KEANN AT 17:23:40 <ON TIME>"

A ROGER/ENTER response by the pilot will result in the assigned time being inserted as required time of arrival (RTA) in the provisional flight plan. The assigned time is also displayed as the metering fix time under

CURRENT ASSIGNMENTS on the VIEW CLEARANCE page with either ROGER or ROGER/ENTER response. This entry will appear as follows:

MF TIME: HH:MM:SS $Y...Y$

where $Y...Y$ is now a message indicating the arrival time error at the metering fix. This message is updated continuously while this menu is being displayed. If the CDU is in provisional mode, the message is computed using the TMIN and TMAX as described above for the incoming time assignment message. If the CDU is in active mode, the possible entries are:

<ON TIME> if |time error| is less than 6 seconds.

<EARLY SSS> if time error < -5 seconds, SSS = |time error|

<LATE SSS> if time error > 5 seconds.

<NOT 4D> if 4D time guidance is not active.

If the RTA in the FMC does not agree with the assigned metering fix time, the message "<NOT ENTRY>" is displayed.

9. Descent advisor (DA).

DADDDMMCCC   DDD MILES DME, .MM MACH, CCC KNOTS.

example,

515ATCTAC:CLRKEANN:DA07668280:123456:
"NASA 515,   CLEARED FOR KEANN ARRIVAL,
              76 NMI DME, .68 MACH, 280 KNOTS"

10. Voice frequency assignment (VF).

VFFFFFFXXXYYY   CONTACT XXX YYY ON 1FF.FFF

          XXX = facility name

          YYY = DEP,   DEPARTURE
                 APR,   APPROACH
                 GRN,   GROUND
                 CNT,   CENTER
                 TWR,   TOWER

example,

515ATCTAC:VF23450DENCNT:123456:
"NASA 515, CONTACT DENVER CENTER ON 123.450"

11. Free text entry (FT).

FTXXX   XXX (free text exactly as typed)

example,

515ATCTAC:HETLT210:FTFOR TRAFFIC AVOIDANCE:123456:
"NASA 515, TURN LEFT TO 210, FOR TRAFFIC AVOIDANCE"

ATC route clearance message (ROU)

This message is used to deliver a horizontal route clearance to the aircraft. The Route (RT) field is required, with optional fields for path stretching (PS) and proceed direct (PD).

1. Route (RT).

RTXXX.YYY.ZZZ   CLEARED TO UPLINKED ROUTE:
                        XXX.YYY.ZZZ

XXX, YYY and ZZZ are a list of legal names for flight plan elements separated by periods. Any number of waypoints may be contained in this list, within the limitations of a single data link message size (220 chars). This list can include:

1. 3-5 character published navigation aid name.
2. published jet (J) or victor (V) airway name.
      - entry and exit waypoint names must be specified.
3. NXXXXXXXXWYYYYYYYY, latitude and longitude of RNAV point.
      XXX.XXXX and YYY.YYYY degrees.

2. Path stretch (PS).

PSXXXXX   PATH STRETCH TO XXXXX

Including this field gives aircraft the clearance to path stretch along current heading prior to heading to waypoint XXXXX on new route.

example:

515ATCROU:RTPONNY.KEANN.SWEET:PSPONNY:123456:

"NASA 515, CLEARED TO UPLINKED ROUTE:
PONNY.KEANN.SWEET (not read by voice system)
PATH STRETCH TO PONNY"

3. Proceed direct (PD).

PDXXXXX   PROCEED DIRECT TO XXXXX

Including this field gives the waypoint XXXXX on new route which the aircraft is to proceed directly toward.

example:

515ATCROU:RTPONNY.J114.KEANN.SWEET:PDPONNY:123456:

"NASA 515, CLEARED TO UPLINKED ROUTE:
PONNY.J114.KEANN.SWEET (not read by voice system)
PROCEED DIRECT TO PONNY"

18

The route clearance message is automatically inserted into the aircraft flight management system, as a provisional flight plan, as soon as it is received. If the PS flag is received, the CDU is forced into DIRECT TO mode with path stretching enabled. A PD flag will force a DIRECT TO without path stretching. A single pass through the DIRECT TO logic is then executed in order to provide a complete horizontal and vertical profile on the provisional path while the ATC dialog window is on the data link display. A ROGER/ENTER response by the pilot will insert the RT field into the CURRENT CLEARANCE section of the VIEW CLEARANCE page and leave the provisional path in the CDU. The pilot must still press EXECUTE on the CDU to make the route active. A ROGER response enters the RT field into the VIEW CLEARANCE page, however, the provisional path is erased from the CDU. The pilot must manually enter the clearance.

ATC profile request (REQ)

This message is used to deliver a proposed horizontal route to the aircraft. The aircraft is requested to down link a proposed profile for the route. The route (RT) field is required, with optional fields for path stretch (PS), proceed direct (PD) and metering time (MT).

1. Route (RT).	same as ROU message.
2. Path stretch (PS).	same as ROU message.
3. Proceed direct (PD)	same as ROU message.

4. Metering time (MT)

MTHHMMSS	CROSS METERING FIX AT HH:MM:SS

example:

515ATCREQ:RTN0404507W1024915.KEANN.SWEET:MT170345:PSN0404507W1024915:123456:

"NASA 515, SEND PROFILE FOR UPLINKED ROUTE:
N0404507W1024915.KEANN.SWEET (not read by voice system)
CROSS SWEET AT 17:03:45
PATH STRETCH TO N0404507W1024915"

This message is **not** automatically inserted into the aircraft flight management system as soon as it is received. The pilot can only ROGER or UNABLE the message. A ROGER response will enter the route and time constraint into the provisional flight plan and force a single vertical path computation (or one full pass through the DIRECT TO mode). A PROfile message will then be ready for down link to ATC when the vertical path computations are completed. The provisional flight plan is erased from the CDU after the PROfile has been down linked.

ATC profile clearance (PRO)

This message is sent in conjunction with a tactical CLR (cleared for arrival) message. The message is the same format as the downlinked PROfile report message, however the TOD range is referenced to the arrival airport VOR. The TOD range, descent Mach, and descent CAS are extracted and displayed in the time critical window as:

ARRIVAL: RRR.R NMI DME, .MM MACH CCC CAS

The pilot can only ROGER or UNABLE the message. A ROGER response results in the above message string being inserted in the Current Clearance section of the View Clearance data link page below the route field.

PONNY.J114.KEANN.SWEET
ARRIVAL: 76.5 NMI DME, .72 MACH, 280 CAS

Aircraft down link messages

1. ROG = Positive acknowledgment (roger) of ATC message.

   example,

   ATC515ROG:123456:123535:
   "NASA 515 rogers message 123456"

2. UNA = Negative acknowledgment (unable) of ATC message.

3. POS = Aircraft position report.

   NYYYYYYY:WXXXXXXX:AAA:CCC:HHH

   > NYYYYYYY = north Latitude, XXX.XXXX degrees
   > WXXXXXXX = west Longitude, YYY.YYYY degrees
   > AAA = altitude / 100 feet
   > CCC = calibrated airspeed, knots
   > HHH = magnetic heading, deg

   example,

   ATC515POS:N0390515:W1044322:310:250:275:123456:

4. PRO = aircraft profile report.

   FFFFF:HHMMSS:NYYYYYYY:WXXXXXXX:.MM:.DD:CCC:RRRR:

   > FFFFF = metering fix name
   > HHMMSS = arrival time in hours, minute, seconds
   > NYYYYYYY = North latitude of turn point, YYY.YYYY degrees
   > WXXXXXXX = West longitude of turn point, XXX.XXXX degrees
   > .MM = cruise Mach, .MM
   > .DD = descent Mach, .DD
   > CCC = descent indicated airspeed, CCC knots
   > RRRR = range from top of descent to metering fix, RRR.R nmi.

   example,

   ATC515PRO:KEAMF:172848:N0404507:W1024915:.72:.72:295:0764:123456:

5. RDR = aircraft position for simulated radar tracking.

    XXXXXYYYYYAAAHHHVVVWFFFFF

             XXXXX = X pos * 100 in Denver coordinates (nearest hundredth of nmi).
             YYYYY = Y pos * 100 in Denver coordinates (nearest hundredth of nmi).
             AAA = Altitude * 100 above sea level (nearest hundredth of nmi).
             HHH = True heading in degrees.
             VVV = Ground speed in knots.
             W = Weight on wheels (0 = in air, 1 = on ground).
             FFFFF = Voice Comm frequency tuned by aircraft (1FF.FFF).

             (all fields are left filled with zero's)

    example,

    ATC515RDR:0992103456234270238023450:123456:

Other messages

  1. INF = free text information

        TT...TT = up to 202 characters of text

Appendix B

ATC Clearances

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 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. 1), and have been refined for this study. The procedures for this study are experimental, and should be considered a basis for further evolution.

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.

Clearance Categories

For the purposes of discussion, the clearances to be used in this simulation have been divided into three major categories:

Strategic:
    ARRIVAL clearance
Navigation (flight plan 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 flight plan 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 data link, to complete each clearance. 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. Mastery of the details of this clearance is essential to the effective use of both the airborne and ground-based systems.

ARRIVAL Clearance (Strategic)

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 the metering fix on time and "conflict-free." The arrival clearance allows the pilot to follow a "published" arrival procedure which simplifies the issuance of common restrictions/constraints. 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 down linking 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 down link 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 be kept 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 (NASA 515):

Data link communications. An arrival clearance must be preceded by a valid routing clearance 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 data link software will automatically send the appropriate arrival 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 data link, 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 - non 4D FMS:

The arrival clearance (also called a "DA" descent clearance) must also be preceded by a valid arrival routing clearance to the metering fix (via data link or voice). For both data link 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 canceled, 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.

Examples:

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, expect new 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."

At this point, 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, which ever 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 and/or 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 canceled the ARRIVAL. If an ARRIVAL clearance is canceled, the aircraft must maintain its last assigned altitude and speed.

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 aircraft must turn to a heading to intercept the waypoint and then proceed along the RNAV path. 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 canceled the ARRIVAL. If an ARRIVAL clearance is canceled, the aircraft must maintain its last assigned altitude and speed.

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 path 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).

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 canceled). 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 overshooting 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 flexibility 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 assignments cancel any previously issued arrival clearance. However, an arrival clearance does not cancel a previously issued altitude assignment.

Example:
If an aircraft in cruise (e.g. level @ 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 assignment, 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 canceled, 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 canceled, and the aircraft must continue its descent to the assigned altitude.

SPEED Assignment

Definition: The SPEED assignment clearance constrains the pilot to fly an ATC specified cruise or descent speed until otherwise advised by ATC.

Purpose: SPEED assignment clearances are generally 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 has deviated from the planned path (not going to make its time at the metering fix) or if a potential conflict develops.

Context: In general, this clearance may be issued at any time. As part of the profile negotiation process, 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 constrained, does not cancel a previously issued cruise speed assignment.

Example:
If an aircraft in cruise (e.g. level @ FL350 @ 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 CLEARANCE was issued first, followed by the SPEED assignment, the result would be totally different. 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 canceled, but the aircraft must continue its descent to the last assigned altitude at the assigned speed.

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9. Steinmetz, George G.: *Development and Evaluation of an Airplane Electronic Display Format Aligned With the Inertial Velocity Vector.* NASA TP-2648, 1986.
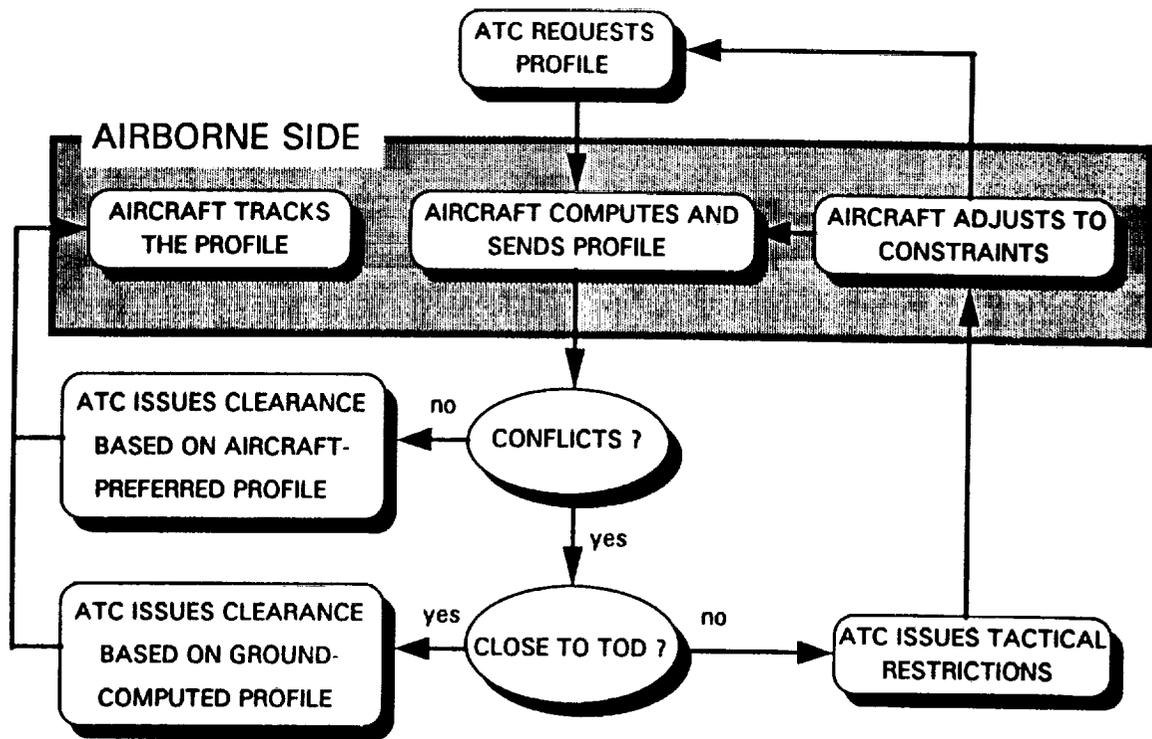
Figure 1.- Profile negotiation process.
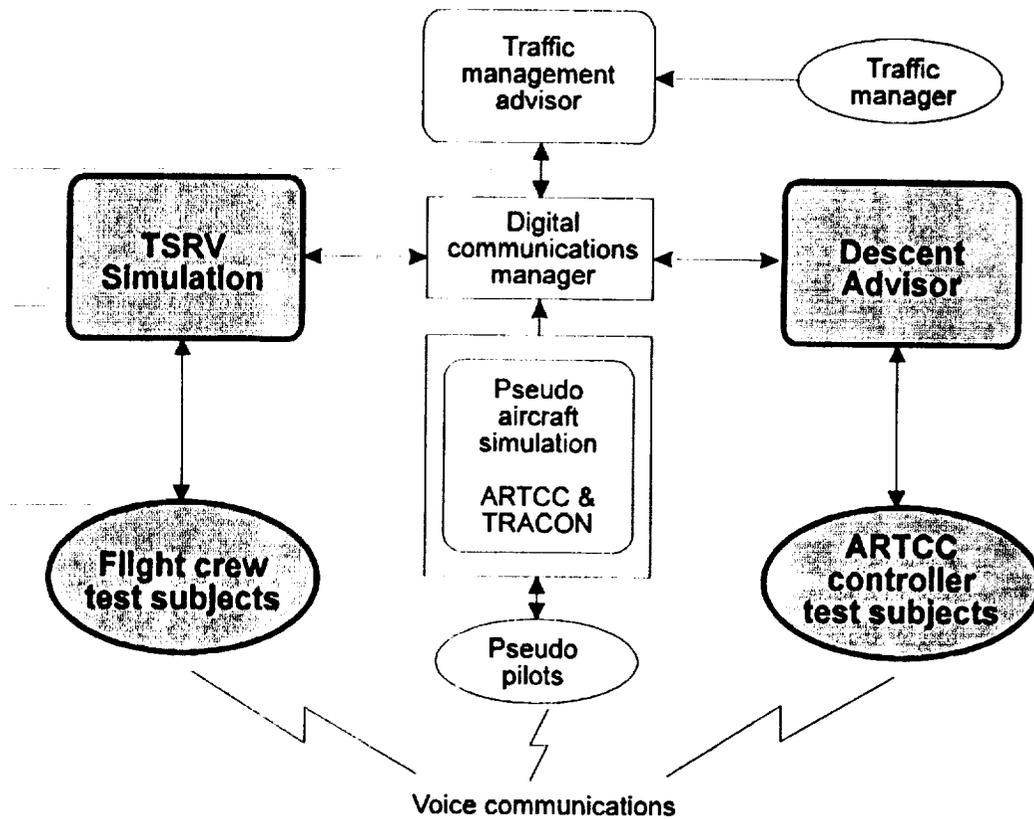

Figure 2.- Block diagram of research system.
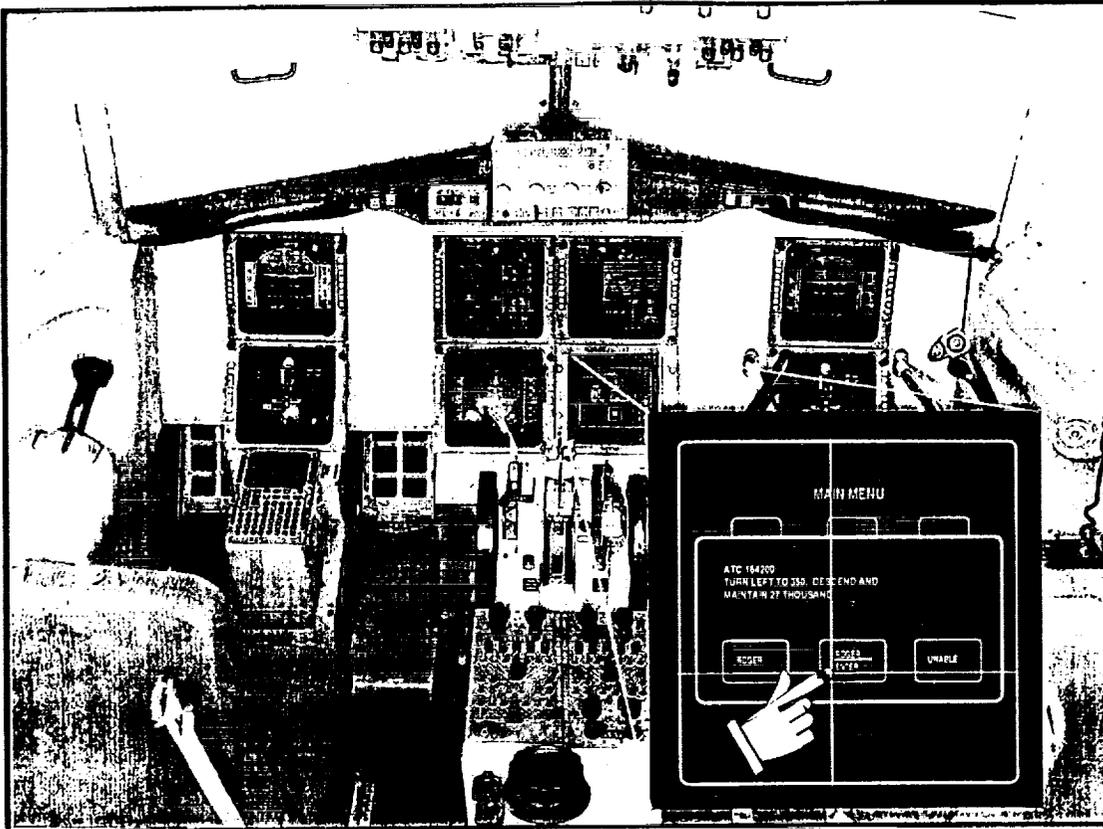
Figure 3.- TSRV cockpit simulator showing location of data link display.
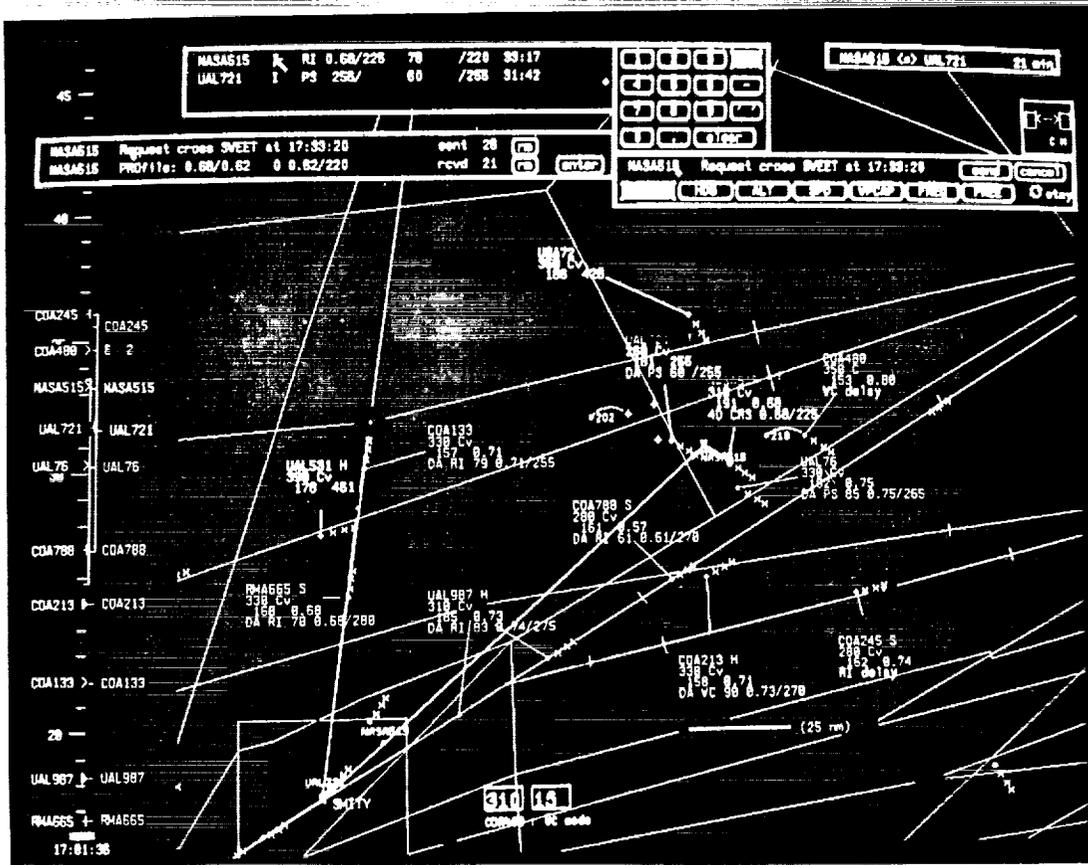

Figure 4.- ATC display.
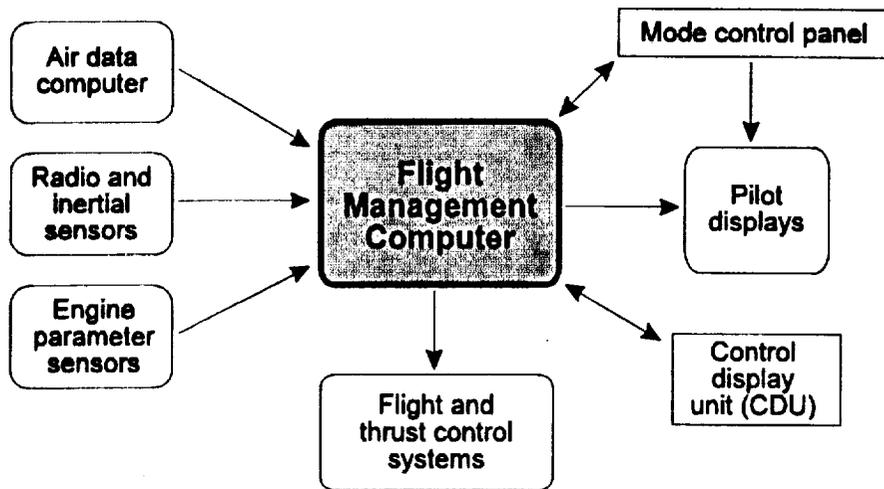
Figure 5.- Schematic diagram of TSRV 4D flight management system.
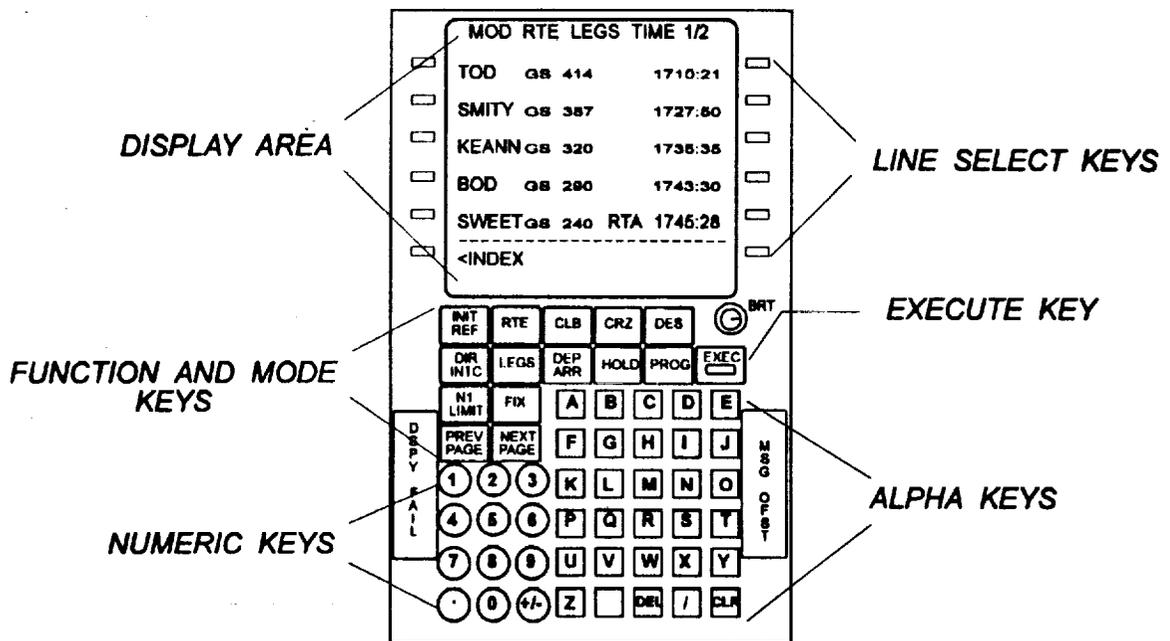
Figure 6.- Control display unit (CDU) format in TSRV simulator.

```
                PROGRESS      1/2
   WPT          DTG          ETA
   SMITY       12.5NM      1727:50z
   ALT          FPA          XTKE
   27850       - 3.1         1.25L
   AE           FPAE         TKAE
    150HT      + 0.1           10 R
   ------------------------------
   86 NM TO RTA  SWEET
   RTA 1745:28   TERR +00:15
   MIN 1744:35   MAX 1746:15
   ------------------------------
   <CRZ
```

Figure 7.- Progress page on CDU showing RTA information.

```
                PERF INIT     1/1
   GROSS WT              CRZ ALT
   92.1                   FL310
   FUEL                 OPT ALT
   15.7                  -----
   ZFW
   76.4


   COST INDEX
    20                 CRZ MODE>
   ------------------------------
   <INDEX              TAKEOFF>
```

Press to
select mode

Toggles between
CRZ MODE and
CI MODE

Figure 8.- Cruise (CRZ) and cost index (CI) selection options on CDU.

Large window -- main menu

Medium window -- downlink messages and information viewing

Small window -- uplinked messages.

Figure 9.- Data link display format.

MAIN MENU

| ATC | WEATHER MENU | ATIS |
| NASA GROUND | VIEW CLEARANCE | VIEW MESSAGES |
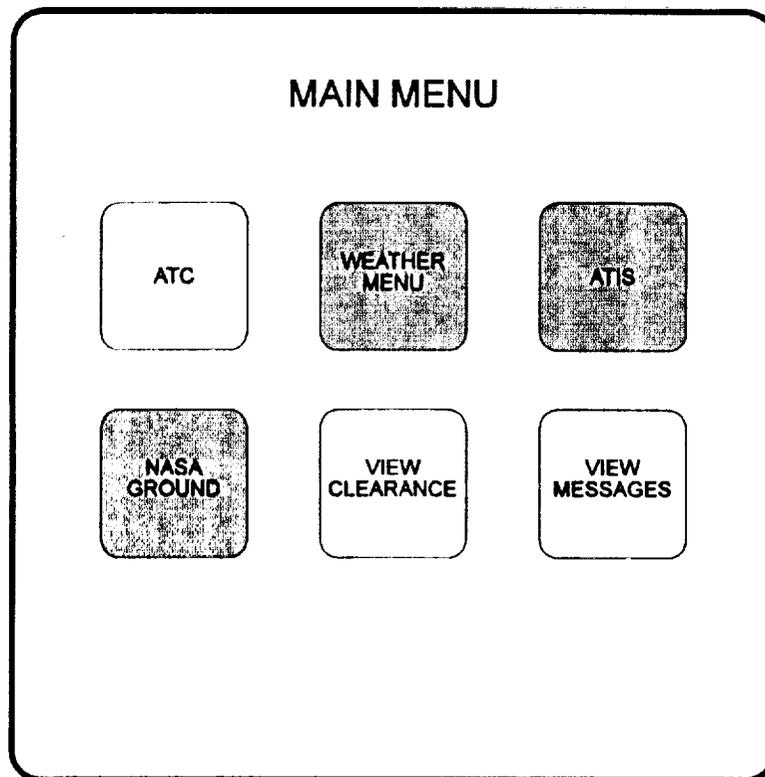
Figure 10.- Data link display main menu.

MAIN MENU

TO ATC

NASA 515 REQUESTS:

ALT FL310	SPEED .72
HDG 270	PROFILE
RTE MOD REQ	CLEARANCE

COMPOSE	SEND	CLEAR	CANCEL
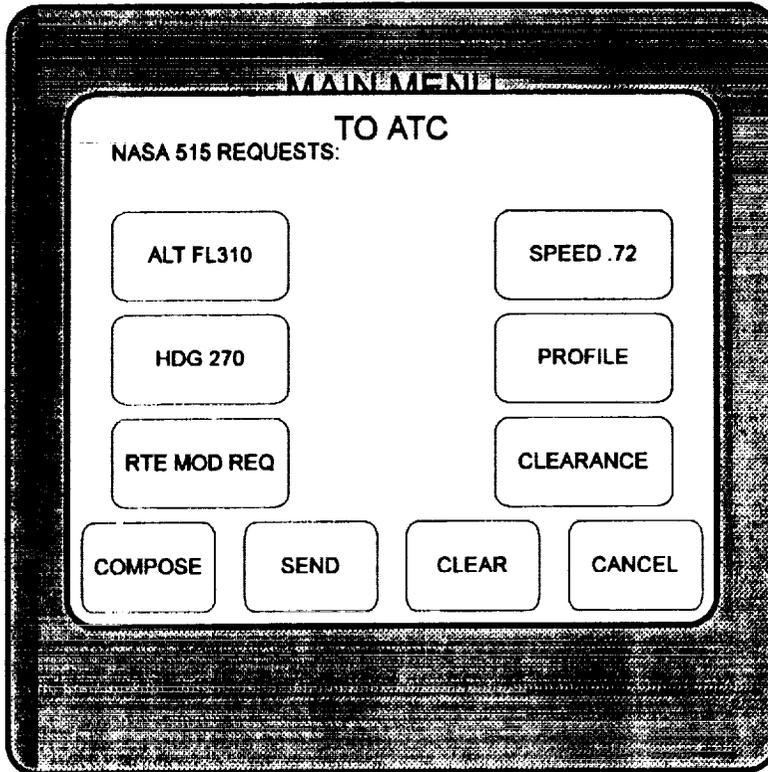
Figure 11.- ATC request data link page.

MAIN MENU

PROFILE TO ATC

NASA 515 REPORTS:

METERING FIX:	SWEET
ETA:	17:28:45
NEXT WPT:	N40 45 7
CLIMB:	—/.—
CRUISE:	.72
DESCENT:	.72 / 280
TOP OF DESCENT:	76 NMI SWEET

SEND

CANCEL
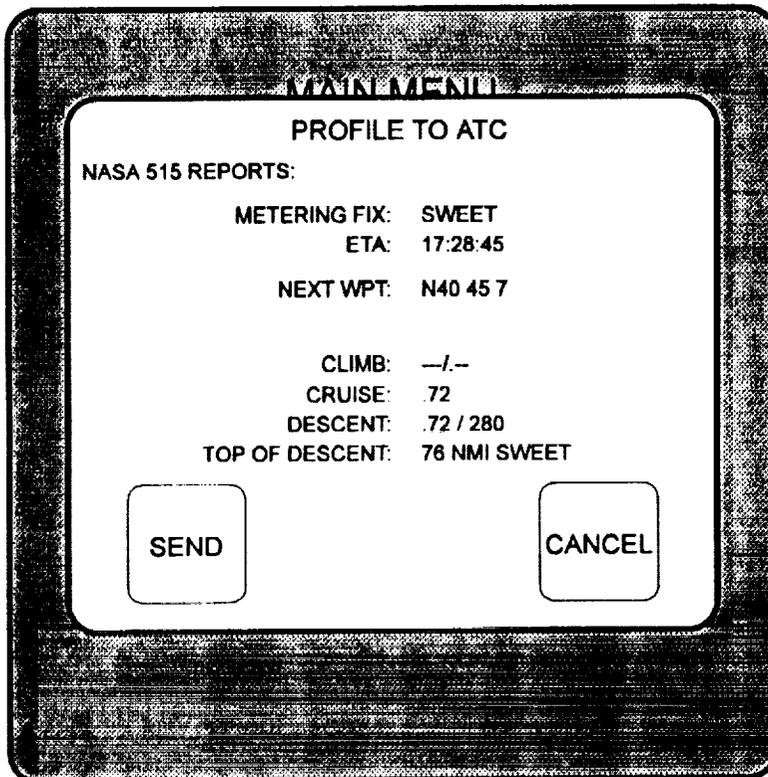
Figure 12.- Profile request data link page.

34
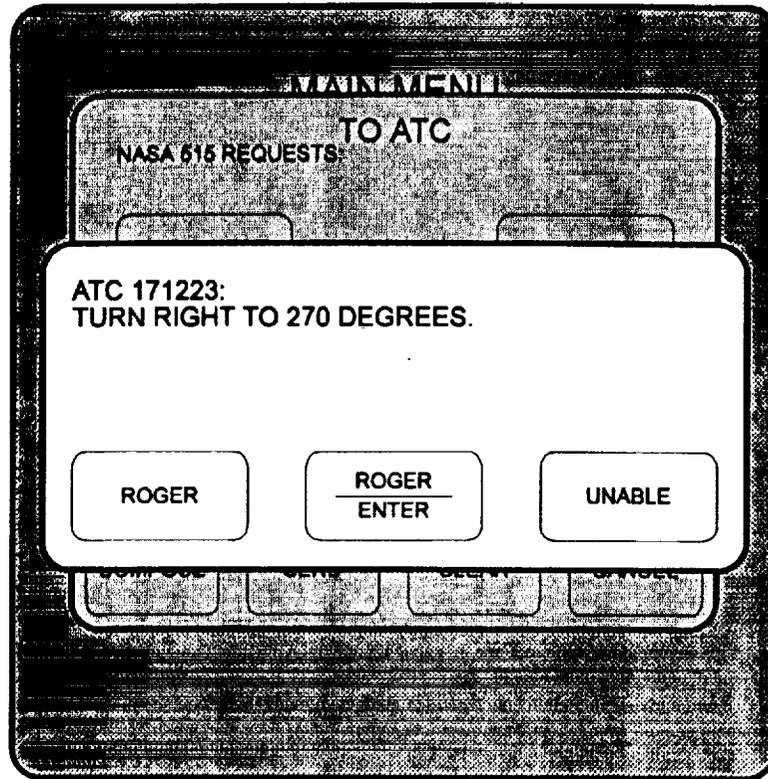
Figure 13.- Sample ATC uplinked tactical message.

Figure 14.- Data link view message display page.

CURRENT CLEARANCE:

KMSP.ONL.J114.KEANN.KDEN

CURRENT ASSIGNMENTS:

|	
ALTITUDE:	FL310
HEADING:	—
SPEED:	.72 MACH
MF TIME:	17:45:10 <EARLY 15>
VOICE FREQ:	134.4 DEN CNT

MAIN
MENU
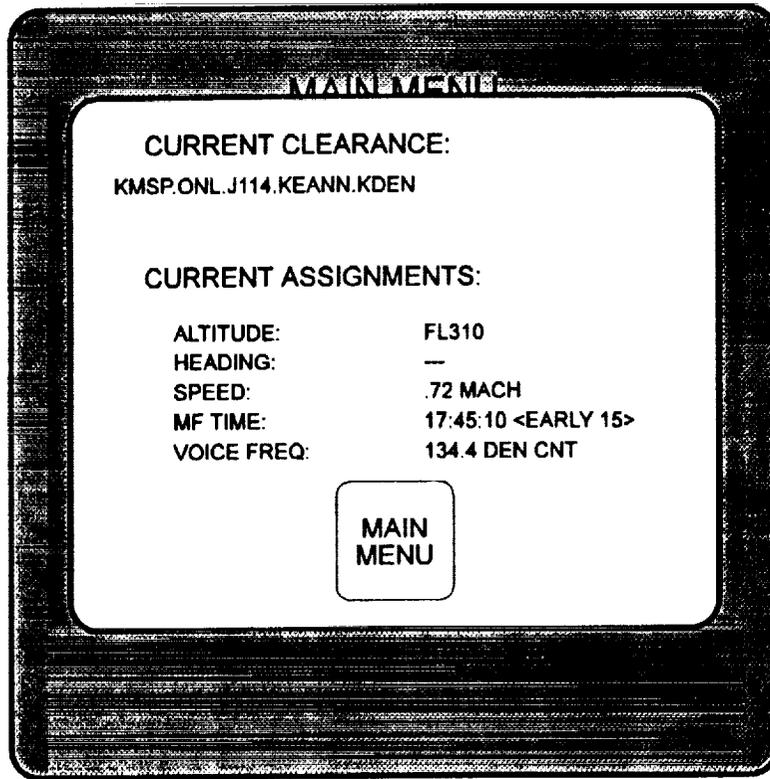
Figure 15.- Data link view clearance display page.
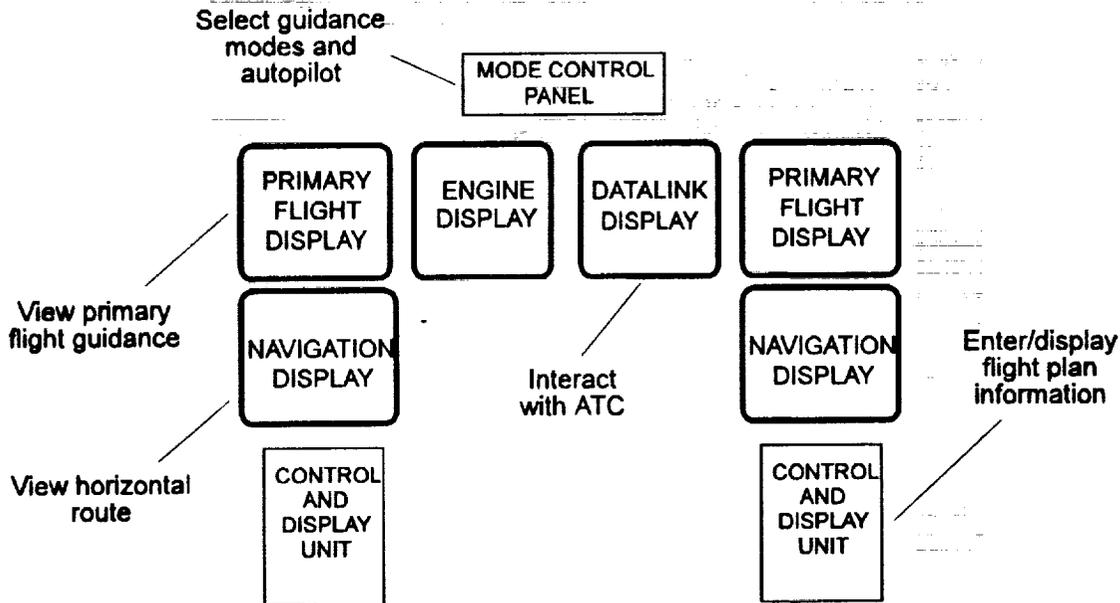
Figure 16.- Display arrangement in TSRV simulator.
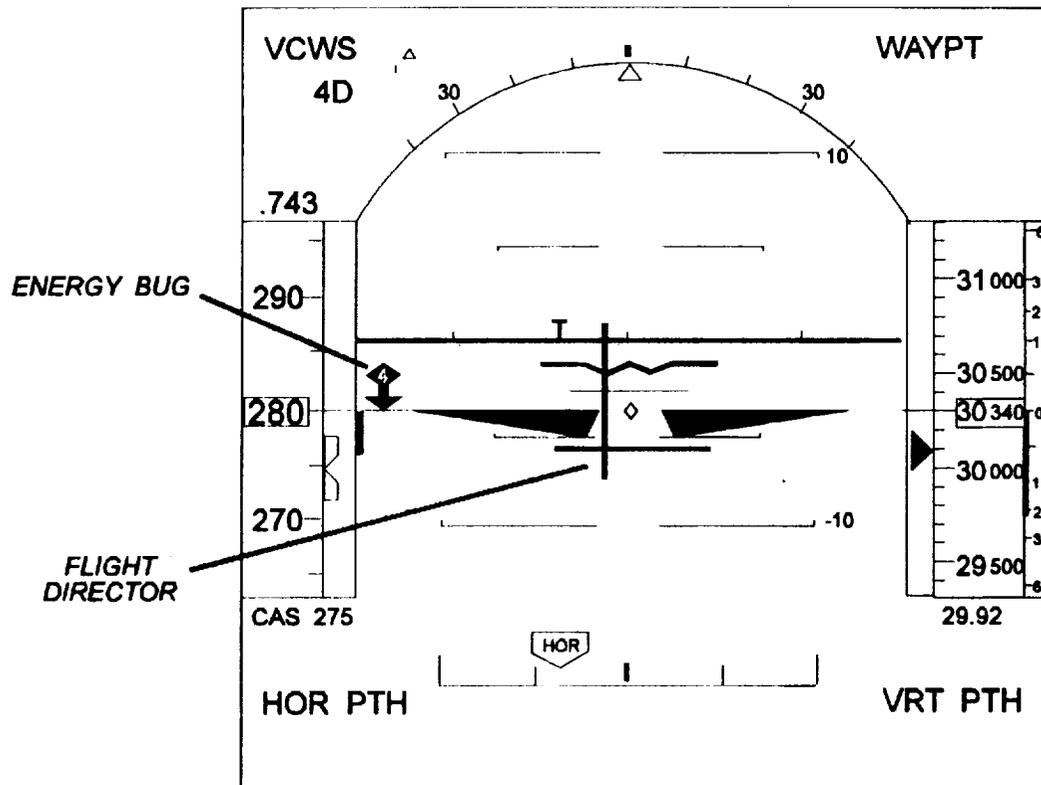
Figure 17.- Primary flight display (PFD) format in TSRV simulator.
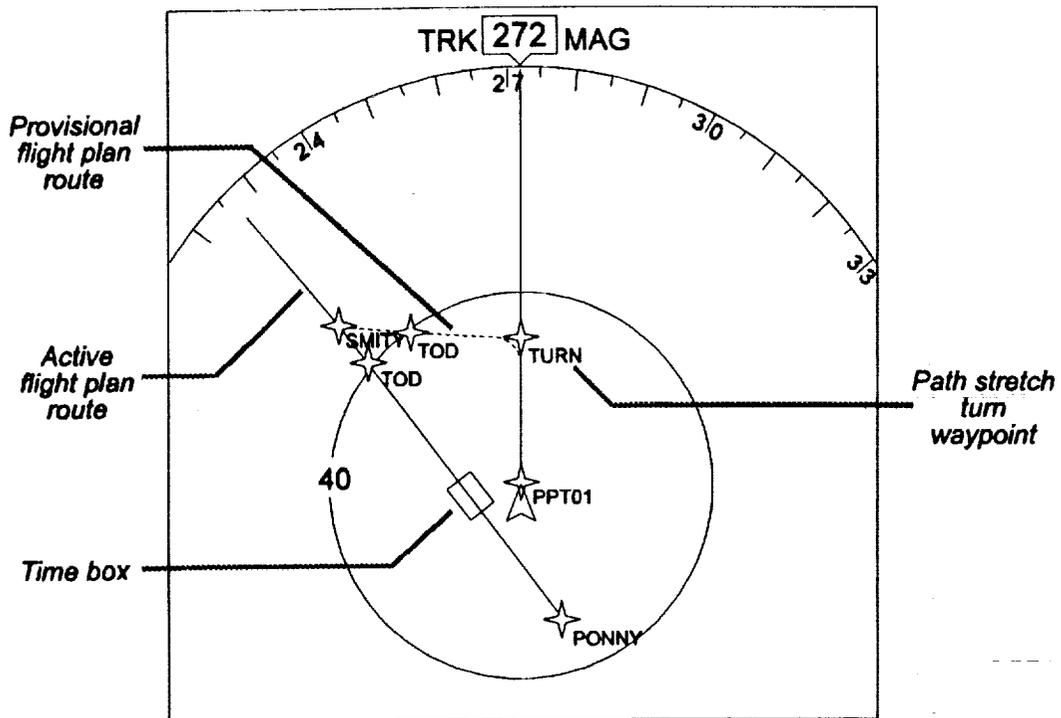
Figure 18.- Navigation display (ND) format in TSRV simulator.
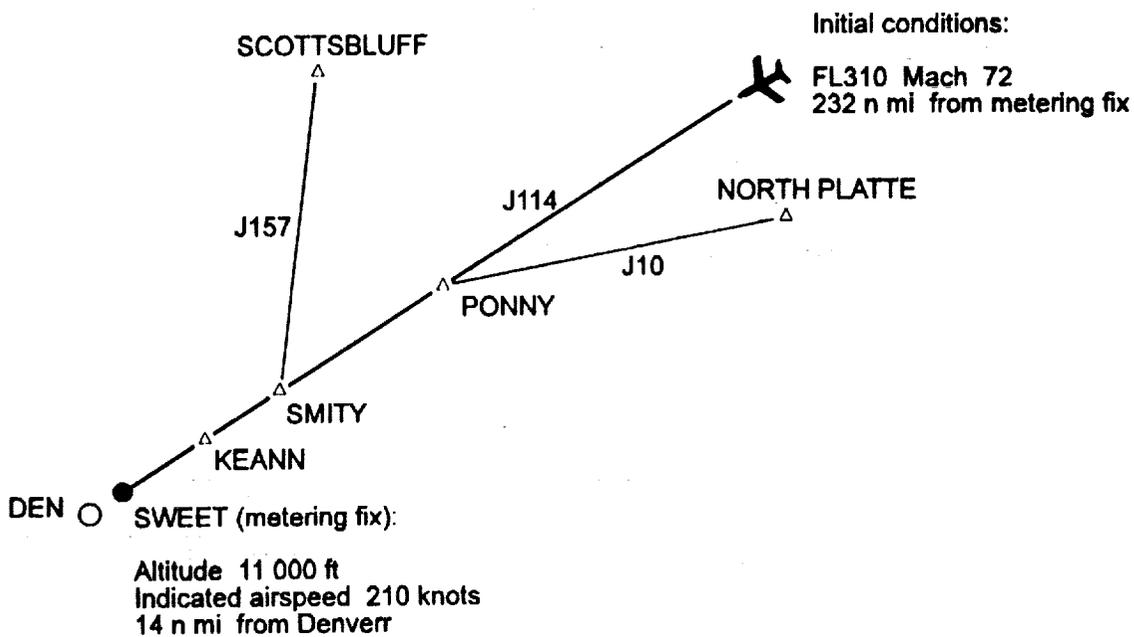
Figure 19.- Simulation scenario showing the arrival route of the TSRV simulator.

```
ATC 173440:

NASA 515, SEND PROFILE FOR UPLINKED ROUTE:
PONNY, J114, KEANN, SWEET, PROCEED DIRECT
TO PONNY, CROSS SWEET AT 17:45:28


    ROGER                          UNABLE
```
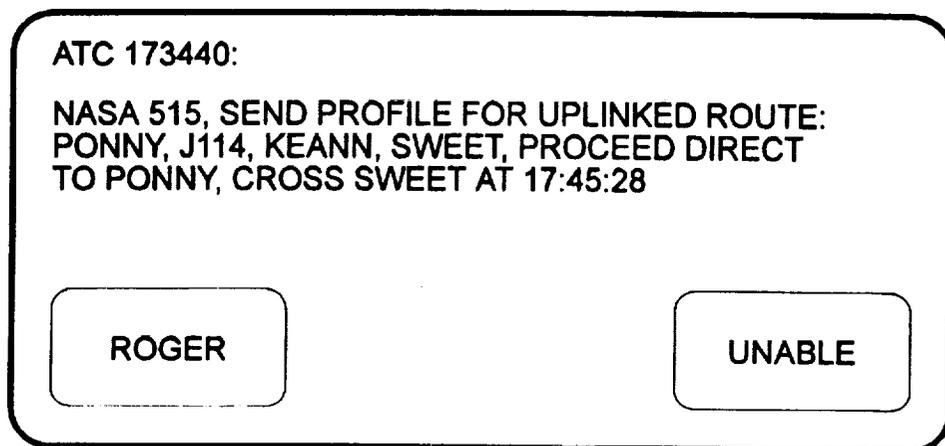
Figure 20.- Profile request data link message.

```
ATC 173510:

NASA 515, CLEARED FOR UPLINKED ROUTE:
PONNY, J114, KEANN, SWEET, PROCEED DIRECT
TO PONNY


    ROGER          ROGER          UNABLE
                   ENTER
```
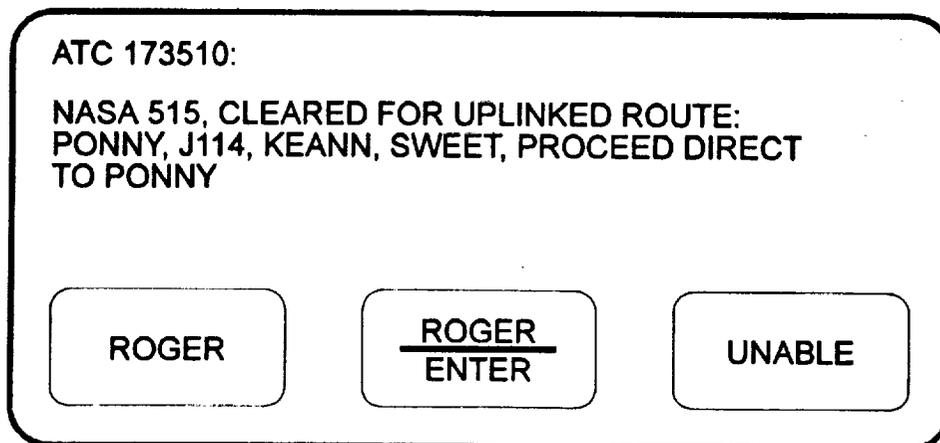
Figure 21.- Route clearance data link message.

ATC 173520:

NASA 515, CLEARED FOR SWEET ARRIVAL,
CROSS SWEET AT 17:45:28 <ON TIME>

ROGER

ROGER
ENTER

UNABLE
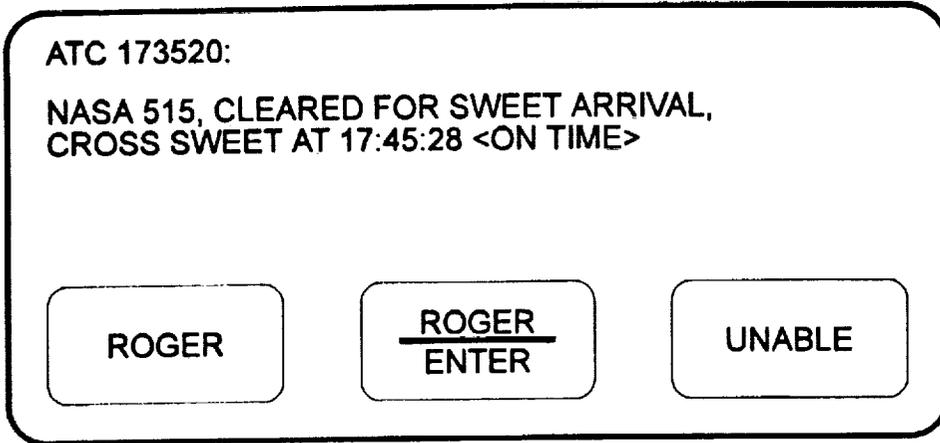
Figure 22.- Arrival clearance data link message.

ATC 173528:

NASA 515, DESCEND 76 NMI DME, .70 MACH
280 CAS

ROGER

ROGER
ENTER

UNABLE
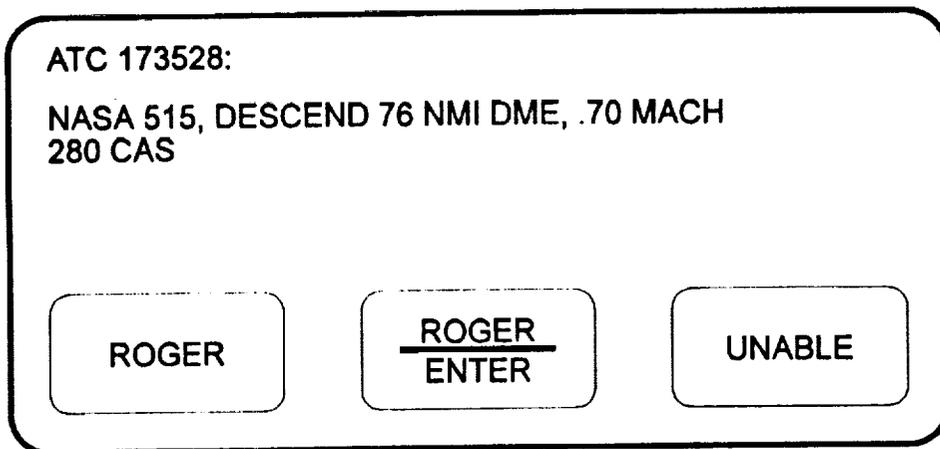
Figure 23.- Vertical profile data link message.

CURRENT CLEARANCE:

KMSP.ONL.J114.KEANN.KDEN

CURRENT ASSIGNMENTS:

ALTITUDE: FL310
HEADING: ---
SPEED: .72 MACH
MF TIME: --:--:--
VOICE FREQ: 134.4 DEN CNT

MAIN
MENU
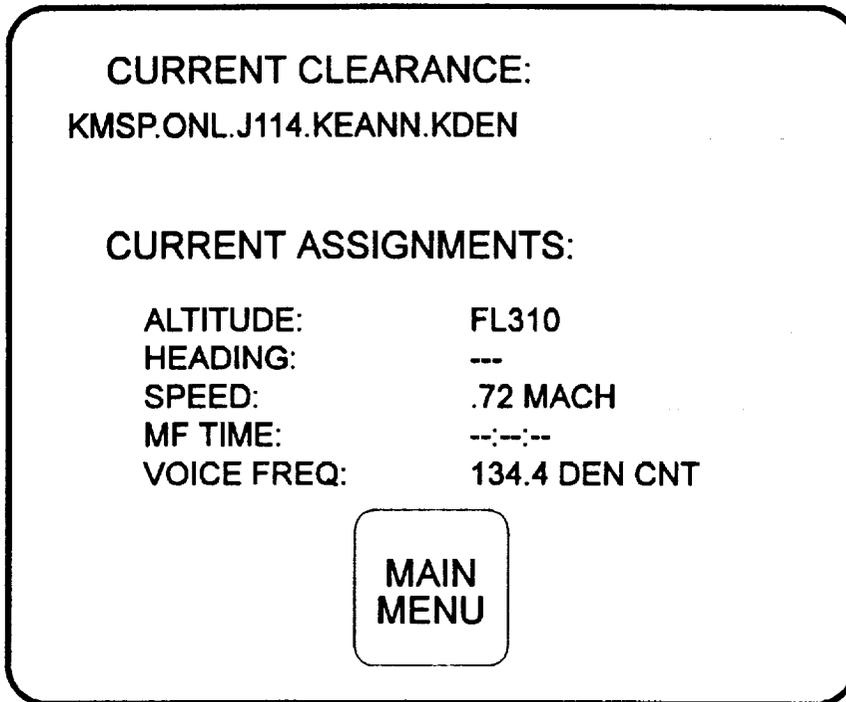
(a) Prior to acceptance of 4D arrival clearance.

CURRENT CLEARANCE:

PONNY.J114.KEANN.SWEET:SWEET ARRIVAL
DESCEND: 76 NMI DEN, .70 MACH 280 CAS

CURRENT ASSIGNMENTS:

ALTITUDE: FL310
HEADING: ---
SPEED: .70 MACH
MF TIME: 17:45:28 <EARLY 15>
VOICE FREQ: 134.4 DEN CNT

MAIN
MENU
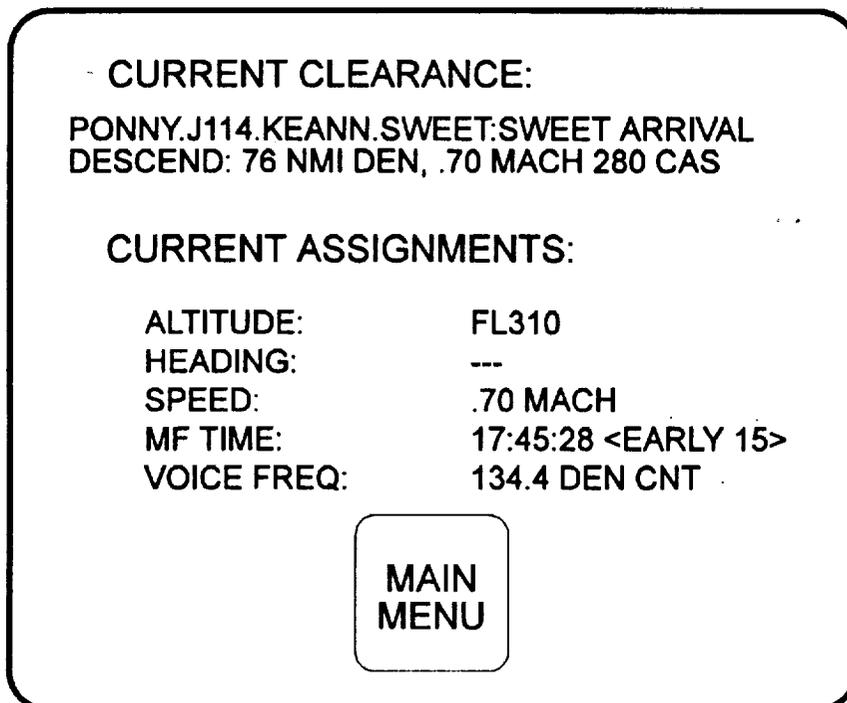
(b) After acceptance of 4D arrival clearance.

Figure 24.- Presentation of 4D arrival clearance on view clearance data link page.
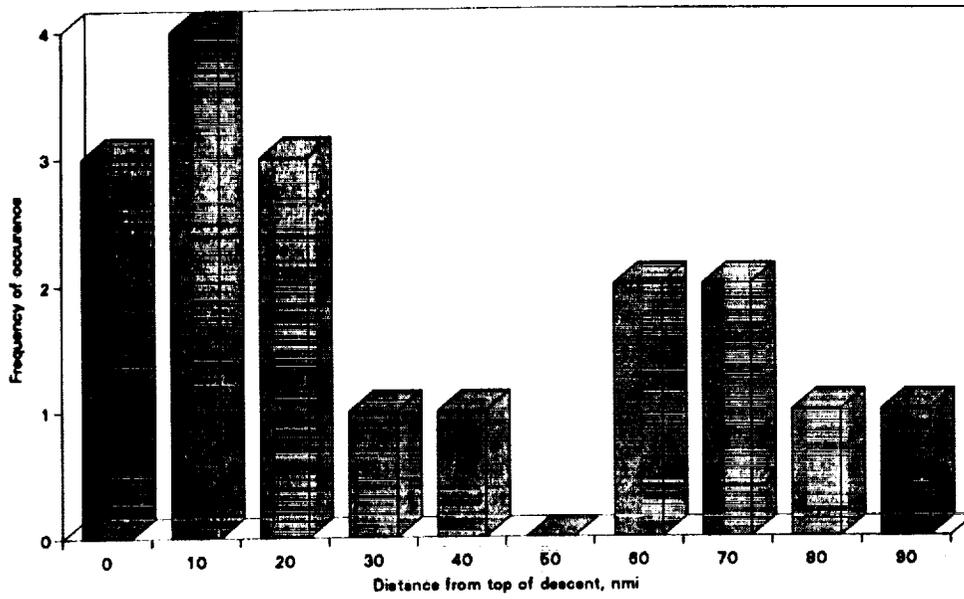
Figure 25.- Distance from top of descent when 4D arrival clearance was issued.
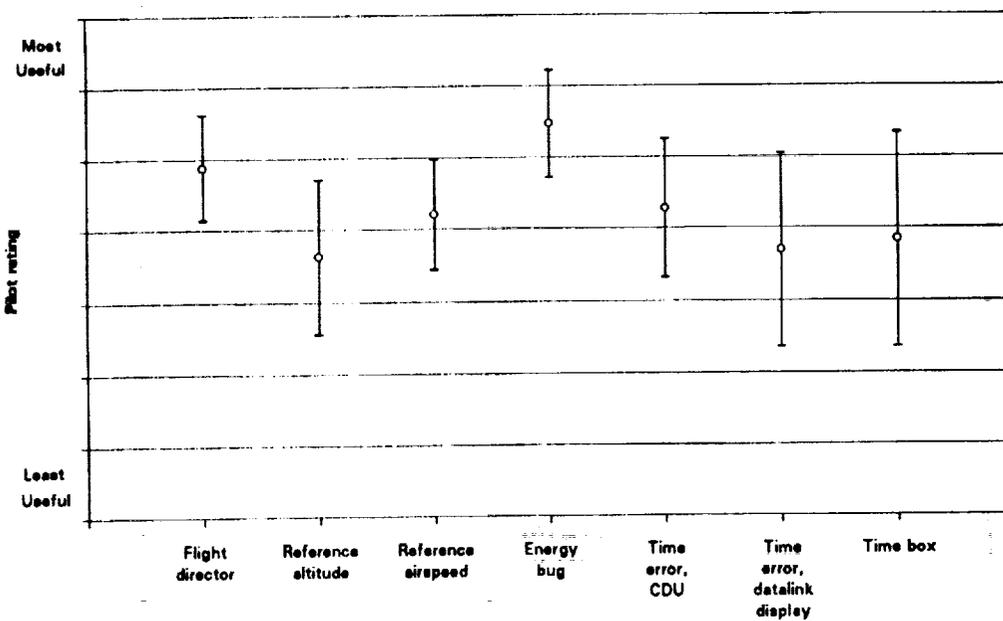
Figure 26.- Pilot ratings on usefulness of display guidance (mean and standard deviation).

Initial Conditions:

FL310, Mach .72
232 nmi from metering fix

DEN
O

SWEET (metering fix)
11000 ft., 210 knots

KEANN

SMITY

PONNY

Delay Method:

1. Holding pattern.
2. Path stretch at cruise speed.
3. Path stretch at nominal speed.
4. Path stretch at minimum fuel speed.
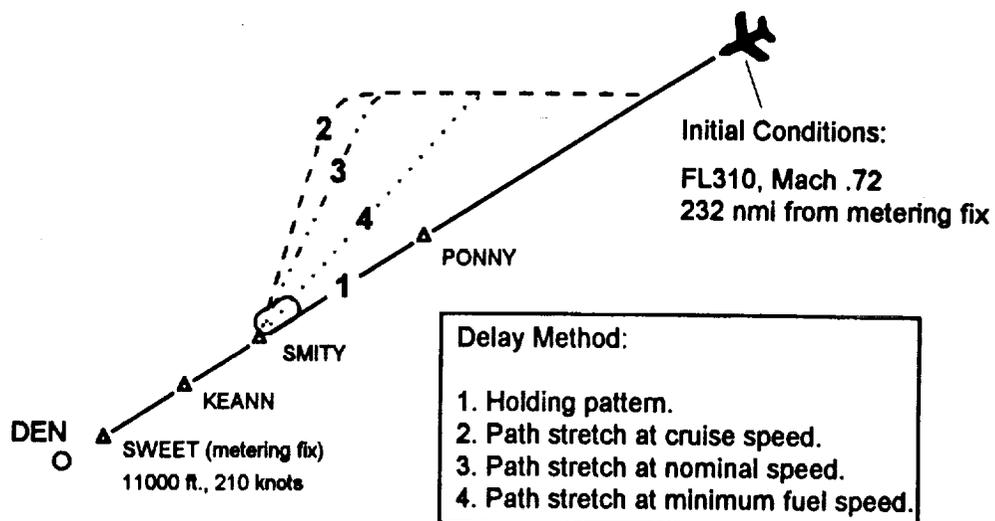
Figure 27.- Horizontal path geometry for the moderate time delay path stretch techniques.

REPORT DOCUMENTATION PAGE

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13. ABSTRACT *(Maximum 200 words)*   Historically, 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. A joint program, between NASA's Ames Research Center (Ames) and Langley Research Center (Langley), is underway to investigate the issues of, and develop systems for, the integration of ATC and airborne automation systems. A simulation study was conducted to evaluate a profile negotiation process (PNP) between the Center/TRACON Automation System (CTAS) and an aircraft equipped with a four-dimensional flight management system (4D FMS). Prototype procedures were developed to support the functional implementation of this process. The PNP was designed to provide an arrival trajectory solution which satisfies the separation requirements of ATC while remaining as close as possible to the aircraft's preferred trajectory. Results from the experiment indicate the potential for successful incorporation of aircraft-preferred arrival trajectories in the CTAS automation environment. Fuel savings on the order of 2 percent to 8 percent, compared to fuel required for the baseline CTAS arrival speed strategy, were achieved in the test scenarios. The data link procedures and clearances developed for this experiment, while providing the necessary functionality, were found to be operationally unacceptable to the pilots. In particular, additional pilot control and understanding of the proposed aircraft-preferred trajectory, and a simplified clearance procedure were cited as necessary for operational implementation of the concept.

14. SUBJECT TERMS
Flight management systems; Air traffic control; Data link; Time-based metering; Profile negotiation

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