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Operational Evaluation of Initial Data Link Air Traffic Control Services, Vol I

Nicholas J. Talotta, et al.

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16. Abstract This report details the results of an operational evaluation of Initial Data Link Air Traffic Control (ATC) Services. The Operational Evaluation was conducted at the Federal Aviation Administration (FAA) Technical Center utilizing the Data Link test bed. Initial Data Link services were evaluated in order to identify service delivery methods which optimize controller acceptance, performance, and workload.					
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PREFACE

This report documents a Federal Aviation Administration operational evaluation of the initial group of four air traffic control services which have been designed for implementation on the Mode S Data Link system. The report is organized in two volumes.

Volume I contains the main body of the report. It includes a detailed description of the objectives of the evaluation and of the technical approach and test methods that were used. In addition, the primary results of the controller and aircrew portions of the study, conclusions, and recommendations are presented.

Volume II contains a set of appendixes to the report. These appendixes are referenced in Volume I and include technical documentation of the test hardware and of controller and pilot Data Link procedures. The appendixes also present detailed analyses of the data which were collected in the study. These appendixes were the basis for the primary results sections presented in Volume I.

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FAA Technical Center, ACD-320

Nicholas Talotta
Albert Rehmann
Thomas Pagano
Thomas Zurinskas
F. Paul Zito
George Chandler
Richard Olson
Francis R. Mullin
Henry Marek

Air Traffic Data Link Validation Team

James O'Malley, ATR-157
Gregg Anderson, Ocean TRACON
Edward Brestle, Ft. Worth ARTCC
Michael Bullington, Sacramento TRACON
Barbara Cassada, Denver ARTCC
Greg Colclasure, Kansas City ARTCC
Mona Colclasure, Kansas City ARTCC
Joe D'Alessio, New York TRACON
Evan Darby, Miami ARTCC
Dana Jones, Ft. Worth ARTCC
Jerry Karrels, Madison, WI Tower
Charlotte Long, Ontario, CA TRACON
Michael Moss, Denver TRACON
Tom Ray, Tulsa Tower
Steve Reutepohler, Cleveland ARTCC
Joe Strietzel, Anchorage ARTCC

NTI, Incorporated

Dr. Clark Shingledecker

DTC Corporation

John Evans
Dan Kashey
James Merel

MITRE Corporation

Alex Alstein
Frank Buck
Preston Cratch
Haim Gabrieli
Dr. Karol Kerns
Dave Sweeney
William Van Campen

Midwest Systems Research Incorporated

Marc Neumeier
Michael Reynolds

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EXECUTIVE SUMMARY

INTRODUCTION.

The Federal Aviation Administration (FAA) is pursuing an initiative to develop and implement a Data Link system intended to enhance communications between ground-based air traffic control (ATC) and airborne systems. By providing digital information transfer with the ability to discretely address individual aircraft, Data Link is expected to relieve frequency congestion on existing voice radio channels while increasing the overall safety and productivity of the ATC system.

In order to insure that the introduction of Data Link will have an optimal positive impact on ATC, the FAA is conducting a program of research to guide system design efforts, evaluate the benefits of Data Link to ATC, and assess its effects on the air traffic controllers and aircrews who will use the system. Preliminary design studies completed during the past year (Talotta, et al., 1988, 1989) defined the detailed configurations for the initial group of ATC services and functions scheduled for implementation on Data Link. This report presents the results of the first operational evaluation of these initial capabilities in a full scale, ATC simulation manned by en route air traffic controllers. In addition, this report presents the findings of a concurrent study in which aircrews flying simulated aircraft in the ATC scenarios evaluated the initial services and a preliminary flight deck display/control device for Data Link communications.

OBJECTIVES.

The general purpose of the air traffic controller substudy was to assess the impact of the initial package of Data Link ATC services and functions in the context of a high fidelity simulation of en route ATC activity. The specific objectives were to measure the beneficial effect of Data Link on voice radio frequency congestion and to determine the impact on ATC performance and effectiveness, controller workload, and controller acceptance. The aircrew substudy was designed to evaluate the overall effectiveness of Data Link communications in aircraft operations both for the ATC services uplinked by the subjects in the controller substudy, and for a set of Data Link weather services available by direct aircrew interaction with simulated data bases.

DATA LINK SERVICES.

Two ATC services and two general Data Link functions were tested in the controller substudy. The ATC services were altitude assignment and transfer of communication. Data Link procedures for both of these services were designed to closely parallel current en route controller procedures with the addition of a minimal

number of keyboard actions. The status of Data Link transactions with aircraft were displayed in a Plan View Display (PVD) list and in the Full Data Block (FDB). Aircraft equipage and uplink eligibility were indicated by graphic characters in the first field of the FDB.

The Data Link ATC functions were menu text and free text. Menu text permits standard or frequently required ATC messages to be stored in a menu displayed on the PVD and selected for uplink as required. For the present study, menu messages were restricted to interim altitude assignments, sometimes combined with fix crossing restrictions. Free text provides controllers with the ability to engage in unconstrained ground-air communications using typed keyboard entries. This function is envisioned primarily as a back-up communications capability.

In addition to the primary ATC services delivered by the controllers, the aircrew substudy also examined a group of weather services which the pilots could request by direct downlink to a data base. These services were terminal forecast, winds/temperatures aloft, surface observation, and Pilot Reports (PIREPS). The aircrew received and responded to Data Link messages on a touch sensitive display.

APPROACH.

The evaluation was conducted in the FAA Technical Center's Data Link Test Bed. Two 30-minute test scenarios presented controllers with realistic en route ATC problems involving four sectors of adjacent airspace. A majority of the aircraft in the scenarios were simulated radar targets controlled by simulation operators. However, two of the targets in each test run were driven by high fidelity simulators representing a large transport aircraft and a small General Aviation (GA) aircraft. The airliner was manned by professional aircrews, while the small aircraft was flown by GA pilots.

The eight en route controllers participated in teams of four in 14 test runs in which Data Link equipage levels of the air traffic ranged from 0 (voice radio only) to 20 and 70 percent. In one of the runs, average uplink and downlink times were extended to assess the impact of "worst case" Data Link communication transmission delays. Each of the four participating aircrews and the four GA pilots participated in two Data Link runs and one baseline, voice-only run.

Controller measures included records of voice and Data Link usage, ratings of controller workload and service design acceptability, estimates of operational effectiveness, a wrap-up questionnaire, and extensive debriefing to elicit required Data Link design modifications. Aircrew measures evaluated perceptions of the effectiveness of the services and the usability of the preliminary

flight deck Data Link Input/Output (I/O) device. Times required for aircrew to detect and respond to Data Link and voice messages also were recorded.

PRIMARY RESULTS.

The controller substudy clearly demonstrated the benefit that the initial group of Data Link services can be expected to have on relieving frequency congestion of voice radio channels. The availability of these functions reduced the number of controller voice transmissions by up to 41 percent, and total controller occupation time of the radio frequencies by up to 15 percent (see figure ES-1). Furthermore, as more Data Link equipped aircraft were introduced, there was an apparent increase in the efficiency of the communication process as requirements for repetition of voice messages and clarification of clearances were reduced.

The positive impact of Data Link was not achieved at any observed loss in ATC performance or controller capability. No critical ATC incidents were noted during the tests, and controller workload estimates were statistically identical in the voice and Data Link conditions (figure ES-1). The results also showed that Data Link transmission delays failed to have a negative effect on controller activities. All of the specific designs for the Data Link services were rated as operationally effective and acceptable to controllers.

The results of the aircrew substudy indicated that initial pilot perceptions of Data Link were positive and that its implementation would enhance the quality of air-ground communications. Additional findings indicated that the average total times between receipt of a message in the aircraft and the crew response to ATC ranged from 9.8 seconds in the voice conditions to 10.9 seconds in the Data Link conditions.

The workload associated with Data Link operations was considered acceptable to pilots. Furthermore, while the aircrew subjects indicated further development of display formats and crew coordination procedures will be required, they felt that persistent Data Link displays will reduce demands on pilot memory and that Data Link will be capable of replacing most functions currently served by voice radio in en route environments.

RECOMMENDATIONS.

Based on the results outlined above, it is recommended that the initial group of Data Link ATC services be incorporated as modifications to current en route ATC software and hardware, and that they be subjected to operational test and evaluation (OT&E). Minor outstanding design issues and potential enhancements revealed by the present study should be examined by the Air Traffic Data Link Validation Team (ATDLVT) and resolved. It is further

recommended that, because of the success of the operational evaluation and the positive impressions expressed by participating controllers and pilots, research and development work be expedited to extend Data Link applications to the full range of en route and terminal ATC services.

Because the development of refined flight deck interfaces has lagged behind corresponding ground controller work, it is recommended that additional studies be conducted to facilitate the integration of Data Link with the aircrew task environment.

Finally, in order to identify mutually acceptable rules and procedures which will govern pilot and controller communications using Data Link, it is recommended that a mechanism be created to promote relevant interactions between the ATDLVT and a representative pilot group.

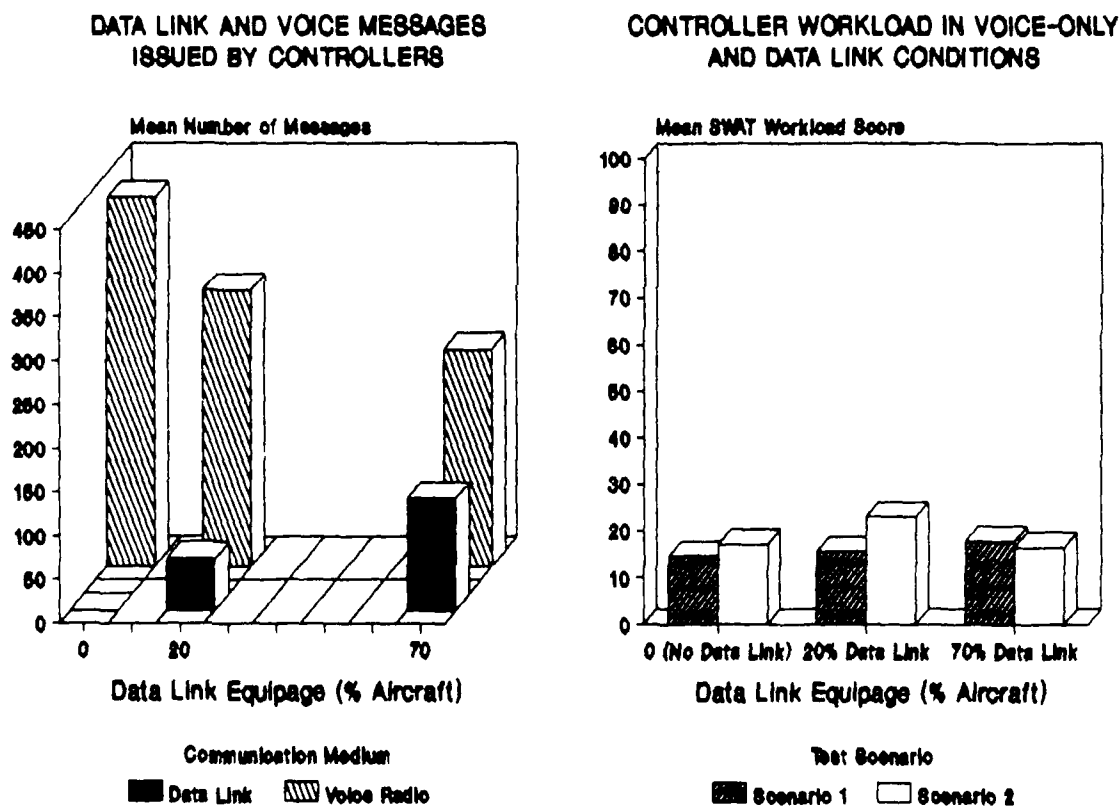


FIGURE ES-1. MESSAGES ISSUED AND WORKLOAD

1. INTRODUCTION.

1.1 PURPOSE.

This document presents the results of a Federal Aviation Administration (FAA) operational evaluation study of the initial package of en route air traffic control (ATC) services designed for implementation in the Mode S Data Link system. The study employed high fidelity, integrated simulations of the ATC and flight deck environments involving both en route air traffic controllers and pilots. Test trials were conducted to compare Data Link communications to current voice radio procedures using measures of system effectiveness and productivity as well as controller and pilot performance, workload, and acceptance.

1.2 BACKGROUND.

1.2.1 Data Link Requirements.

The extraordinary increase in commercial and general air traffic in recent years has begun to tax the practical limits of the ATC system in the United States. Because this growth is expected to continue into the next century, the FAA has devised the National Airspace System (NAS) Plan to update and enhance ATC technology. Implementation of the NAS Plan commenced in 1982 with the primary goals of improving ATC system safety, increasing its efficiency, improving the ability of air traffic controllers to handle increasing levels of traffic, and reducing operational errors.

One of the major factors which constrains the productivity of the current ATC system is the communication channel between the air traffic controller and the aircraft pilot. Because this voice radio link operates in a broadcast mode between a single controller and all aircraft contained within the airspace under his control, frequency congestion rapidly consumes available communications time and reduces system efficiency when the volume of air traffic increases. In addition, the resulting interference from simultaneous attempts by multiple pilots to contact a controller, and from other noise factors common to very high frequency (VHF) voice communications, increase the possibility of interpretation errors in crowded ATC environments.

A key component of the NAS Plan that was developed to address the problems of frequency congestion and communications errors is the ground-air Data Link. In general, Data Link provides digital, two-way communication between an aircraft and the ATC system. Unlike voice radio, Data Link can offer both automatic error checking of uplinks and downlinks, and a discrete addressing capability so that an aircraft receives only those communications directed to it by the ground system.

1.2.2 Mode S Data Link.

The NAS Plan technology which will be used to implement Data Link is the Mode Select Beacon System (Mode S). Mode S is a secondary surveillance radar which will replace the current Air Traffic Control Radar Beacon System (ATCRBS). ATCRBS uses a ground-based rotating antenna that transmits continuous radio frequency interrogations to which a transponder equipped aircraft will respond. The replies provide the ATC system with an aircraft identification code or the aircraft altitude. Aircraft location information is derived from the rotational position of the antenna and the transponder delay at the time a reply is received.

Mode S will provide the same functions as ATCRBS, but will do so more accurately while offering the additional capabilities of a Data Link. These enhancements are possible because each aircraft will be assigned a unique address code which will be used in the system's interrogations to select only the requested aircraft to respond. Figure 1 illustrates the primary airborne and ground-based components of Mode S.

Because of its flexibility and large capacity, the Mode S Data Link will be a primary enabling technology for the final phases of the NAS Plan which call for high levels of automation and direct communication between ground-based computers and aircraft avionics. In addition, however, Data Link holds the potential for enhancing the ATC system in both the near term and the more distant future by providing controllers and aircrew with a second means of conducting essential communications that can be used to relieve the growing burden on the voice channel.

1.2.3 Impact on Controllers and Aircrews.

The primary way in which Data Link can improve the safety and efficiency of ATC is through its potential positive impact on the tasks of the human operators in the system. The first service to be provided by Data Link will be automated delivery of weather information to aircraft. Pilots will benefit from this service because it will provide weather data on demand which often will be more current and relevant than the information currently available via voice radio requests. In addition, this service should favorably affect controller task load by eliminating any requirement to verbally relay weather data to aircraft, thereby allowing them to concentrate on the primary duty of maintaining aircraft separation.

Beyond the enhancements that will be achieved by removing weather communications from the voice radio channel, even more significant improvements will be possible through the delivery of primary ATC services using Data Link. ATC instructions such as transfer of communication, altitude assignments, and heading changes currently

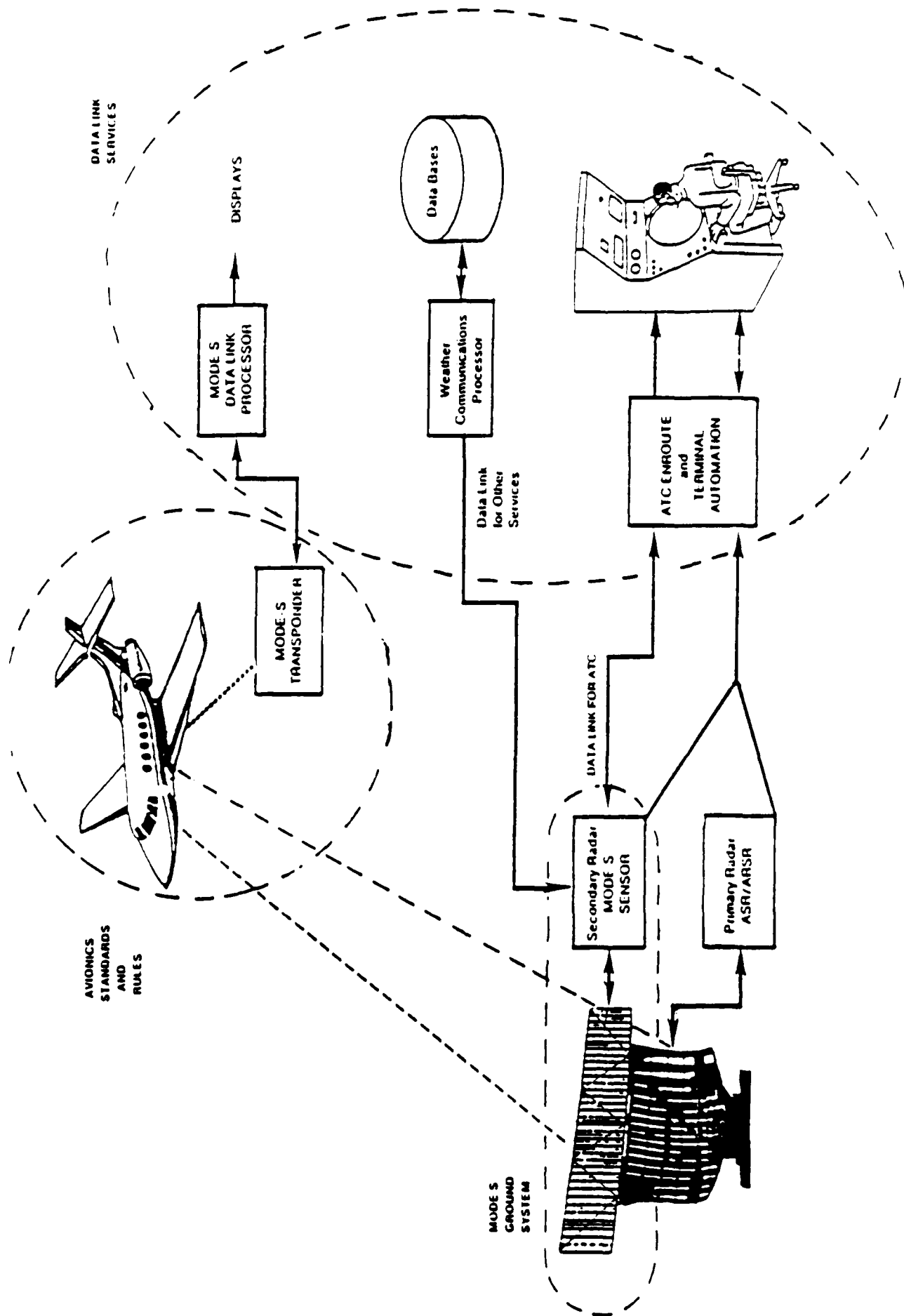


FIGURE 1. MODE S SURVEILLANCE AND DATA LINK

form the bulk of radio transmissions which contribute to frequency congestion. With a dual channel communications system it will be possible to transfer many of these essential messages to Data Link, while reserving voice radio for time-critical instructions. Thus, controllers should be able to circumvent situations where the voice channel is unavailable for issuing important directions. Likewise, pilots stand to benefit from uplinked ATC clearances because they will be required to monitor fewer radio transmissions for messages directed to their aircraft. Furthermore, because Data Link will provide digital information to the avionics display system, pilots will have an accurate and recallable record of uplinked clearances. This feature should reduce the pilot's memory load and reduce misinterpretation of messages, requests for repeats of instructions, and possible flight control errors.

A final potential advantage of Data Link for both the airborne and ground-based participants in the ATC system will accrue from its application as a general secondary communications channel. The availability of Data Link for emergency communications required because of radio failures, mistuned radios, and blocking of channels by inadvertently actuated microphone switches will provide both pilots and controllers with a "safety net" that is unavailable in the current system.

1.2.4 Requirement for Operational Testing of Data Link.

As noted above, Data Link offers a number of technical features which have the capability to enhance the safety and productivity of the ATC system. However, Data Link will also profoundly change both the way in which ATC tasks are accomplished by controllers and the way in which pilots will receive and respond to ATC instructions. Because of this, the ultimate success of Data Link is critically dependent on the extent to which it is employed to produce a system that is fully integrated with the human operators who will be required to use it.

The goal of the operational evaluation study reported here, and that of other pilot and controller studies conducted under the Data Link program, is to promote this human-machine integration through scientific testing of procedures and pilot-controller interfaces under simulated ATC and flight conditions. The specific intent of this program of research and evaluation is to assess the actual benefit of Data Link to ATC and to insure that these benefits are not outweighed by decrements in the performance or increases in the workload of controllers and aircrew who use the system.

1.3 DATA LINK TEST BED.

The research reported in this document was conducted in the Data Link Test Bed Facility located at the FAA Technical Center. The test bed was assembled to provide both engineering testing and evaluation capabilities during controller and pilot in-the-loop

simulation. Figure 2 presents a functional diagram of the main components of the test bed and their interconnections.

A central feature of the test bed facility is that it permits development and evaluation of Data Link services on actual en route ATC workstations and associated computers rather than on emulation systems. As a result, subject controllers are able to make confident evaluations of the operational feasibility of the tested services. In addition, the capability to integrate high fidelity flight simulators into the communications and radar display systems of the test bed makes it possible to elicit similarly confident judgments from pilots, and to examine issues involving the interaction between controllers and pilots.

During each test run of the simulation study described in this report, subject controllers were presented with simulated radar data and ATC system information from the HOST computer. The majority of the simulated aircraft in the test scenarios were controlled from computer terminals by simulation operators who also provided voice and Data Link responses to the air traffic controllers.

In addition, two of the aircraft in each scenario were full fidelity flight simulators linked to the test bed and under the control of professional and private pilots serving as test subjects. One of these aircraft was a Boeing 727 simulator located at the National Aeronautics and Space Administration (NASA) Ames Research Center in California and manned by commercial airline flight crews. The second was a GAT-2 general aviation simulator located at the FAA Technical Center and controlled by private pilots.

1.4 TESTED DATA LINK SERVICES.

The initial package of services scheduled for implementation in the Data Link system and tested in this study includes weather information and four ATC services and functions. These ATC services and functions are altitude assignment, transfer of communication, menu text, and free text.

The altitude assignment service will transmit digital altitude clearances to an aircraft display as a substitute for the voice radio clearance used in the current system. Transfer of communication is presently accomplished by a voice contact with a pilot following a transfer of control between two sectors. Using Data Link, a digital message containing the new radio frequency will be prepared automatically when the transfer of control is accepted. The transferring controller will then uplink the new frequency to the aircraft before it crosses the sector boundary.

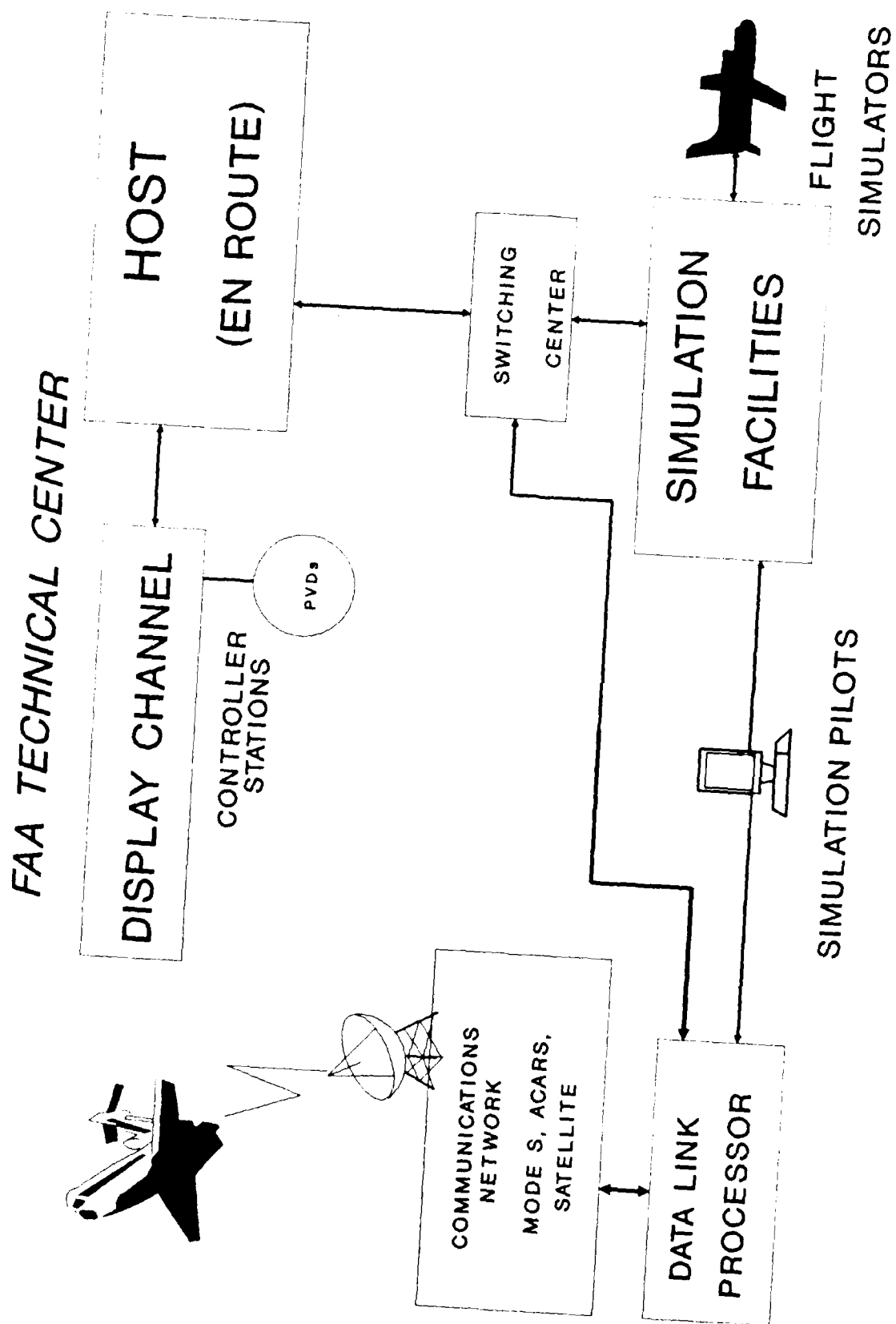


FIGURE 2. DATA LINK TEST BED

Menu text is a general Data Link function which will permit standard or frequently required ATC messages to be stored in menu form on the controller's display. These common clearances can then be uplinked as needed by designating the appropriate menu item. For the operational evaluation, menu text was incorporated into the altitude assignment service to provide uplinks of repetitively required interim altitudes and fix crossing restrictions.

Free text will provide controllers with a capability to engage in unconstrained ground-air communications with Data Link equipped aircraft using typed keyboard entries. This service will permit controllers to compose and uplink textual messages, thereby providing an emergency back-up channel for voice transmissions.

In the present study, controllers used the four ATC services and functions described above to provide pilots with radio frequency changes, unconstrained free text messages, and altitude clearances which, when sent via menu text, could include crossing restrictions. The aircraft Data Link displays were touch-sensitive, light emitting diode (LED) units which presented clearance and weather information and received manual response inputs for downlink to the controllers. Additional pilot inputs to the unit were used for display management and issuing weather requests. As intended in the Data Link system design, the weather services involved direct interaction between the pilots and a weather data base. Since the controllers did not participate in these transactions, they did not evaluate the weather services.

1.5 ORGANIZATION OF THE REPORT.

The following sections of this report present the detailed results, conclusions, and recommendations derived from the operational evaluation study. Because somewhat different issues were addressed from the two perspectives, individual chapters are devoted to the design and results of the controller (section 2) and aircrew (section 3) substudies. Section 4 emphasizes those results of both substudies which bear on joint aircrew and controller issues. Section 5 presents the overall conclusions of both substudies, and section 6 lists the recommendations for future work that were derived from the operational evaluation.

All appendixes referenced in sections 2 through 4 are contained in volume II of this report.

2. DATA LINK CONTROLLER SUBSTUDY.

2.1 OBJECTIVES.

2.1.1 The Data Link Controller Evaluation Program.

The overall test plan for controller evaluation of Data Link ATC services calls for research to achieve two major objectives.

First, the results of controller studies must determine the design of operational procedures, data display methods, and controller inputs for each of the subject services. Second, these studies must also evaluate the impact of Data Link services on overall operational ATC system performance and insure that they are acceptable to controllers and fully usable in operational environments.

In order to address both of these objectives in an efficient manner, a two-stage process was devised to evaluate individual groups of Data Link services as they are developed. In the first stage, highly controlled, part-task simulation studies are conducted to reduce the number of potential service design alternatives to a reasonable set. These "mini" studies focus on formal testing of display and procedural options rather than on high fidelity simulation of the ATC environment. The primary criteria for option evaluation in the mini studies are measures of projected controller workload and acceptance. These metrics are supplemented by structured discussions and design critique sessions conducted to elicit expert controller opinions.

In the second stage of the evaluation process, operational evaluation studies are planned to exercise the finalized designs in the context of full-scale ATC simulations. The general goals of the operational evaluation stage are to confirm the optimality of the design for each Data Link service, and to verify the projected benefits of Data Link under various realistic operational conditions.

2.1.2 Preliminary Controller Mini Studies.

In accordance with this test plan, two mini design studies and several design generation and critique sessions were conducted on the initial package of Data Link services with en route air traffic controllers from the Dallas/Ft. Worth Air Route Traffic Control Center (ARTCC), and with the recently formed Air Traffic Data Link Validation Team (ATDLVT). These iterative research efforts examined basic display and procedural issues and produced designs for the transfer of communication, altitude assignment, menu text, and free text services.

Complete documentation of the results of these mini studies are contained in two FAA Technical Center reports (Talotta, et al., 1988, 1989). Particularly noteworthy findings of the studies included strongly positive controller responses to Data Link and the individual services that were evaluated. Specific results produced modified display designs which present the status of ongoing Data Link transactions in both a list form on the Plan View Display (PVD), and in an abbreviated form in the Full Data Block (FDB). Controller inputs from the studies also contributed to the evolution of service designs which minimize keyboard and trackball entries with automatic preparation and deletion of messages.

Procedurally, the controllers who participated in the mini studies preferred service delivery methods which were designed to be as similar as possible to current ATC practices. In addition, the controllers supported the use of Data Link as a primary service delivery mode rather than as a confirmatory follow-up to voice clearances.

As dictated by the results, all designs require a downlinked "WILCO" response from pilots to complete a transaction. Finally, while automatic procedures were considered useful by the test subjects, the findings of the mini studies also revealed a requirement to design a majority of the services with a capability for controllers to maintain manual control over the specific destination for entries into the system (e.g., to the pilot, to the NAS data base, to the FDB display, or any combination of the three) and over the time at which an uplink occurs.

2.1.3 Objective of the Operational Evaluation.

The research reported in this document represents the culmination of the series of studies conducted on the initial package of Data Link ATC services and functions. As mandated by the test plan, this study was designed to assess the optimality of the services developed during the mini studies in the context of a high fidelity simulation of en route ATC activity. The specific objectives of the study were to assess the projected beneficial impact of Data Link on voice frequency congestion, and to determine the effects of the introduction of the initial package of Data Link services on operational ATC system performance, controller workload, and controller acceptance. The operational tests described in succeeding portions of this section of the report evaluated each of these factors in two realistic test scenarios, and under aircraft Data Link equipage levels representing both early and late stages of system implementation.

2.2 TEST APPROACH.

The approach that was adopted to meet the objectives of this operational evaluation involved the participation of eight en route air traffic controllers in a series of 30-minute ATC test scenarios presented at the workstations in the Data Link test bed. Each test run required a subgroup of four of the controllers to actively control traffic in adjacent sectors of en route airspace. The two test scenarios provided realistic ATC problems involving the movement of traffic between two airports, climbing and descending aircraft, departing and arriving aircraft, handling interfering overflight traffic, and merging of different streams of traffic into a single air route.

During each test run, objective data were automatically collected on controller usage of voice frequencies and Data Link. Following each test, the subjects provided quantitative workload ratings and

reports of any incidents that may have affected the safety or efficiency of ATC during the run. In addition, after completing all test runs, the subjects rated both the operational effectiveness and acceptability of each of the four service designs. Post-test debriefing sessions were used to elaborate and explain the results obtained in the test bed and to complete a wrap-up questionnaire.

The rationale underlying the test design was to create a series of realistic ATC test conditions in which it would be possible to evaluate the predicted benefits of the Data Link services in terms of their effect on voice frequency usage in comparison to current voice-only conditions. Measures of controller workload, system effectiveness, and user acceptance were employed to determine whether any measured benefits of Data Link would be potentially outweighed by corresponding "costs" to ATC system performance.

2.3 TEST CONDUCT.

2.3.1 Subjects.

The subjects for this study were eight en route air traffic controllers from the Anchorage, Cleveland, Memphis, Miami, Dallas/Ft. Worth, and Washington ARTCC's. All but two of the subjects were current, full performance level (FPL) controllers. The FPL subjects had an average of 11.2 years of experience with a range of 2.5 to 33 years.

Two of the subjects had participated in earlier Data Link mini study evaluations. The remaining six subjects had not received any formal exposure to the specific Data Link service designs or procedures tested in the present study prior to their participation in the operational evaluation.

2.3.2 Test Configurations for Data Link Services.

As noted earlier in this section of the report, the displays, controller inputs, and procedures for the four Data Link services tested in this study were based on the findings of preliminary mini studies and design generation meetings conducted with controllers at the FAA Technical Center. In accordance with those results, The Data Link transaction list was located on the PVD rather than a peripheral display. In addition, for transfer of communication and altitude assignment, an FDB display of key transaction states was provided. The FDB also contained a Data Link equipage symbol which identified those aircraft capable of receiving uplinks, and indicated whether a controller was eligible to uplink to the aircraft. Eligibility for both Data Link and voice communications was transferred to a receiving controller after a transfer of communication uplink had been received from a sending controller and acknowledged by a pilot via a downlink.

Altitude assignments were accomplished by entering the information to the NAS data base in the same manner as this system update is currently accomplished. If the controller chose to uplink the assignment, the entry was preceded by an "S" to initiate the transaction. For this study, the implementation of menu text was used only in conjunction with temporary altitude assignments. Fixed menus containing appropriate temporary altitudes and crossing restrictions were prepared prior to the study and displayed on the PVD. Controllers selected specific messages using the trackball or by typing the message's letter code. Free text messages were composed on the controller's keyboard in real time and uplinked by a single key stroke.

Detailed descriptions of the procedures and display formats for each of the Data Link ATC services outlined above are documented in appendix A.

2.3.3 Test Scenarios.

Three basic scenarios were created for the operational evaluation study. One of these was a training scenario used only during initial familiarization sessions designed to teach the subjects the procedures for composing and transmitting Data Link messages. The remaining two scenarios were test scenarios used during the data collection runs. All scenarios used the Universal Data Set (UDS) adaptation of the en route HOST system. UDS is a fictional airspace which includes a variety of air routes and geographical features. UDS was chosen in lieu of an actual site adaptation to avoid any effects of preliminary differences among the subjects in familiarity with the test air space. Fixes and sector boundaries were selected from UDS to create the air routes used in the three scenarios. Appendix A presents detailed documentation and maps for all versions of the three basic scenarios employed in the study. A brief description of the scenarios is presented below.

The training scenarios contained two routes carrying traffic between airports arbitrarily defined as Philadelphia and Atlantic City. One of the routes was used for outbound traffic from Philadelphia which departed through a low altitude sector, crossed two high altitude sectors, and descended to a low altitude sector to arrive at Atlantic city. The second route completed the loop between the two airports, traversing the same sectors in the opposite direction. Two versions of the training scenario were presented to the subjects. In one of these, all 24 aircraft were Data Link equipped. In the second version, only 70 percent of the 45 aircraft were Data Link equipped. Furthermore, in this version of the scenario the additional 21 aircraft were traveling on two overflight routes designed to conflict with the inter-airport traffic.

Test scenario 1 was topologically similar to the training scenario, presenting a circular routing between two airports. However, both

the complexity of the routes and the traffic volume were increased. Twenty-five of the aircraft traveled the routes between the airports, while the remaining 39 were overflights traveling four different routes which conflicted with the primary flow.

Test scenario 2 presented two separate flows of air traffic which operated independently of one other. The first flow simulated two approximately parallel departure routes from an airport through a low altitude sector and into a high altitude sector. A total of 45 aircraft interacted in this traffic flow with 12 traveling over each departure route and 21 conflicting with the flow on three intersecting overflight routes. The second of the two traffic flows represented an arrival problem in which two streams of traffic were to be merged over a fix in a high altitude sector and descended in a single stream through a low altitude sector. A total of 33 aircraft interacted in this traffic flow with 26 traveling over the arrival routes and 7 over a conflicting overflight route which passed through the low altitude sector.

Both of the test scenarios were used in conditions in which all communications were conducted with voice radio, and in which 20 and 70 percent of the aircraft were Data Link equipped. In addition to the simulated aircraft tracks described above, both of the manned aircraft simulators used in the aircrew substudy participated in the test scenarios. Section 3 of this report includes a description of the flightpaths traversed by these aircraft.

2.3.4 Test Procedures.

The operational evaluation study was conducted over a period of 5 days. The first day was devoted to subject prebriefing and training. Days 2 and 3 were used for simulation runs in the Data Link test bed. Additional data were collected during the debriefing sessions which occurred on the final 2 days of the study.

The prebriefing session began with a series of short presentations designed to acquaint the subject controllers with the general concept of Data Link, the overall Data Link test plan, and the four ATC services under evaluation. All presentations regarding the ATC services were conducted by a subgroup of four controllers from the ATDLVT who had participated in the design of the Data Link services and in the development of the test scenarios.

Classroom training on the procedures used to deliver each of the services was followed by a briefing on the measures that were to be used during the test sessions. This briefing explained all rating scales that the controllers would be asked to complete, and discussed the measures of voice radio and Data Link activity that would be collected automatically by the simulation system.

The final 4 hours of Day 1 were devoted to training in the Data Link test bed. Each subject received approximately 2 hours of hands-on experience with the detailed Data Link procedures that had been described during the prebriefings. During the training session the subjects controlled air traffic in the training scenarios under the guidance of ATDLVT members who were thoroughly familiar with the system. Training was terminated when the ATDLVT members judged that the subjects had achieved a sufficient level of expertise to control air traffic in the two test scenarios. It should be noted that in order to avoid over exposure to the test scenarios, the subjects did not receive explicit training with these scenarios during the training session. Thus, other than the opportunity to inspect route maps prior to the start of testing, the subjects' first experience with the test scenarios occurred during actual data collection.

Data collection in the test bed occurred on Days 2 and 3 with one subgroup of four of the subjects participating as controllers on each day. Each subgroup completed seven data collection runs. The first four runs employed test scenario 1 while the last three runs were conducted with test scenario 2. The primary independent variable which differentiated the test runs was the level of Data Link equipage for the aircraft simulated in the test scenarios. One run under each scenario was conducted under current conditions with no Data Link equipped aircraft. This test was included as a comparative baseline against which the Data Link runs could be evaluated. The remaining runs for each scenario presented two levels of partial equipage in the simulated aircraft population. In the low equipage condition, 20 percent of the aircraft were designated as Data Link equipped to produce an ATC environment similar to that expected during relatively early stages of implementation of the Data Link system. In the high equipage condition, 70 percent of the aircraft in each scenario had Data Link capability in order to simulate a more advanced stage of system implementation.

For all partial equipage test runs, Data Link equipped aircraft were identified by an equipage symbol located in the first position of the first line in the corresponding FDB (see appendix A). The test controllers were instructed to use Data Link to communicate with these aircraft whenever appropriate and possible, but to use their personal judgement in switching to voice transmissions if necessary.

In addition to the primary comparison of two levels of Data Link equipage to the baseline, voice-only condition, the test sessions included an evaluation of the potential impact of Data Link transmission delay. For both subgroups of subjects, the fourth run under test scenario 1 was a second test of the 70 percent level of Data Link equipage. It differed from the first presentation of this condition only in the average time delay between the initiation of an uplink to its receipt by the airborne system, and

from the initiation of a pilot downlink to its receipt by the ground system.

Because the Mode S system is a narrow beam radar, these technical delay times will be determined by the rotation speed of the antenna. While all other test runs were conducted using a 6-second assumed rotation period, the extended delay run doubled this time to 12 seconds. Adding a 1-second computer processing time, these parameters yielded an average uplink delay of 4 seconds (ranging from 1 to 7 seconds) for the normal conditions, and an average uplink delay of 7 seconds (ranging from 1 to 13 seconds) for the "worst case" extended delay condition.

For downlinks, Mode S delays will be partially dependent on the latency of the pilot's response to an uplink. If this response time is less than the time taken for a single scan, then the average downlink delay will be approximately equal to the scan period. However, if pilot responses are longer, downlink delays will increase in even multiples of the scan period. Thus, for the present study, pilot responses which occurred in less than 6 seconds after message receipt were received by controllers in 6 seconds in the normal delay conditions. However, a similar response latency in the extended delay condition resulted in a 12-second wait for receipt of the downlink.

In all Data Link test runs, the simulation system was designed so that 5 percent of uplinks attempted by the controllers would not be completed due to a technical failure. This outcome required the subjects either to resend the message or contact the pilot by voice radio, at their discretion. Although the actual rate of technical acknowledgement failure is predicted to be much lower in the Mode S system, the 5 percent level was used in this study to increase the subjects' experience with potential uplink problems. In addition to technical failures, if a simulation operator acting as a pilot, or either of the two aircraft simulator pilots failed to respond to an uplink within 40 seconds after it had been technically acknowledged by the simulated airborne processor, the controller received a "FAIL" message. This outcome required the same controller response as a failed technical acknowledgement.

The order of presentation that was used for the seven test runs in each of the two controller subgroups is shown below:

	Order	Scenario	Data Link Equipage	Delay
Subgroup 1				
	1	1	Baseline (0)	Normal
	2	1	70%	Normal
	3	1	20%	Normal
	4	1	70%	Extended
	5	2	20%	Normal
	6	2	70%	Normal
	7	2	Baseline (0)	Normal

Subgroup 2	Order	Scenario	Data Link Equipage	Delay
	1	1	20%	Normal
	2	1	70%	Normal
	3		Baseline (0)	Normal
	4		70%	Extended
	5		Baseline (0)	Normal
	6	2	70%	Normal
	7	2	20%	Normal

As shown above, all subjects controlled traffic in scenario 1 first and in scenario 2 last. Furthermore, the extended delay run occurred in the fourth position of the test sequence for both subgroups. However, the order of presentation for the baseline, voice radio only condition, and the 20 percent Data Link condition was partially counterbalanced across subgroups and scenarios. This alternation of baseline runs and Data Link runs as the first and last conditions within a scenario was introduced to the experimental design in order to allow for independent statistical evaluation the effects of scenario familiarity and Data Link equipage on controller workload.

2.3.5 Data Collection.

Both objective and quantified subjective measures were collected during the test bed simulation sessions. In order to assess the impact of introducing Data Link to the ATC environment, and to estimate its affect on frequency congestion, the simulation system computers automatically recorded data on voice radio and Data Link usage. For each simulation run, the test bed voice communications system detected and recorded all microphone switch activations and deactivations initiated by the subject controllers on the aircraft communications channels. Analysis software applied to the recordings tallied the number of activation-deactivation events in each test condition as well as the duration of each of these events.

Similar recordings of Data Link transactions provided indices of the number and types of services uplinked during each test run. As noted earlier, a majority of these transactions were with simulation operators acting as pilots in the laboratory. Because these individuals were not qualified aircrew and were not engaged in realistic flight tasks, their latencies for WILCO downlinks were not valid estimates of the response times for pilots. Thus, no recordings were made of the time required by the simulation operators to complete the delivery of a Data Link service. However, this parameter was assessed for the transactions with the aircrew who flew the flight simulators in each test run. The methods used for collecting these data and the results that were obtained are described in the section 3 of this document (Aircrew Substudy).

A break of approximately 15 minutes was scheduled at the end of each simulation run in order to permit each subject to rate the level of workload experienced during the prior period and to record any comments regarding the test. Controller workload was measured using the Subjective Workload Assessment Technique (SWAT). SWAT is a workload rating and scaling system which was developed in the early 1980's by the U.S. Air Force as a standardized method for obtaining quantified estimates of perceived workload in a broad variety of occupational tasks. SWAT has received extensive use in simulation and operational testing environments within the Department of Defense, and was used successfully with air traffic controllers during the preliminary Data Link mini studies.

Briefly, SWAT consists of a set of three 3-point rating scales referring to the dimensions of time load, mental effort, and psychological stress. Subjects indicate the workload of a session of activity by marking the appropriate points on each scale. A unique feature of SWAT is that these ordinal ratings are converted to single points on an interval measurement scale ranging from 0 (low workload) to 100 (high workload) using a mathematical analysis method known as conjoint measurement. This method not only yields data which are amenable to powerful, parametric statistical testing, but also tailors the measurement scale to each individual's (or homogeneous group's) concept of how the time, effort, and stress dimensions combine to produce an overall perception of workload.

The interval measurement scale used to interpret the ordinal ratings is created by having subjects generate an ordering of all 27 combinations of the time, effort, and stress levels which reflects their individual concept of how the three dimensions combine to produce different workload levels. The card sorting task used during this scale development exercise was completed by all eight controller subjects during the prebriefing session on the first day of the study. A copy of the SWAT scale used by the subjects to make their workload ratings and a transcript of the instructions for the card sort task are included in appendix B.

After completing the SWAT rating for the previous test run, subjects were given an opportunity to write comments on their rationale for the rating. In addition, a "critical incident" form was provided to permit subjects to record any ATC events that had occurred during the prior test run which would have compromised operational safety or efficiency.

Immediately after each subject had completed all seven test runs of the study, they were asked to complete a set of two rating scales for the four tested Data Link services. The first of these scales required a rating of the operational effectiveness and suitability of the specific design for a service. The data form permitted the subject to rate a service as "not operationally

suitable" or on a 7-point scale ranging from "1" (highly effective in meeting all requirements for this ATC service) to "7" (meets minimal effectiveness requirements). Instructions to the controllers for completing this scale asked them to use their experience in the test bed, as well as their prior background in operational ATC, to assess how well each service design could accomplish its intended task in the full range of en route field settings.

The second rating was an estimate of the acceptability and preferability of each of the service designs to air traffic controllers. The data form permitted the subjects to rate a service design as "completely unacceptable" or on a 7-point scale ranging from "1" (highly preferred) to "7" (acceptable, but not preferred). Instructions directed the subjects to consider the extent to which the controller displays, data input requirements, and procedures used to deliver a service would be usable by air traffic controllers in field settings.

Additional explicit instructions indicated that the dimensions of effectiveness and preference should be made independently of one another since a service might include all functions needed to meet operational requirements and be poorly suited to the way controllers normally perform their duties. Likewise, a design could be easy to use but have missing functions which prevent it from meeting operational needs.

Days 4 and 5 of the study were devoted to debriefing sessions. All eight controllers participated in these group sessions in a conference room setting with test personnel in attendance. The subjects first completed a wrap-up questionnaire containing items requiring numerical, ordinal level ratings, and/or written comments. The questionnaire addressed specific details of the designs for the four Data Link services, the general impact of Data Link on ATC, and the subjects' impressions of the quality of the operational evaluation study.

After completing the individual wrap-up questionnaires, the subjects participated in a structured discussion session designed to elicit final comments on the Data Link system. This session was guided by test personnel using issues and questions presented on overhead projection slides. Hard copies of the slides were provided to the subjects to record individual comments. The content of the verbal discussions was recorded in test personnel notes and on audio tape for later review.

2.4 TEST RESULTS.

The detailed results obtained with the data collection methods described in section 2.3.5 are contained in four of the appendixes to this report. Analyses of the workload, operational

effectiveness, and controller preference ratings are presented in appendix B. Records of voice and Data Link transmissions are contained in appendix C. Finally, the results of the group debriefing discussions and of the wrap-up questionnaire are presented in appendixes D and E, respectively.

This section of the report draws upon the contents of all four appendixes to address findings which are pertinent to each of the following topics.

2.4.1 Data Link and Voice Radio Activity.

A primary goal of Data Link is to enhance ATC productivity and safety by reducing its dependence on congested voice radio frequency channels for communications between air traffic controllers and aircrew. In order to estimate the extent to which implementation of the initial package of four Data Link services and functions will provide this benefit, detailed records were made of both voice and Data Link transactions during all simulation test runs in this study.

For the baseline runs in which only voice radio communications were used, controllers completed an average total of 422 voice transactions. Thus, each individual controller engaged in an average of approximately 105 sequences of microphone activation and deactivation during a 30-minute test run. The average duration of each voice sequence was 3.8 seconds, representing a total average channel occupation time of 1591 seconds per test run. It should be noted that these times do not include the additional contribution to frequency congestion of pilot responses to controllers or of pilot-initiated communications.

The impact of introducing Data Link on these baseline communication levels is summarized in figure 3. As illustrated by this graph, in the low equipage condition where only 20 percent of the total aircraft in the scenarios were eligible for Data Link communications, the availability of the transfer of communication, altitude assignment, and text functions reduced total voice transmissions by 25 percent. This produced a corresponding reduction in total radio channel occupation time of 28 percent. Similarly, in the high equipage condition where 70 percent of the aircraft were eligible for uplinks, the availability of the initial Data Link services reduced voice transmissions by 41 percent, while radio channel occupation time dropped 45 percent. It should be noted that the 25 percent decrease in voice transmissions observed for the 20 percent Data Link equipage level may be an inflated estimate attributable to an overall decrease in the amount of communications which occurred as controllers became increasingly familiar with the test scenarios (see appendix C).

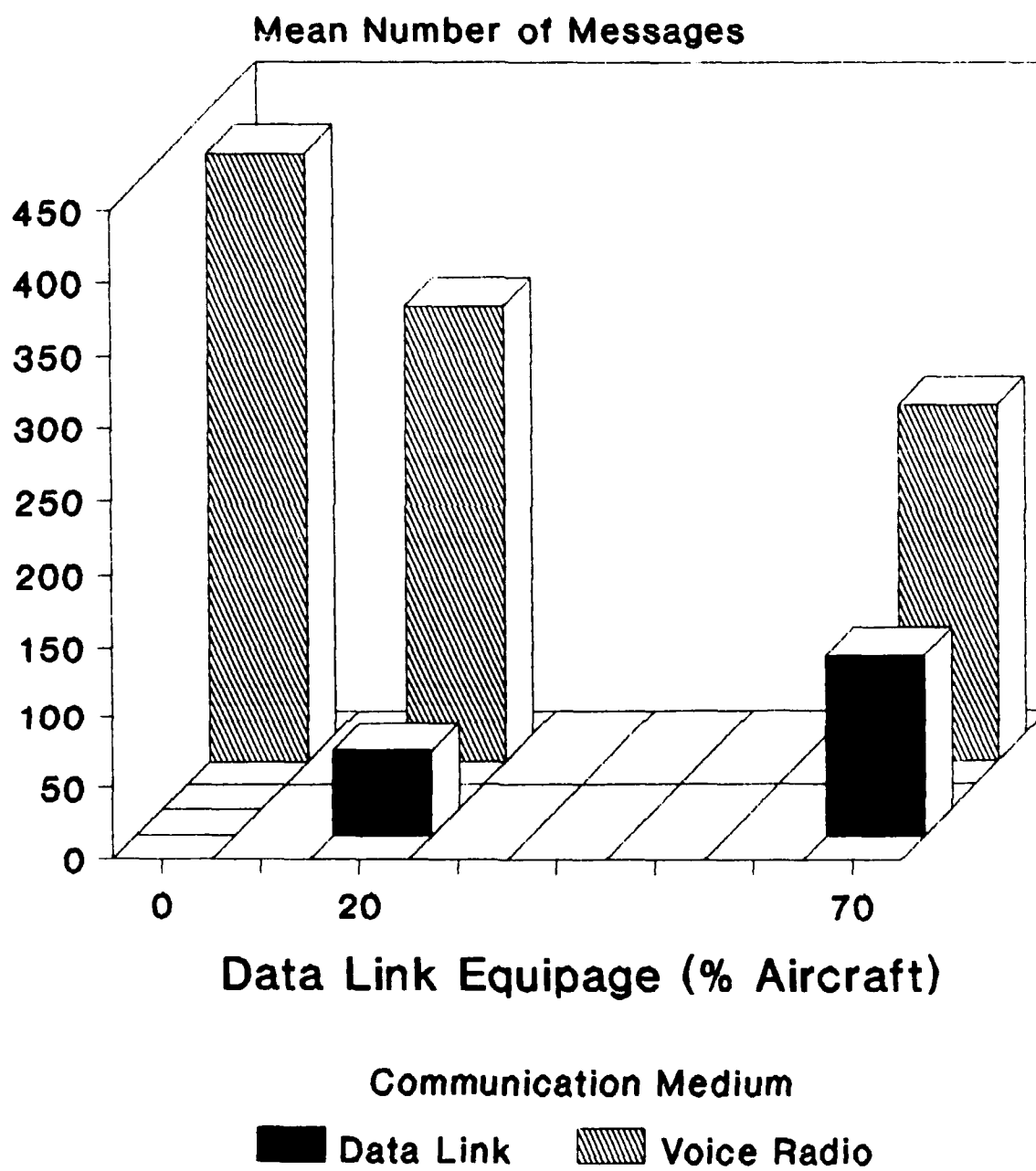


FIGURE 3. DATA LINK AND VOICE MESSAGE ISSUED BY CONTROLLERS

The change in Data Link activity which accompanied the reduction in voice radio usage in the two mixed equipage conditions is also presented in figure 3. When examining these data, the reader should be aware that while voice activity was measured in terms of individual microphone activations, of which several may have been required to deliver an ATC clearance, Data Link activity was assessed by tallying complete transactions. Thus, the simple numbers of transactions in the two communications modes cannot be directly compared. Nevertheless, the direction and proportional degree of change in the two indices provide interpretable measures of the relative results.

As shown in figure 3, the reduction in voice frequency usage was generally mirrored by an increase in the employment of Data Link. However, if the total number of both voice and Data Link transmissions in the mixed equipage conditions are examined, it can be seen that there was an overall decrease in communications activity in comparison to the baseline, voice only tests. This result indicates that, in addition to its impact on frequency congestion, Data Link may provide an overall increase in the efficiency of communication. One likely source of this improvement may be the reduction in requirements for repeats of clearances that often are required when voice transmissions are misinterpreted on the radio channel.

Analyses of the way in which Data Link was employed during the test runs showed that transfer of communication accounted for 29 percent of the service deliveries, while altitude assignments accounted for 57 percent of the transmissions. Hard altitudes and interim altitudes sent using menu text accounted for approximately equal proportions of the altitude assignment uplinks. Free text messages comprised the remaining 14 percent of Data Link transmissions.

A final implication of these measurements was derived by examining Data Link usage over time in the test scenarios. Analyses of the density of air traffic in the scenarios showed that the number of aircraft handled by each controller increased steadily from the early to the later portions of a test run. A similar inspection of Data Link activity showed that uplinks tended to increase at the same rate as did traffic levels. This finding indicates that the Data Link system was equally effective and usable by controllers across the full range of traffic loads tested in the study.

2.4.2 Controller Workload of Data Link ATC.

In order to determine whether the positive benefit of Data Link that was observed in this study had been achieved at a cost to ATC system capabilities or air traffic controller performance; measures of ATC safety and controller workload were also examined. The quality of ATC performance obtained in this study was assessed using controller comments on critical incidents that were recorded

after each test trial. As noted in appendix B, these reports detected no aircraft separation errors or other safety related events in any of the test runs. Thus, no losses in ATC capability were apparent with Data Link.

While measures of system performance provide valuable indices of the safety and efficiency of ATC, they can be relatively insensitive to the long term effects of changes to the system when assessed in a relatively brief series of simulation runs. This insensitivity is partially attributable to the ability of human operators to compensate for possible system deficiencies in the short term by increasing their level of effort expenditure. Because of this, more sensitive predictive measures of ATC capability were obtained by evaluating the perceived workload of the air traffic controller.

In the present study, the SWAT rating and scaling technique was used to compare controller workload in the baseline, voice only conditions and in the mixed equipage Data Link test runs. Figure 4 presents the mean SWAT workload scores produced by the subjects in these conditions for both of the test scenarios. Statistical evaluation of these data revealed no significant differences between the workload of the voice radio trials and either of the two Data Link equipage conditions. As described in appendix B, the single statistically significant effect detected in these tests was the contribution of scenario familiarity to controller workload. That is, workload tended to be higher for initial tests with a scenario than later tests, regardless of whether Data Link or full voice procedures were used.

The results of the workload analysis also showed no differences between the 20 and 70 percent Data Link equipage levels. One hypothesis that had been considered during the development of the initial service package was that controller workload may be high during the initial stages of Data Link implementation when relatively few aircraft will be equipped with Mode S transponders and Data Link capabilities. This hypothesis was based on the concept that it may be extremely difficult for controllers to move from familiar voice procedures to the new Data Link procedures in order to service a small portion of the aircraft fleet. The workload results of the present study did not support this hypothesis. In addition, written comments recorded between test trials indicated that the level of Data Link equipage had no apparent effect on controller tasks, and that no problems were encountered in shifting between the two communications systems either because of nonequipage or to engage in expedient communications with Data Link equipped aircraft.

2.4.3 Data Link Transmission Delays.

The speed with which Mode S Link transactions can occur will be partially dependent upon the rotation period of the surveillance

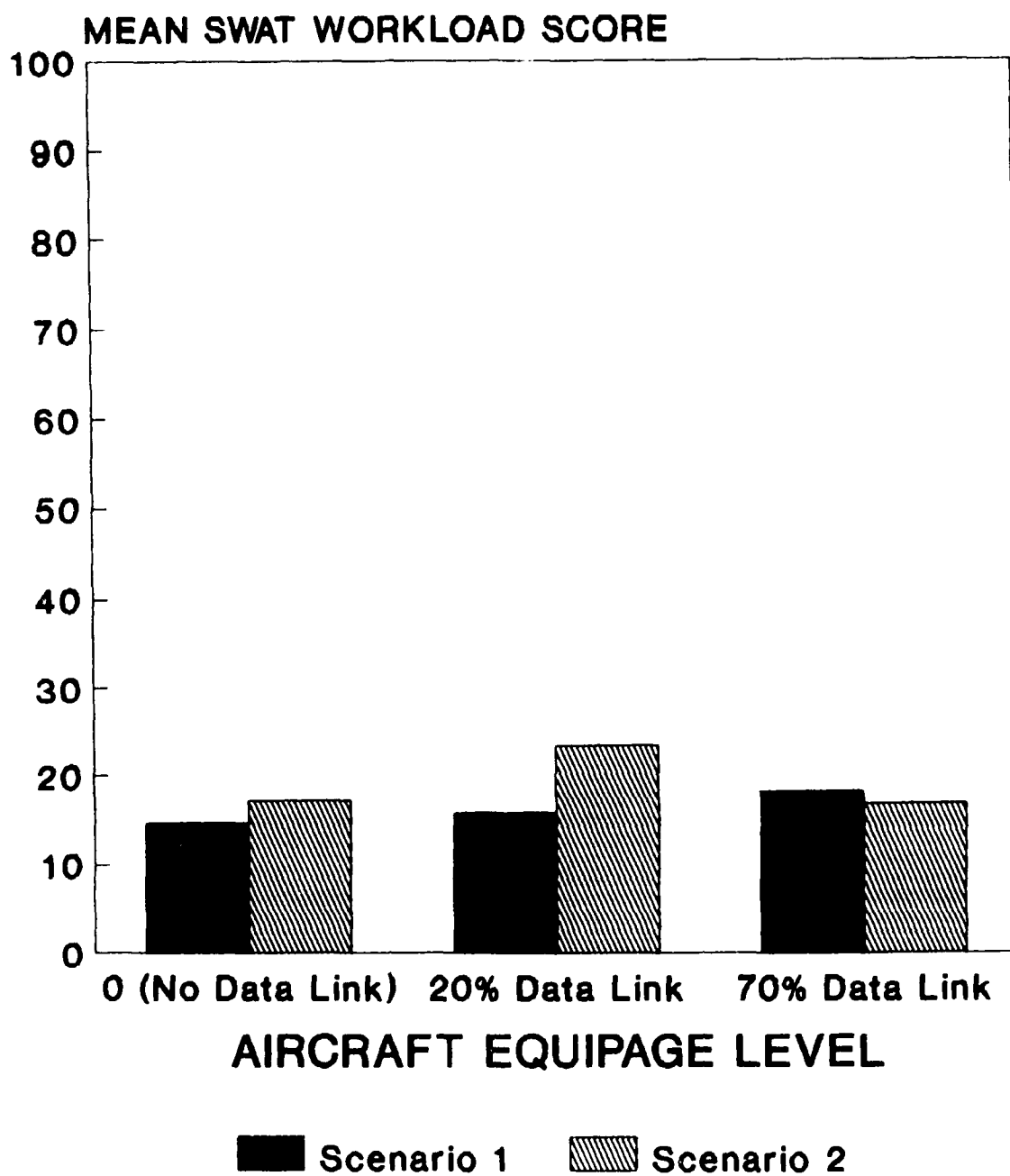


FIGURE 4. DATA LINK CONTROLLER WORKLOAD

radar antenna. This technical characteristic will produce a variable lag in the transmission of uplinks or downlinks which will range from nearly instantaneous to several seconds. Since, in comparison, voice transmissions on a clear radio channel are not subjected to such potential delays, an important issue in operational evaluation research is to determine whether expected technical Data Link delays are tolerable by air traffic controllers.

In the present study, both predicted delays for a 6-second antenna rotation period and a worst case 12-second period were investigated under the 70 percent level of aircraft equipage. No differences in ATC performance were detected for the two delay conditions. Furthermore, SWAT workload ratings revealed no differences between the workloads experienced by the test controllers in the two conditions. Comments recorded after the extended delay test trials and the results of the wrap-up questionnaire also indicated that the additional delays had no effect on the subjects.

2.4.4 Operational Effectiveness and Controller Preference.

In addition to the direct measures of the impact of Data Link on ATC activity and controller resources that were collected in the test bed, a variety of subjective measures were used to examine controller perceptions of the specific designs of the four services that were evaluated in this study.

Two rating instruments were administered immediately after the subjects had completed the seven test trials in order to obtain global evaluations of the operational effectiveness and usability of each service. As shown in appendix B, none of the service designs were rated "not operationally suitable" by any of the test subjects. Furthermore, the designs for transfer of communication, altitude assignment, and menu text were all rated significantly higher than the scale midpoint, indicating that they contained most, or all features required to support a full range of operational situations. While free text was rated lower than the other three services, it was not rated significantly poorer than "meeting most operational requirements."

Ratings of controller acceptance and preference for the service designs also were uniformly high. None of the subjects indicated that the procedures, manual inputs, or displays used to provide any of the services would be completely unacceptable to field air traffic controllers. In addition, the transfer of communication, altitude assignment, and menu text designs were all rated higher than "moderately preferred." Free text was not rated as being significantly different than this scale midpoint.

The comparatively lower effectiveness and preference ratings assigned to free text appear to be largely attributable to specific experiences with this service as reported by a number of subjects

during the test bed sessions. Although free text was designed primarily for use in emergency situations where voice communication is lost, some subjects experimented with using free text as a method for sending ATC clearances such as heading changes. In doing so, the subjects noted that the excessive keyboard requirements of entering complete text messages, as well as the potential for input errors, would make free text unsuitable for issuing clearances under normal conditions. In light of these comments, it seems likely that the design of the unconstrained free text service will be as effective and acceptable as the other tested services, if its use is confined to the exceptional situations for which it was intended.

2.4.5 Data Link Enhancements and Revisions.

Although, as shown above, the Data Link service designs were generally considered suitable and acceptable for implementation in the ATC system, a number of suggested enhancements to service delivery procedures, displays, and inputs were received from the test controllers in written comments and in responses to the structured debriefing interview. These suggested improvements are described in detail in appendixes B and D and are summarized below.

Individual controllers offered several comments relevant to the design of Data Link displays. Since the shift of some communications responsibilities from the auditory to the visual channel entails different controller monitoring demands, these inputs predictably centered around potential improvements in the ease with which Data Link information presented on the PVD can be detected and interpreted. Suggestions included changes to the symbology used to indicate Data Link equipment and eligibility. While the tested diamond and hourglass indicators presented in the first position of the first line of the FDB were apparently acceptable to most subjects, some of the controllers felt that they might be confused with graphic symbols that have been used in en route displays for other purposes. In addition, one controller noted that the change from the diamond to the hourglass symbol, indicating a controller's eligibility to send uplinks to an equipped aircraft, should be a more salient event.

Previous mini study results had shown that controllers would require a FDB display of key Data Link transaction states, as well as a more complete status list to reduce the visual workload of monitoring ongoing Data Link events. Comments regarding the FDB presentation indicated that the display duration of 6 seconds for a pilot's downlinked WILCO response may be too short to ensure detection. Several subjects also noted that the PVD list display became cluttered and difficult to read when several transactions were in progress during the simulation runs. Suggestions to alleviate this problem included the possibility of using a separate list for transfer of communication transactions, or limiting the

list content to only those transactions which had failed because of technical problems or the absence of a timely pilot response.

The procedural issues which appeared in controller comments and debriefing discussions addressed both operational procedures for use of the Data Link service and specific service design requirements. As noted earlier, the subjects concurred that, for safety purposes, operational procedures will be required to restrict the use of free text to emergency communications and other noncritical communications. In addition, operational procedures will have to be specified to define the conditions under which controllers in adjacent sectors will be permitted to issue Data Link clearances while a transfer of communication is in progress. With respect to interactions with aircrew, the test controllers agreed that a standard procedure will be needed to cover the situation where a pilot is unable to comply with an ATC instruction issued via Data Link. Generally, the controllers felt that a downlinked UNABLE response was insufficient in this contingency, and that a voice radio call to the controller should accompany, or be substituted for, the UNABLE response. The controllers also concurred that the pilot's voice radio check-in call to a new controller could be eliminated after a Data Link transfer of communication.

Finally, the controllers emphasized a requirement to identify procedures for assigning some Data Link duties to a radar associate, "D-side", controller. While the operational evaluation study did not address the possibility of allocating Data Link tasks to other members of a control team, the subjects indicated that it would be feasible for the radar associate to provide transfer of communication services, and to compose lengthy free text messages.

Further specific comments addressed the detailed procedures used to deliver individual Data Link services. Early mini study research had indicated that while a transfer of communication message could be generated automatically after a receiving controller had accepted a transfer of control, the uplink of the new radio frequency should not occur until the sending controller has made an explicit input. This manual uplink procedure was needed to make it possible for controllers to complete the transfer of control procedure prior to relinquishing voice contact with an aircraft. Controllers in the present study agreed with this design feature, but indicated that an automatic uplink could be used in some special situations where the transfer of control and transfer of communication events repetitively occur at the same time. Thus, it was suggested that manual uplinks would be the normal default procedure, but that provision be made for the selection of the automatic feature.

Minor changes to the design of the menu text service for altitude assignments also were recommended. In the current design, separate keyboard entries are used to select "hard" altitude assignments and

interim altitudes. In the case of interim altitudes this input gives the controller access to the menu of standardized messages for simplified uplink. One type of message contained in the menu automatically uplinks a final altitude previously requested by the pilot, or a standardized final altitude. Because these special menu entries do not represent interim altitudes, it was suggested that these items be contained in a menu which is accessed by pressing the hard altitude key, rather than the interim altitude key.

A second common comment regarding the menu text service was that the items be extended to include more compound clearances. In the tested design, the menu items included an altitude as well as a geographical fix crossing restriction in some cases. Since even longer compound messages are commonly sent in a single voice transmission in the current ATC system, the controllers suggested that it be possible to expand menu items to include such things as standard headings.

A final comment provided by several of the controllers was that Data Link should not be limited to the services provided in the initial package tested in this study. Rather, it was suggested that the system be rapidly enhanced to provide the full range of ATC services currently delivered over voice radio channels.

2.4.6 Controller Opinions of Data Link and the Operational Evaluation.

In agreement with the findings of previous mini studies, the controllers who participated in this operational evaluation were extremely positive about the impact that Data Link will have on ATC in the NAS. Of 17 unsolicited written comments on the overall effect of Data Link that were recorded during the test sessions, all referred to significant benefits to the controller. The most common remarks included reduced frequency congestion, lowered requirements to monitor and respond to voice read-backs and pilot check-in, and an increase in the accuracy of communication. In addition, the results of the wrap-up questionnaire indicated that the controllers predicted Data Link will have significantly positive effects on the overall safety and efficiency of ATC, system capacity, and controller workload.

In evaluating the quality of the operational evaluation study, the realism of the simulation received varied ratings, with some controllers indicating that the simulation scenarios could have been more varied and complex. However, despite some inherent limitations of the simulation environment, average controller ratings of the traffic in the two test scenarios were "moderate" and only slightly below the level where the subjects indicated that a D-controller would have been required in an actual operational setting to assist the radar controller. In addition, the controllers agreed that Data Link training had been sufficient, and

that they had received sufficient experience with each of the tested services to make a fair evaluation of the system.

2.5 DISCUSSION.

The combined findings of the ATC portion of the operational evaluation study clearly confirmed the feasibility of implementing the initial package of en route Data Link ATC services. As defined by the results of the preliminary mini studies, the service designs were shown to produce a significant reduction in voice radio frequency congestion in the context of realistic, manned simulations of ATC activity. Furthermore, this evaluation indicated that the substitution of Data Link for voice communication procedures will not adversely affect controller workload, and that the service designs would be both operationally effective and acceptable to controllers in a broad range of ATC environments.

In addition to demonstrating the viability and potential benefits of introducing Data Link to the contemporary ATC system, the operational evaluation also presented an opportunity to collect controller inputs regarding additional refinements to the service designs. Because these comments and suggestions were made in the context of a previously untested level of simulation realism, they should prove invaluable during final design iterations. Specific recommendations derived from these inputs appear in section 6 of this report.

3. DATA LINK AIRCREW SUBSTUDY.

This section of the report documents an investigation into pilot perception and acceptance of the concept of using Data Link in lieu of voice for some ATC and weather (WX) services. As a conceptual investigation, it was constrained to readily available equipment which could be easily adapted to this purpose.

3.1 OBJECTIVES.

The objective of the operational evaluation was to conduct an initial (early) exploration of the concept of using Data Link in lieu of voice for some of the communications between the aircrew and ground. Both objective and subjective measures of effectiveness were employed. Objective measures were various time intervals associated with requesting, receiving, and reviewing data link obtained information. Subjective measures were obtained from post-test questionnaires.

The essence of the Data Link program is to change the way pilots and controllers interact. Thus, the major focus for the evaluation was that interaction. The major question to be answered was whether aircraft operations are enhanced by altering, through Data Link, the way information is exchanged.

3.2 TEST APPROACH.

The aircrew operational evaluation was viewed as preliminary research to provide guidance for follow-on research and systems design. The aim was to depict pilot performance in the context of the whole ground-air Data Link system. The operational evaluation placed pilots and air traffic controllers into realistic interaction by simulating their tasks. The primary independent variable of interest was the communication source, i.e., Data Link vs. voice. A portion of the information which is currently transmitted by radio was transmitted through the Data Link system.

The pilot's tasks were to evaluate four weather (WX) and two ATC services that were exercised under simulated Data Link and voice environments. Various time intervals such as request creation time, system time, response latency, and message processing time were measured to assess the difference between the two conditions. Subjective measures in the form of post-test questionnaires provided additional data as to the effectiveness of the Data Link system.

The pilot tasks were accomplished in two aircraft simulators. One of these was the General Aviation Trainer (GAT), which is housed at the FAA Technical Center. The other was a simulator of the Boeing 727 (B-727) aircraft, which is located at the Ames Research Center of the National Aeronautics and Space Administration (NASA), Moffett Field, California. The GAT facility consists of a Cessna 421 motion-base simulator. A visual system was not used in the evaluation. The B-727 at NASA AMES is housed in the Man Vehicle Systems Research Simulator (MVSRS) facility. The system is a 6° of freedom motion-base design with a high-fidelity out-the-window visual system.

Each run was a flight in a simulated airspace which could be heavily populated with simulated aircraft. Each pilot/crew flew three runs; two were Data Link and the other traditional voice communication. An evaluation team made up of human factors engineers and pilots briefed/trained the subject pilots prior to data collection exercises. During each run an experienced pilot acted as an inflight observer. The inflight observer at each location (FAA and NASA) was responsible for answering subject-pilot questions regarding the simulators, flight test scenarios, and any other pilot-specific questions made by the subject pilots. During the data runs the inflight observer used a cueing sheet to cue the subject pilots on weather service requests and, as necessary, the type of response required for a given service and/or the appropriate procedure to be followed. The inflight observers observed the data runs and provided comments on the subject pilot's operation of Data Link.

Two general aviation and two airline oriented flight scenarios were created for the evaluation. Various ATC and weather services were exercised in the data runs. Objective data consisted of response time measures; subjective data were obtained in an extensive questionnaire.

3.3 TEST CONDUCT.

3.3.1 Subjects.

The pilot subjects were selected in such a way that General Aviation pilots flew the GAT and current airline flight deck crews (Captain and First Officer) flew the 727 simulator. For the FAA GAT, four General Aviation pilots participated, and for the NASA 727, four airline crews participated.

FAA personnel solicited the Aircraft Owners and Pilots Association (AOPA) for assistance in providing general aviation pilots. Airline type pilots were obtained through a NASA/Ames subject pilot/crew pool. All pilots were simulator experienced. A summary of pilot experience is presented in table 1. Each designated pilot subject was contacted by telephone to obtain assurance of availability on the scheduled days.

An information packet was prepared and mailed to each crew/pilot scheduled to participate. This packet described Data Link, the nature and purpose of the test, schedule, and what was to be accomplished on each day of the schedule.

3.3.2 Configurations for Data Link Services.

3.3.2.1 Display Interface.

The approach to the Data Link pilot interface was an alphanumeric touch sensitive input/output (I/O) device from the Teledyne Controls Corporation. The Teledyne Interactive Display Unit (IDU) is designed to display 20 characters on each of nine lines. A matrix of infrared beams is used to permit an interactive capability. The number of touch sensitive areas can be controlled by programming and can vary from one area encompassing the whole screen (or any part) to as many as 20 abutting rectangular areas. As implemented, touching a finger to one of the designated areas causes the display in that area to switch to reverse video presentation. Removing the finger from the display triggers activation of the function cited in that area. The Teledyne display output was the conventional ASCII character set with special modifications to accommodate unique display characters. Also, an audible alert was presented to alert the aircrew that a Data Link message was received in the cockpit. Other engineering specifications on the Teledyne can

TABLE 1. PILOT EXPERIENCE SUMMARY

General Aviation

	<u>Approx. Total Hours</u>	<u>Aircraft</u>
1	2500	E-2 T-34, etc.
2	1100	C182 PA-28, etc.
3	4950	C-421 Aero Commander, Piper Twin E, etc.
4	1825	BE100 PA-31 DAC-6, etc.

Average = 2600 Hours

Airline

	<u>Approx. Total Hours</u>	<u>Aircraft</u>	<u>Primary Role</u>
Crew 1			
Captain	20000	B-727	Captain & F/O
First officer	5500	B-727	F/O
Crew 2			
Captain	5000	B-727	Captain
First officer	25000	B-727	Captain
Crew 3			
Captain	6000	B-727	Captain
First officer	n/a	n/a	n/a
Crew 4			
Captain	16000	B-727 B-737 B-747	Captain & F/O
First officer	8000	B-727 DC-10	F/O

Average = 12200

n/a = not available

be found in appendix G. Display brightness is either automatically controlled with an ambient light sensor or manually adjusted by the display user.

The Teledyne display was installed in the NASA B-727 in the weather radar position. The Teledyne display was installed on the GAT instrument panel, centered between the pilot and copilot position. Photos of the display in each cockpit are provided in appendix G.

3.3.2.2 Data Link Services.

The package of services for the airborne evaluation included two ATC and four WX services. The ground/controller evaluation included two additional ATC functions: menu text and free text. The menu text function facilitates the prerecording and transmission of repetitive ground-to-air messages. The free text function could provide one line (up to 20 characters) of brief instructions (ground-to-air only). For the purposes of the airborne evaluation menu text provided the same information/instruction, to the pilot as did the altitude assignment; therefore, data on these two services were combined. A brief description of each of the tested services is presented below. Details on format characteristics and switching logic are described in appendix G.

3.3.2.2.1 Weather.

Terminal Forecast (FT) - A 24-hour prognosis of weather conditions within the immediate vicinity of a selected location; includes sky and ceiling, visibility, weather, obstructions to vision, cloud heights, and whether visual or instrument conditions are expected.

Winds/Temperatures Aloft (FD) - A report of projected winds and temperatures for a range of altitudes; includes wind speed, wind direction, and temperature.

Surface Observation (SA) - A report of current ground weather at a selected station; includes sky conditions, ceiling, visibility, weather, obstructions to vision, wind direction/speed, altimeter setting, and additional remarks.

Pilot Reports (PIREPS) (UA) - Pilot reports of inflight conditions which may include information on sky cover, flight visibility, flight weather, and indications of icing or turbulence, etc.

3.3.2.2.2 Air Traffic Control.

Altitude Assignment - An ATC command to change assigned altitude. The command may also contain time or crossing references and, if required, an altimeter setting.

Frequency Change (or transfer of communication) - An ATC command to a pilot to change to a new traffic control sector/facility frequency.

3.3.3 Test Scenarios.

The simulated airspace for the operational evaluation was a section of the FAA UDS. The UDS is a fictitious airspace created to allow simulations of the NAS. Four experimental scenarios (two for GAT and two for the 727) were created for this evaluation and are discussed briefly below.

In test scenario 1, 64 simulated aircraft flew in the UDS. The GAT (designated N8417P), which flew at low altitudes (12,000 feet and below), was one of the 64 aircraft. The remaining aircraft (including the NASA B-727, designated EAL55, Eastern Airlines) were strictly high altitude types (between 12,000 and 27,000 feet). Six different airways were used by the aircraft in this scenario.

Test scenario 2 contained 78 aircraft, 1 of which was the GAT and 1 the NASA B-727. The GAT was, again, the only low altitude aircraft. Nine different airways were used by the aircraft in this scenario.

Each data run consumed approximately 30 minutes of operating time. Time between each data run was approximately 15-20 minutes. Detailed descriptions of the GAT and B-727 scenarios are provided in appendix F.

3.3.4 Test Procedures.

3.3.4.1 Training.

The subject pilots initially received a complete briefing on the simulator they were to fly. Afterwards they were briefed on the evaluation and trained on the Data Link system. Questions were encouraged to insure complete understanding of all aspects of the evaluation and systems involved.

3.3.4.2 Testing.

Prior to each data run, the subject pilot/crew was given flight plan materials (dispatch papers) as required and informed of the run details (start time, scenario number, voice or Data Link). During the runs the subjects were cued to make specific weather

requests; the ATC type messages were acted upon as required. The scenario descriptions in appendix F describe the events in detail. An attempt was made to exercise each of the four weather services during each run. The number and type of ATC messages were, however, variable. A breakdown of the services exercised in each run is provided in appendix H.

The GAT pilot was responsible for both flying the simulator and operating the Data Link system. In the B-727 portion of the evaluation a two-person crew flew the simulator (the inflight observer sat in the Second Officer/Flight Engineer seat). The Captain was responsible for flying the simulator while the First Officer (F/O) operated the Data Link system. The Captains were asked to monitor the operation of Data Link to the extent safe operation of the aircraft would allow.

The test was conducted over 2 days. Six data runs were completed each day at each location for a total of 24 runs. Each pilot/crew flew three runs; two with Data Link and one using voice (as a baseline control condition). The counterbalanced sequence of runs and conditions is presented below. The ground Data Link group also allowed time for up to four supplemental runs. The airborne group at NASA participated in one of these runs because of a technical problem in a data run. The airborne group at the FAA Technical Center participated in two of these runs (for additional data, no technical problems occurred).

Randomized Run Sequence

<u>Run</u>	<u>Pilot/Crew #</u>	<u>Voice/Data Link</u>	<u>Scenario</u>
1	1	Voice	1
2	1	Data Link	1
3	1	Data Link	1
4	2	Data Link	2
5	2	Data Link	2
6	2	Voice	2
7	3	Data Link	1
8	3	Data Link	1
9	3	Voice	1
10	4	Voice	2
11	4	Data Link	2
12	4	Data Link	2

3.3.5 Data Collection.

3.3.5.1 Objective Data.

The objective measures of performance during the evaluation were various time intervals. A graphic representation of the specified time intervals and an example script of voice-weather transactions are included in appendix H. Definitions of the critical time intervals (in both Data Link and voice) follow.

The inflight observers observed the operation of the system and obvious errors/difficulties on the part of the subjects were noted.

The aircrew substudy was planned to provide data on the performance of pilots with a prototype Data Link interface system in the context of realistic ATC Data Link simulation. The time intervals were defined in such a way as to provide baseline data to allow detailed comparisons with evolving displays and controls.

3.3.5.1.1 Time Interval Definitions.

3.3.5.1.1.1 Weather.

a. MCT - Message Creation Time.

Voice - The interval begins with the pilot activating the mike switch (PTT-Push to Talk-ON), during which a request for weather is made, and ends when the pilot releases the mike switch (PTT- OFF).

Data Link - The interval begins when pilot touches one of four WX products on the MAIN menu; included is the time required in selecting the appropriate LOCID. The interval ends upon touching "SEND" in the LOCID menu.

b. ST - System Time.

Voice - The interval begins with the release of the mike switch in MCT and ends with the FSS/Flight Watch release of the mike switch after announcing that WX is available, i.e., "I have your request, over."

Data Link - The interval begins with touching "SEND" in MCT and ends when "Touch for WX Message" is displayed. This interval includes simulated random Data Link transmission delays.

c. RL - Response Latency.

Response latency denotes that this interval may not be readily describable as a reaction time. From the standpoint of pilot performance, there is a difference between receiving the voice message and receiving the one on a controllable visual display. The voice message did not persist, but the visual display remained until the pilot did something about it. The response latency measure acknowledges that pilot performance may be quite different with a stable display. Pilots are usually performing a variety of tasks at any given time. When some new stimulus appears, they may not be free to attend to it immediately. Instead, they tend to put the new stimulus in a queue to be attended to as current priorities dictate. It is useful for later uses to maintain a separate identity for the latency data.

Voice - The interval begins with the FSS/Flight Watch release of mike switch and ends when the pilot presses mike switch to announce, "Yes, Flight Watch, go ahead."

Data Link - The interval begins with the annunciation of "Touch for WX Message" and ends when the pilot touches the prompt "Touch for WX Message."

d. MPT - Message Processing Time.

Voice - The interval begins when FSS/Flight Watch activates the mike to "read" the WX message to the pilot and ends when FSS releases the mike after reading the complete message. Any repeats of information required added to the time as appropriate.

Data Link - The interval begins with the appearance of requested weather on the screen and ends when the pilot touches MAIN menu.

3.3.5.1.1.2 Air Traffic Control.

a. RL - Response Latency.

Voice - No counterpart to Data Link.

Data Link - The interval begins when "Touch for ATC Message" appears on the display and ends when the pilot touches the prompt "Touch for ATC Message."

b. WUT - WILCO/UNABLE Response Time.

Voice - The interval begins with controller's PTT-ON (during which the ATC instruction is delivered) and ends with the pilot's release of the mike switch after acknowledging the instruction. If the pilot requested a "SAY AGAIN," this time was included.

Data Link - The interval begins with the appearance of the ATC Instruction on the display screen and ends with the touch of WILCO or UNABLE.

3.3.5.2 Subjective Data.

Subjective data were collected in a post-evaluation questionnaire. The questions asked of the subject pilots were grouped around each particular service provided. As the subject pilots/crews were completing the questionnaire, a human factors engineer was available to answer questions and/or discuss issues. In addition to the questionnaires, a debriefing session was held

with the GAT subject pilots, controllers, and experimenters. This session was held the day after data collection via a telephone conference call. The B-727 crews were unable to participate due to schedule constraints. The B-727 crews were given the opportunity to debrief with this same group immediately after their data collection runs were complete.

3.4 TEST RESULTS.

The data presented are from 24 data runs; 12 runs each by general aviation and airline pilots. The data presented are specific to the flight deck. Controller/ground oriented data are presented in section 2.

It should be noted that when more than one request for a given weather service was accomplished in a single run, the data were not considered in the analysis to ensure balance. The B-727 run 2 data were gathered from a supplemental type run because of a technical problem in the actual run 2.

3.4.1 Objective Data.

Various time intervals were measured and subsequently reduced into descriptive statistics to show means and variability. Breakdowns according to pilot type (general aviation or airline), scenario type, and COMM type (Data Link or voice) will be provided. Note that in the ATC voice condition, no response latency is definable. No inferential tests were conducted on the time data because of the small sample size (number of pilots and runs).

Figure 5 presents the pilot time response data for overall ATC WILCO or UNABLE time differences between Data Link and voice by GAT and B-727. The overall weather/pilot response time data by Data Link and voice (by GAT and B-727) are presented in figure 6. The overall time data (average and standard deviation) for WX/ATC for GAT and B-727 are presented in table 2. Time data for each individual ATC and WX service are provided in appendix H.

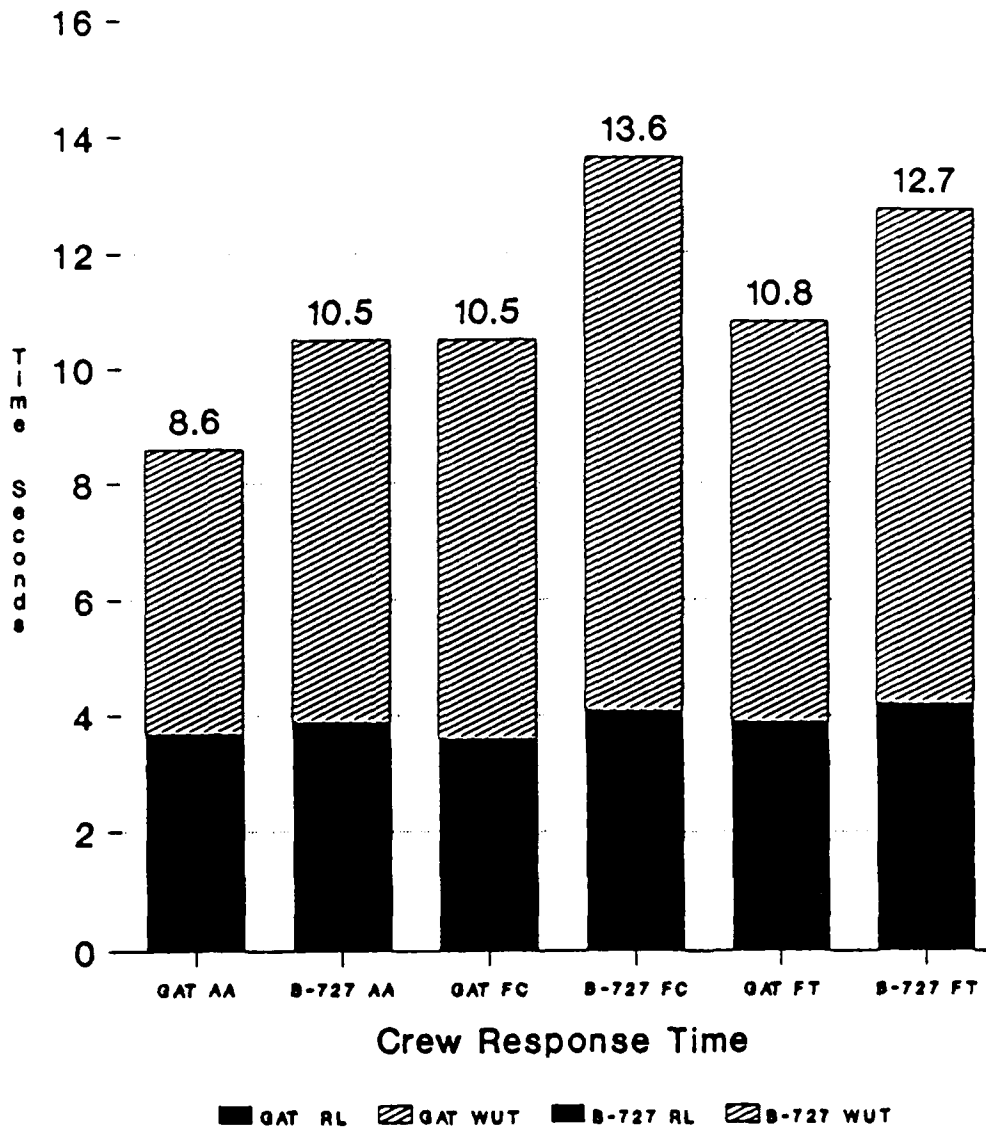
3.4.2 Subjective Data.

The questionnaire was administered to four general aviation pilots and four airline crews. A total of 12 questionnaires was obtained. The questionnaire was divided into three parts: ATC Services (questions 1-11); WX Services (questions 12-19); and, Overall (questions 20-30). The numerical average (Avg) and standard deviation (Std) was calculated for each rating type answer. The Avg and Std was calculated for the GAT group, the B-727 group, and the combination of groups. The standard rating scale used in many of the questions is presented below.

DATA LINK

CREW RESPONSE TIME

Response Latency plus Wilco/Unable Time



AA - Altitude Assignment
 FC - Frequency Change
 FT - Free Text

FIGURE 5. PILOT/CREW RESPONSE TIME

DATALINK VS. VOICE Overall - Weather

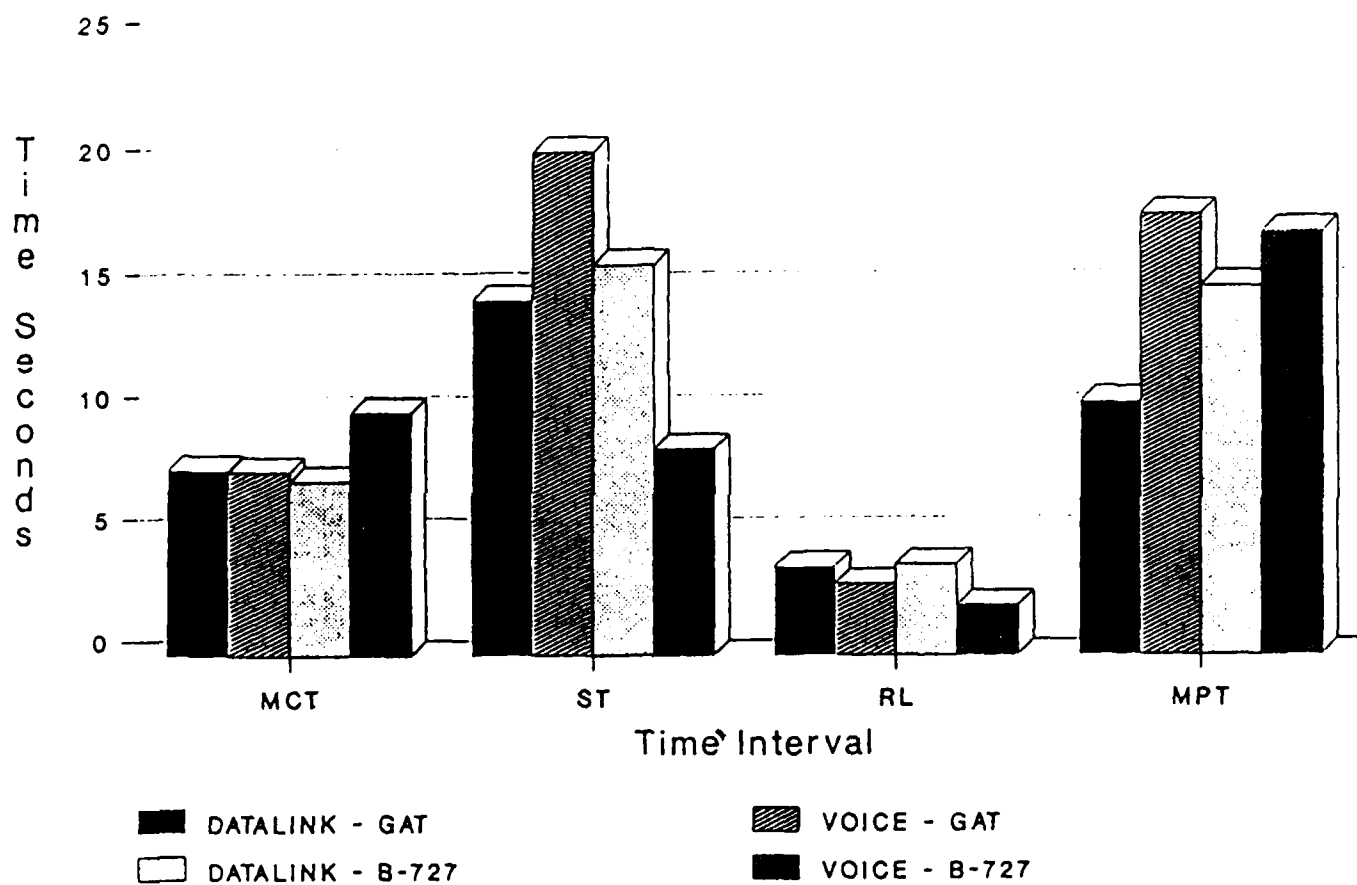


FIGURE 6. WEATHER-PILOT TIME DATA

TABLE 2. GAT/B-727 OVERALL TIME DATA

Time in Seconds
Data Link - Weather

	<u>MCT</u>		<u>ST</u>		<u>RL</u>		<u>MPT</u>	
	Avg	Std	Avg	Std	Avg	Std	Avg	Std
GAT	7.6	9.1	14.5	1.7	3.6	1.4	10.3	3.6
B-727	7.1	4.1	15.9	4.8	3.7	0.7	15.0	6.6

Voice - Weather

	<u>MCT</u>		<u>ST</u>		<u>RL</u>		<u>MPT</u>	
	Avg	Std	Avg	Std	Avg	Std	Avg	Std
GAT	7.5	2.6	20.4	1.4	2.9	1.1	17.8	3.7
B-727	9.9	3.9	8.4	3.6	2.0	0.6	17.1	8.6

Data Link - ATC

	<u>RL</u>		<u>WUT</u>	
	Avg	Std	Avg	Std
GAT	3.7	0.6	5.8	1.8
B-727	4.4	3.8	7.9	3.3

Voice - ATC

	<u>RL</u>		<u>WUT</u>	
	Avg	Std	Avg	Std
GAT			9.9	3.1
B-727	n/a		9.7	5.0

n/a = Not applicable

Standard Scale

- 7 - VERY GOOD, no changes are necessary
- 6 - GOOD, a few minor changes are necessary
- 5 - FAIRLY GOOD, a number of minor changes are necessary
- 4 - FAIR, both minor and major changes are necessary
- 3 - FAIRLY POOR, a few major changes are necessary
- 2 - POOR, a number of major changes are necessary
- 1 - VERY POOR, a complete redesign is necessary

The following three sections summarize the individual sections of the questionnaire. Detailed analysis of the subjective results can be found in appendix H.

3.4.2.1 Specific Results Regarding the ATC Services.

For each ATC Service, altitude assignment, and frequency change subject pilot ratings were obtained on six factors: Appearance, Clutter, Amount of Information, Information Clarity, Ambiguity, and Time to Interpret. On all factors the average ratings were GOOD (6) or above with B-727 pilots rating the factors slightly lower than GAT pilots.

In general, all pilots were satisfied with the auditory annunciation of incoming ATC Data Link messages. Two B-727 pilots expressed concerns with high workload situations and the startling effect the tone had. Other comments were made concerning the tone in a real cockpit, missing the tones, and number of tones in the present cockpit.

The visual annunciation of ATC Data Link messages was considered acceptable. One pilot suggested that flashing the entire screen and providing a Master Caution, e.g., light would help attract the pilot's attention. The other pilot suggested a change in terminology of the ATC message prompt "TOUCH FOR ATC MESSAGE"; he added that "TOUCH" was not necessary. Negative responses were obtained for the automatic appearance of ATC messages in which there is no ATC message prompt. Pilots felt that automatic delivery would be too easy to neglect or miss altogether and possibly override an existing message, such as a WX report, which they hadn't finished reading.

The "SENT" indication after a WILCO or UNABLE was considered desirable by most of the pilots. One pilot stated that if the logic was such that WILCO/UNABLE did not disappear until the system accepted the "SENT" command, the display of "SENT" would be unnecessary. In general, a confirmation that the system accepted the input was considered necessary.

For both altitude assignments and frequency changes, the time diverted from flying to operate Data Link was considered acceptable (or minimal). One pilot who was undecided added that

verbal commands may be quicker in certain situations, e.g., instrument conditions or approach to a busy airport. One pilot stated that voice communications also required diversion from flying (to the same extent as Data Link) and that, overall, Data Link is superior to writing clearances, etc.

The ATC Data Link overall design was rated FAIRLY GOOD (5) to GOOD (6). The comments were very positive, e.g., "...better than I thought it would be at this stage of development," "...like the Data Link just the way it is." Suggested changes to the present design dealt with terminology, number of services, information flow rates, etc.

3.4.2.2 Specific Results Regarding the WX Services.

As with the ATC Services, subject pilots rated each of the four WX Services: Surface Observation, Terminal Forecast, Pilot Report, and Wind/Temp Aloft, using the standard rating scale. In all, eight factors for each service were rated. In addition to those factors listed for ATC services in section 3.4.2.1 (excluding Time to Interpret), Information Retrieval Time, Time or Valid Times Concept, and "Return to Main" concept were included. In general, all average ratings were FAIRLY GOOD or above (>5). The standard deviations were fairly high, indicating a wider range of ratings. Several comments were made by the pilots concerning general format, content, amount of information, and logic.

During Data Link runs requests for WX services were made through the Location Identifier menu (LOCID). Preselected stations (made by the experimenters) appeared on the LOCID menu after pilots requested the WX Service desired from the MAIN menu. Using the standard rating scale, the subject pilots rated the LOCID menu on six factors: Menu of LOCID's Concept; Time Required to Input/Enter, Possibility for Error, Number of "Keystrokes," LOCID menu of Location Codes, and LOCID Remaining on Format. The factors were, in general, rated higher by GAT pilots than B-727 pilots. The LOCID menu concept and time to input factors were rated lower by B-727 pilots. The menu of LOCID codes was rated FAIR (4) by both groups. The comments centered on actual implementation, number of LOCID's, ambiguity of LOCID codes, etc.

The "SENT" message after touching SEND was considered a very desirable option. The confirmation it provides that the system is working is critical.

The logic in which weather information remains on-screen until pilot input was considered very desirable. The ability to read the message more than once and/or copy it onto paper is necessary.

For all WX Services, the time diverted from the flying task was considered acceptable by most. Although one pilot felt that improved formats would provide a quicker response and greatly improve the service.

The overall Weather Data Link design was rated FAIRLY GOOD. Problem areas listed were centered on the information presentation, e.g., letter size, amount, etc.

3.4.2.3 General Overall Issues.

For both ATC and WX Services, subject pilots were asked to rate the workload for the services as they appeared during the flight using the scale as presented below.

- 5 Completely saturated
- 4 High workload
- 3 Acceptable at all times, not too high OR low
- 2 Low workload
- 1 Very low, bored, need activity

The ATC workload ratings given by GAT pilots (acceptable) were almost a full point higher than those given by B-727 pilots (low workload). This may be due to the fact that the GAT pilot was alone, whereas, the B-727 portion utilized a two-person crew. Ironically, however, the GAT pilots rated the workload lower for the WX Services.

After entering a weather request, the system remained in the LOCID menu. Upon delivery of the requested service to the Data Link system, a message appeared at the bottom of the display indicating its availability. Upon touching the area, the weather information was presented. The logic flow associated with the LOCID menu/weather retrieval was acceptable by all. One pilot did not want to have to touch to retrieve the weather when available.

3.5 DISCUSSION.

This evaluation represents a significant step toward the implementation of a usable airborne Data Link system. Qualified pilots were used to examine an ATC and WX system in real-time situations. Thus, consideration of the impact upon real flightcrews was undertaken at a stage of development that will permit meaningful response to the needs, desires, and limitations of operational personnel. The results showed that Data Link can be a time saver. However, care must be taken, as pointed out by the pilots, to avoid introducing new problems (e.g., visual annunciation, party line loss, etc.).

Overall, the data, both objective and subjective, indicate that Data Link may enhance the communication link between pilots and

the ground (ATC and WX). Although the number of ATC Services was limited, the objective data may be generalizable across other routine ATC Services. The primary dependent variable (DV) with ATC Services, WILCO/UNABLE Time, would probably be related to the complexity of the instruction. Therefore, for routine instructions the Data Link - voice (WILCO/UNABLE) time differences should be comparable to the observed data. Only further testing will determine the validity of this assumption.

Examination of the ATC time data (WILCO/UNABLE time) will show that, overall and for each service individually (appendix H), the time to interpret and respond to messages was shorter with Data Link. This tendency occurred with both GAT and B-727 pilots. The Data Link - voice time differences were consistently larger with the GAT pilots. For the GAT, the percentage differences in WILCO/UNABLE time between Data Link and voice in altitude assignment, frequency change, and free text cases were, respectively, 40, 43, 36, and 38. Conversely, the B-727 time data indicate percentage differences of only 18, 33, 7 and 5.

This difference in favor of the GAT pilots should be interpreted cautiously. It is frequently a mistake for external observers to attach importance to a particular time measure of aircrew performance. One must first determine whether the aircrew members themselves felt that performance time to be important. Pilots have many duties to perform. Any particular function is attended to in the context of all the other things to be done. One particular function may seem important to the external observer, but the pilot tends to select out those of highest priority at the moment. How quickly they do perform a particular function may not be related to how quickly they can perform it.

The experimenters did make some observations about pilot behavior during the test runs. Contrary to instructions, a few of the B-727 pilots would act on an ATC command before pressing WILCO (or UNABLE), e.g., they would change the altitude hold setting of the autopilot or change the voice radio frequency, then WILCO the message. The larger response times may be related to the "two-person" operation. In a single-pilot operation, the pilot is the only human component. Conversely, in the airline case, the First Officer must decipher the message, then vocalize it to the Captain, who then makes a decision, tells the First Officer to either WILCO or UNABLE. The airline environment results in an additional component in the information loop, i.e., the First Officer is not present in the single-pilot environment. The crew coordination process (in this test) appears to have added to the response time.

The weather data are not as conclusive as the ATC data. Examination of the overall data will show that message creation times (MCT) were essentially equal (Data Link vs. voice, GAT vs. B-727). The B-727 voice condition took slightly longer. The DV of overall message processing time (MPT) favors Data Link (both

GAT and B-727). The Data Link-voice MPT time differences for GAT and B-727 are, 42 and 12 percent, respectively. The response latency DV favors voice, both GAT and B-727.

System time for Data Link was essentially equal between GAT and B-727. System time for voice between GAT and B-727 was considerably different. This difference is related to the fact the voice weather came from two different individuals. The individuals were to receive the request, wait for approximately 10-15 seconds (as if getting the information from an on-line computer), then read the information to the pilot. Individual differences in wait time probably account for this time difference.

The DV's, MCT, and MPT are considered most critical in this discussion because they are pilot specific. The Response Latency (RL) variable is pilot specific; but, because of the small times involved, is not as critical (in the test engineers' opinions). Given this assumption, further examination of the GAT data will show MCT essentially the same in Data Link and voice overall and in each of the services individually. GAT MPT differences between Data Link and voice are relatively large. Percentage differences for MPT overall, terminal forecasts, surface observations, wind/temperature, and PIREP's were 42, 51, 37, 35, 41, respectively.

Again, accepting the above criticality assumption, examination of the B-727 data will show that MCT overall with voice requires 28 percent⁺ more time than Data Link. For terminal forecasts, surface observations and wind/temp aloft, respectively, the voice condition required 49, 19, and 38 percent more time than Data Link. B-727 MPT percentage difference between Data Link and voice for overall terminal forecasts, surface observations, and wind/temperatures were 12, 20, 7, and 32, respectively. There were no voice PIREP's accomplished by the B-727 pilots.

In examining the time data, consideration must be given to the fact that eight Data Link runs and four voice runs were accomplished. This inequality in number of runs may contribute to the differences. Also, one must be careful of GAT B-727 comparisons because (a) the GAT and B-727 flew in two different altitude/traffic environments, and (b) the B-727 time data were obtained from a non-flying operator of Data Link; whereas, the GAT pilot flew and operated Data Link.

A point for the reader to consider in evaluating the weather time data, specifically, message creation time, is presented. In a voice environment, where an aircraft only has one radio, a frequency change to a Flight Service Station (Flight Watch) must occur. Conversely, in Data Link, the pilot simply inputs the request. The point - - message creation time in voice could justifiably be defined as the time from when the pilot starts the

request to ATC to be off the air (obtaining weather) through changing the frequency, and finally, calling for the weather. If this definition of message creation time were accepted, instead of the definition applied to the data (defined earlier in this report), the difference in time would be emphasized. The authors chose the conservative definition in analyzing the data to avoid possible differences of opinion. Nonetheless, the point is presented for consideration.

Other points to consider are: a limited number of services were presented, thus, limiting judgments on workload (as in a fully implemented system), the frequency of voice callbacks to clarify information which resulted in longer WILCO/UNABLE time, and equipment constraints limited the system capability. Despite these constraints, there were substantial time savings for Data Link over voice. This, in itself, would warrant furtherance of this concept. In support of the time data, pilot perceptions of the value of Data Link were very positive. Together, the time data and pilot perceptions emphasize the validity of the Data Link concept.

4. JOINT CONTROLLER AIRCREW ISSUES.

The two substudies presented in this report used a common simulation environment to address human interface and procedural design issues relevant to the roles of aircrew and air traffic controllers in producing an effective implementation of Data Link. Many of these issues are concerned with problems that are unique to either the airborne or ground elements of the system, and are essentially transparent to controllers or their pilot counterparts working in separated environments. For this reason, the two substudies were designed and conducted in a relatively independent manner.

However, because a significant determinant of the success of Data Link will be the extent to which effective, two-way communications can be accomplished, the operational evaluation also include measures and limited debriefing discussions which emphasized the interaction between controllers and pilots that will occur over this system. This section of the report draws upon the individual results of both substudies, prior findings from the controller mini studies, and preliminary contacts with pilot organizations to examine several joint design issues.

4.1 DATA LINK AS A PRIMARY SERVICE DELIVERY MODE.

Two concepts were originally proposed for the application of Data Link to the delivery of ATC services. One of these designated Data Link as a primary delivery mode which would act as a substitute for voice messages. The alternative approach viewed Data Link as a secondary mode in which a digital uplink would be redundant with a voice clearance. When both of these concepts were presented to

controllers during the preliminary mini studies, the subjects were unanimous in their preference for the use of Data Link as a primary communications method which would be fully interchangeable with voice. The general consensus was that, in order to reduce frequency congestion and keep controller workload within acceptable bounds, Data Link would have to be sufficiently reliable to eliminate redundant voice messages. The sole precaution suggested by the controllers was that voice radio linkage must be maintained as a back-up to Data Link and as a means to deliver messages that are inappropriate for digital transmission. Subsequent studies, including the operational evaluation, were conducted without redundant voice transmission and no controller inputs have been received which contradict this philosophy.

In general, it appears that pilots agree with the use of Data Link as a primary service delivery method. Comments received from aircrew who participated in the operational evaluation indicated that Data Link should be able to serve all communication functions currently performed using voice radio, and that Data Link can be expected to improve the accuracy and reduce the workload of ground-air communications.

4.2 REQUIREMENT FOR A DOWNLINKED WILCO TO ATC MESSAGES.

As dictated by the results of the preliminary controller mini studies and by current ATC doctrine, the Data Link procedures used in the operational evaluation study required pilots to downlink a WILCO response to confirm receipt of a message and an intent to carry-out the ATC instruction. The controller philosophy behind this requirement is that a message is not considered delivered to the flight deck unless it is followed by a confirmatory response. This concept was embodied in the software logic developed for Data Link by making receipt of the WILCO response the key event which updates information about an aircraft in the NAS data base.

The pilots who participated in the operational evaluation appeared to agree that the downlinked response is an appropriate means for indicating their intent to comply with an ATC instruction. Overall, the response concept received an average rating of 6.27 (1 - 7 scale), indicating a high level of acceptance.

4.3 THE UNABLE DOWNLINK.

Early controller inputs to the tested designs for Data Link suggested that the receipt of a downlinked from an aircraft as an indication that the pilot could not comply with an instruction was an insufficient response. Some of the controllers felt that the capability to send this response should be eliminated from a Data Link cockpit hardware design. The rationale underlying this recommendation was that the message was uninformative and time consuming, and should be replaced by a procedure requiring an immediate radio contact from the pilot.

Informal discussions with pilots prior to the operational evaluation suggested that there could be some resistance to eliminating the UNABLE key, presumably because this would restrict downlinks to confirmation responses. During the operational evaluation pilots were instructed to use both the UNABLE downlink and an immediate radio call to the controller to resolve any problem. Although not directly addressed by any evaluation instruments, this procedure for handling exceptions did not prompt negative comments from controllers or pilots.

4.4 DATA LINK DELAYS.

As noted in the results of the controller substudy, Data Link delays associated with radar antenna rotation did not affect controller workload or result in negative comments; even when these delays were extended to twice those predicted for an operational Mode S system. While the tested time lags could be relatively long, controllers appeared to adjust to the system quite rapidly, either by issuing clearances in a more anticipatory fashion or by switching to voice in time-critical situations.

Pilots in the operational evaluation were also largely unconcerned with Data Link turn around times for ATC clearances. This response was predictable since the aircrew reacts to an ATC message only after it arrives on the airborne display, and is unaware of the total delay which transpires from the issuance of a clearance to the receipt of a confirmatory response by the controller. Nevertheless, the fact that pilots did not notice an effect of Data Link delays for ATC messages suggests that these lags had no negative impact on the perceived timeliness of controller instructions.

The pilots did comment on the delay which elapsed between a request for weather information and its receipt in the cockpit. For these services, where the aircrew was cognizant of the full cycle of downlinks and uplinks, delays were considered potentially problematic.

4.5 INITIAL CALL.

In the current ATC system pilots are required to call the controller on the newly assigned frequency after they receive a transfer of communication message. Controllers who participated in the design and evaluation of the Data Link transfer of communication service have suggested that this initial call could be eliminated since the pilot will have a verified, recallable display of the new radio frequency available in the cockpit at all times. From the point of view of the controller, removing the requirement for initial call would reduce workload while maintaining positive contact with each aircraft.

Informal discussions with pilots and unsolicited comments from the operational evaluation indicate that aircrews may be somewhat reluctant to relinquish this radio contact. The general opinion was that the initial call serves to verify the radio link and assure the pilot that the aircraft is under positive ATC surveillance in the new sector. Controller responses to this comment suggest that the initial call only verifies the existence of the radio link during the call itself, and that, in any case, the pilot has the back-up assurance of the Data Link connection.

Although no consensus was achieved on this issue, it appears that the disagreement may be resolved as pilot confidence in the integrity and reliability of Data Link is gained during the system implementation process. In the transitional phase, both controllers and pilots appear to feel that the initial call may be retained. Additionally, elimination of the initial call will necessitate reconsideration of operational procedures since, under some conditions, this transaction is currently required as a check on an aircraft's assigned altitude and on the Mode C readout.

4.6 LOSS OF THE "PARTY LINE".

A general concern expressed by many pilots in their informal considerations of Data Link and in comments recorded during the operational evaluation was that this discretely-addressable communications system may sacrifice an important source of flight information. Although the ability to receive only those messages directed to one's own aircraft will help to eliminate confusion and the need to monitor all broadcasted voice transmissions, pilots feel that this feature of Data Link could result in the loss of a source of general knowledge about other air traffic in the vicinity, and advance information about local weather aloft and ATC clearances that can be expected in the near future. For many pilots this "party line" currently provided by voice transmissions appears to be an important basis for maintaining situation awareness.

Approached with the problem, controllers have argued that use of the incidental information from the party line often can lead pilots to take inappropriate anticipatory action and that a "silent" Data Link environment is unlikely to be experienced by pilots in the foreseeable future. In addition, some controllers have projected that as Data Link begins to relieve voice frequency congestion, controllers will be able to use voice to provide pilots with more direct data to support their knowledge of the current and expected flight environment.

Pilots also made comments regarding possible ameliorating factors. In particular, they have noted that the importance of the party line may diminish as more situation data are made available to the cockpit using systems such as the Traffic Advisory and Collision

Avoidance System (TCAS), or from automatically uplinked information about surrounding aircraft positions from the NAS data base.

4.7 CONDITIONS FOR REVERSION TO VOICE.

Although pilots and controllers agreed that the use of Data Link for ATC clearances was appropriate, both groups indicated that there are conditions under which voice radio should be used exclusively for transmission of control instructions. The majority of these situations involved communications which were time-critical, where potential Data Link delays may be intolerable. In addition to emergency calls, recommended conditions for mandatory voice contact included busy terminal area final approach and arrival, and other cases where the pilot's visual attention is focused outside of the aircraft.

While pilots and controllers tended to concur on this issue, it should also be noted that the speed of Data Link communication and the ease with which aircrew can interpret and utilize uplinked information may vary with the specific Data Link transmission medium (e.g., Mode S vs. satellite) and the design of cockpit interfaces (e.g., text vs. graphics or synthesized voice). Thus, it is possible that the boundary conditions for the use of Data Link may change as these technologies evolve.

4.8 DISCUSSION.

Examination of the data presented in this section of the report suggests that although controllers and aircrew appear to agree on many topics, several issues governing ground-air interaction over Data Link remain unresolved. Most of these issues appear to be concerned with problems that can be addressed through the development of jointly determined controller and pilot operational procedures rather than major hardware or software modifications to Data Link.

5. CONCLUSIONS.

The results of the study presented in this report warrant a number of conclusions about the ground and airborne components of the Data Link system. Conclusions derived from the results of the controller and aircrew substudies are listed below in separate sections. A final conclusion addresses those issues which impact the interaction between controllers and pilots.

5.1 CONTROLLER SUBSTUDY.

a. General perceptions of Data Link recorded during the operational evaluation were in agreement with the findings of earlier mini design studies. The controller participants indicated

that implementing Data Link in operational en route field environments will have positive effects on the overall safety and efficiency of ATC and on system capacity.

b. The results of the study provided the first empirical evidence of the extent to which Data Link can be expected to alleviate the problem of voice radio frequency congestion in the ATC system. Using only the transfer of communication, altitude assignment, and text functions included in the initial Data Link service package, individual voice transmissions and channel occupation time were significantly reduced in comparison to tests in which current, voice-only procedures were used.

c. Comparisons of current and Data Link procedures indicated that in addition to a reduction in voice radio usage, Data Link may increase the overall efficiency of controller-pilot communication by reducing requirements for resending garbled and misinterpreted messages.

d. Data Link usage in low and high traffic portions of the test scenarios indicates the tested services are likely to be equally effective across a broad range of operational situations.

e. The observed benefits of Data Link to Air Traffic Control (ATC) productivity were not gained at any measurable loss in ATC safety or increase in the perceived workload of the test controllers. Because the subject controllers received only basic training with the Data Link services and were unfamiliar with the ATC test scenarios, it is projected that the workload associated with Data Link operations may be even lower than that experienced with current voice communication procedures when the system is used by fully experienced controllers in familiar field environments.

f. Controllers reported no negative effects of extending Data Link transmission delays beyond those currently projected for an operational Mode S system.

g. Controller workload did not differ between the 20 and the 70 percent Data Link aircraft equipage tests. Furthermore, controllers reported no significant problems in switching between voice and Data Link in mixed equipage environments. These results suggest that Data Link should be equally usable by field controllers in early and later phases of Data Link system implementation.

h. The tested designs of the four Data Link services were defined by the results of preliminary mini studies. The operational evaluation demonstrated that these en route controller procedures, displays, and data entry protocols were sufficiently effective and acceptable to controllers to warrant their implementation for field evaluation.

i. As noted above, the quantitative results of the operational evaluation did not reveal major deficiencies which would prevent implementation of the tested Data Link services. However, individual controller comments and the group discussion sessions surfaced some open issues and suggestions for enhancements to the current service designs which should be addressed in future work. Those topics requiring further consideration are treated in the "Recommendations" section of this report.

5.2 AIRCREW SUBSTUDY.

a. The operational evaluation study represented the first FAA investigation of aircrew responses to Data Link communications using preliminary hardware and software designs for pilot information displays and controls. Overall pilot perceptions of the Data Link concept were positive, and suggested that its implementation would enhance the quality of air-ground communications. Evaluations of the specific methods used for presenting Data Link information in this study indicated that minor changes in display logic and format would enhance interaction between pilots and the system.

b. Comparative measures indicated that the time required by pilots to process and respond to ATC instructions was shorter when using Data Link than when using current voice radio procedures. This improvement was attributable to an increased rate of information transfer as misunderstandings and requirements to call-back for repetition or clarification were reduced.

c. Pilot processing time for weather messages were also reduced by Data Link as a result of the enhanced interpretability of messages. No major differences between voice and Data Link were detected for preparing and sending weather requests.

d. The workload associated with Data Link operations was rated as acceptable by the subject pilots. Data Link can be expected to reduce aircrew workload by minimizing memory demands and requirements for maintaining notes regarding ATC clearances. However, effective and timely crew coordination will be needed with Data Link to ensure that messages reaching one crew member are communicated to others.

e. The subject pilots in this study concurred that Data Link can effectively replace most functions currently served by voice radio in en route and outer terminal control environments. Voice should be used as a primary back-up to Data Link and as a channel for emergency communications.

5.3 JOINT ISSUES.

Based on the results of the operational evaluation and those of earlier investigations, it appears that pilots and controllers

agree on a number of basic procedures which will govern air-ground interactions via Data Link. However, additional formal meetings between pilot and controller groups will be necessary to resolve other outstanding issues. These issues include elimination of the initial call after a transfer of communication, procedures for communication when a pilot does not confirm receipt of an ATC clearance, and compensation for the potential loss of pilot situation awareness which is currently supported by monitoring broadcasted radio calls to other aircraft.

6. RECOMMENDATIONS.

The following recommendations for future efforts under the Federal Aviation Administration (FAA) Data Link program are derived from the findings and conclusions of the present research:

a. This operational evaluation study demonstrated that the tested Data Link ATC services and functions can significantly reduce ground-air radio frequency congestion without impairing air traffic control (ATC) safety or the performance capabilities of air traffic controllers. Therefore, it is recommended that these services be incorporated as modifications to current en route ATC software and hardware, and that they be subjected to operational test and evaluation (OT&E).

b. It is recommended that the following outstanding issues and potential enhancements to the current Data Link service designs be addressed by the FAA.

1. Available graphic symbologies for display of Data Link equipage and uplink eligibility in the full data block (FDB) should be reviewed to identify alternatives which could enhance the perceptual discrimination and detectability of this information by air traffic controllers.

2. The persistence of the FDB display of a downlinked WILCO response should be reconsidered to determine whether an increased display time will reduce the demands of monitoring Data Link transactions.

3. The list display of transaction status should be examined to determine any requirement to reduce display clutter by creating a separate list for transfer of communication transactions, or by displaying information regarding only those transactions which have not been successfully completed.

4. An option which would permit automatic uplinks of the transfer of communication service should be reviewed.

5. Uplinks of requested altitudes using menu text should be evaluated to determine whether this type of clearance should be accessed by selecting a separate "hard" altitude menu.

6. Menu text should be examined to consider the need for inclusion of extended, compound clearances as menu items.

7. Proposed operational procedures should be developed to govern the conditions under which the free text service will be used, and to define eligibility rules for engaging in Data Link communications while a transfer of communication transaction is in progress.

8. Proposed procedures for assigning Data Link duties to associate (D) controllers should be identified. These should include any software modifications that would be needed to provide Data Link control to the appropriate workstation position.

c. It is recommended that the topics outlined above, as well as any additional outstanding issues, be addressed through formal presentation to the Data Link Validation Team (ATDLVT). The results of the deliberations of this team should define any requirements for additional research to refine the designs of the initial Data Link services.

d. Based on the success of the operational evaluation and the comments of the participating controllers and pilots, it is recommended that research and development work be expedited to extend Data Link applications to the full range of ATC services.

e. The existence of outstanding questions regarding the rules and procedures which will govern pilot and controller interactions using Data Link dictates that a mechanism be developed for resolving these issues. Therefore, it is recommended that formal meetings between the ATDLVT and a representative pilot group be instituted to address joint issues and to suggest direction for additional relevant research.

f. Based on the positive findings of the aircrew substudy, it is recommended that Data Link services to aircraft be implemented in the National Airspace System (NAS) as rapidly as possible.

g. Because the design and development of airborne Data Link procedures and crew interfaces has lagged behind corresponding work with ground based air traffic control (ATC) at the FAA Technical Center, it is recommended that additional design studies and end-to-end operational evaluations be conducted to address the following requirements:

1. Research is required to investigate methods for integration of Data Link into the cockpit environment. This research should address the physical location of cockpit displays and controls, integration of Data Link with other airborne systems (e.g., navigation), and integration of Data Link tasks with other flight duties to minimize the number and complexity of required activities.

2. Additional research is also required to evaluate and refine alternative display and control hardware for Data Link; and to modify display formats and logic in order to enhance information transfer and reduce switching requirements.

3. Additional work is needed to analyze experimentally the observed differences in performance times between the GAT pilots and the B-727 crews.

4. Additional work is needed to assess the impact of realistic crew response times and Data Link transmission times on ATC system performance. More complex flight scenarios and more pilot participation in the simulated traffic scenarios will be needed.

7. REFERENCES.

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