Report No. FAA-RD-75-133,I
NA-74-21, I

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THE CONTROLLER/COMPUTER INTERFACE WITH AN AIR-GROUND DATA LINK

VOLUME I

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SEPTEMBER 1975

FINAL REPORT

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Prepared for

U. S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
Systems Research & Development Service
Washington, D. C. 20590

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Technical Report Documentation Page

1. Report No. FAA-RD-75-133, I	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle THE CONTROLLER/COMPUTER INTERFACE WITH AN AIR-GROUND DATA LINK VOLUME I		5. Report Date September 1975
		6. Performing Organization Code
7. Author(s) S. Rossiter (NAFEC), R. Wiseman (TSC), M. Connelly (MIT/ESL), T. Morgan (CSC)		8. Performing Organization Report No. FAA-NA-74-21 I
9. Performing Organization Name and Address Federal Aviation Administration National Aviation Facilities Experimental Center Atlantic City, New Jersey 08405		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. 062-222-040
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Aviation Administration Systems Research and Development Service Washington, D.C. 20590		13. Type of Report and Period Covered Final May 1974 to August 1974
		14. Sponsoring Agency Code

15. Supplementary Notes
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16. Abstract
A dynamic simulation study was conducted to determine the display techniques and operating procedures that best enable an air traffic controller to work in a mixed voice/digital communications environment. The study focused on the benefits that might accrue to ground-based automatic control through further automation of the controller's communication tasks. The simulation was performed at the National Aviation Facilities Experimental Center as a joint effort with the Department of Transportation, Transportation Systems Center. A simplified version of the ARTS III Metering and Spacing system was used to assess the controller's communication task when automatically generated control commands were transmitted to voice link or to data link-equipped aircraft in terminal approach traffic. Subject to follow-on testing of a more operational nature, it was concluded that a data link channel efficiently augments the voice channel, the value increasing as the percentage of data link aircraft increases. System test measures and questionnaire results show that further efficiencies can be obtained through the use of computer-generated speech, one-at-a-time display of commands moving with the aircraft target symbol, and by the automatic transmission of commands on both the voice and data link channels. The automatic command transmission eliminates the controller's tasks of approving commands, placing more emphasis on traffic situation monitoring. With a careful optimization of display formats and operating procedures, the controllers' acceptance of automation features will improve while they are still provided with safe traffic management and recovery techniques during system failures.

17. Key Words Air Traffic Control Simulation Data Link Terminal ATC	18. Distribution Statement Document is available to the public through the National Technical Information Service, Springfield, Virginia 22151

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 13	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

PREFACE

This report is volume I of a two-part report. Volume II contains the detailed analytical material. Volume I is the summary report.

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EXECUTIVE SUMMARY

THE CONTROLLER/COMPUTER INTERFACE WITH AN AIR-GROUND DATA LINK

INTRODUCTION.

This report presents the results of a simulation study that addressed the air traffic controller's role in a digital data link communications environment. The study focused on the benefits that might accrue to ground-based automatic control through further automation of the controller's communication tasks. Such benefits may become significant at some time in the future when a sufficient number of aircraft cockpits are equipped with a data link capability. When this occurs, the controllers will be addressing each of these aircraft through a separate channel that supplements and may eventually replace their current voice channel. This newer automatic channel would offer the advantages of quicker and more reliable communication with a corresponding reduction in voice-channel utilization. Moreover, when coupled with automation of ground functions, it would enable the controller to spend more time managing the traffic situation, rather than servicing the air traffic control (ATC) commands. However, automated communications must be carefully structured to allow the controllers to intervene when unusual situations occur. This requires an integrated design of data link message processing with the display and keyboard tools that define the human's interface with the computer-based automatic processes. Also, during the transition phase from a predominantly voice link to a predominantly data link environment, an attempt must be made to keep the controller's voice and data link operating procedures as similar as possible.

OBJECTIVES.

The objectives of the study were to:

1. Assess the controller's performance with varying percentages of data link-equipped aircraft in ATC situations involving:

    a. A high volume of control messages, and
    b. A model of an automated ATC system that was currently under development.

2. Select the most practicable of various candidate modes of operation as the basis for follow-on simulation studies with more realistic versions of the automated ATC system.

The above two objectives were tailored to fit in with ongoing tests of a prototype version of the Automated Radar Terminal System (ARTS) III Metering and Spacing (M&S) system at the National Aviation Facilities Experimental Center (NAFEC). This system was ideal for an assessment of a data link communications workload. The heading, altitude, and speed messages in this system were automatically generated at a high rate and involved an almost continuous, but straightforward, dialogue with the pilots. While modifications for a data link capability were being incorporated in the prototype M&S software, a simplified version of the M&S system was modelled on the NAFEC Digital Simulation Facility (DSF). The purpose here was to reduce the number of candidate modes of operation in a controlled environment before the more operational ARTS III M&S tests were started on the NAFEC Terminal Automation Test Facility (TATF).

SIMULATION ENVIRONMENT.

The DSF simulation environment had the following main features:

1. Simplified M&S simulation model with an approach controller handling traffic from two feeder fixes onto a single runway.

2. Two-channel operation (voice and data links) with automatic M&S command generation replacing the current procedures for manual vectoring.

3. ARTS III-like display formats and workload items (handoffs, separation monitoring, and frequency changes).

4. Exception conditions (link failures, pilot repeat requests, and non-compliances) with voice channel backup procedures.

5. The deliberate insertion of aircraft conflicts (separation violations) for controller detection and correction.

6. Command display techniques: Special video map (for visual cues of the M&S airspace structure), preselected ARTS tag orientations (to minimize overlaps), and identifiers of data link aircraft and pilot compliances (WILCO's).

7. Special function keys for the dispatch of active commands.

The controller's environment consisted of a display and entry console and included a voice link to remote operators acting as pilots. The pilots activated maneuver commands to a target generator program within the computer via keyboard entries. The target generator would alter the displayed position of the various aircraft types after a pilot reaction delay time. All of the test subjects felt very positive toward the simulation and regarded it as realistic.

CANDIDATE MODES OF OPERATION.

Seven different operating modes were selected for evaluation. These modes were made up of various combinations of four design alternatives:

1. Display Format: Full data block versus tabular list;

2. Command Access: Single versus multiple display of active commands;

3. Voice Communication Generation: By controller enunciation or by computer-generated voice; and

4. Command Control: By controller approval of each command or by exception.

DISPLAY FORMAT. The display format issues were concerned with the location of the M&S vector commands. These commands could be placed in a newly created third line of the ARTS data block, close to the aircraft's target symbol. While this location provides a good correlation of the command with the target, it increases the possibility of tag overlaps and does not give the controller a direct view of the number and sequences of active commands. The converse is true for these three aspects when the commands are displayed in a separate, compact, tabular list. The list reduces the trackball motion (required for command dispatch/erasure), but produces annoying jumps in line positions as commands are processed.

COMMAND ACCESS. The command access issue addressed the elimination of the trackball action that was required to identify an aircraft when the controller approved its command. A one-at-a-time (single) selection of commands in a tabular list was compared to (multiple) modes where all commands became active as they were generated. Active commands were defined as those that were both displayed and available for transmission by the controller. In single command modes, the command was selected through a preprogrammed set of priorities within the computer, and could be transmitted by simply depressing a DISPATCH function key. Under normal circumstances, this would produce a faster servicing of all commands because the time lost in slewing the trackball was eliminated. However, the trackball implies that the controller is making the decisions on command priorities when more than one command is active. For backup, a DISENGAGE function was provided to cover unusual situations. The function would effectively stop the flow of M&S commands to an aircraft so that the controller could provide his own manual vectors.

VOICE COMMUNICATION GENERATION. The voice communication generation issue explored the use of computer-generated speech with a voice synthesizer (Vosyn) as opposed to the controller's current method of voicing the commands himself. The voice synthesizer made it possible to use the same function key for dispatching both voice and data link commands, thereby providing some commonality in the procedures. It also offered other future benefits such as speech standardization and the controller's ability to pay attention to other commands while the Vosyn was speaking for him. However, the Vosyn did not have the

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human's capability to adjust its speech rate and to adapt its messages to unusual conditions. Such conditions would occur when the pilots requested a repeat of a command or could not comply with it. These and other extemporaneous communications would have to be voiced by the controller.

COMMAND CONTROL. The issue of command control was centered on the assumption that most of the commands generated by an automated ATC system will be operationally acceptable. It was therefore possible to use a voice synthesizer and a data link to achieve automatic transmission of all commands on both channels without prior controller approval. This mode of operation was called control-by-exception (CBE) and was structured to display commands for a short time in the full data block before they were dispatched. The idea was to eliminate the ordinary tasks of communication servicing (command evaluation, trackball slewing, button pushing, and voicing) in favor of a more careful controller monitoring of the overall traffic pattern and the correction of flightpath anomolies as they appeared. In the few instances where a command was unacceptable, the controller could use his voice link for an overriding instruction to the pilot. Although this method of operation may be faster than "control-by-approval" (CBA) modes, the controller no longer evaluates and transmits individual commands, and this function is an important factor in maintaining his picture of the traffic. In addition, without constant use, the controller may become less skilled in backup manual vectoring procedures when system failures occur.

Given the above issues to be resolved, the seven candidate modes tested were:

1. Full Data Block - Multiple Command - Voice,
2. Full Data Block - Multiple Command - Vosyn,
3. Tabular List - Multiple Command - Voice,
4. Tabular List - Multiple Command - Vosyn,
5. Tabular List - Single Command - Voice,
6. Tabular List - Single Command - Vosyn, and
7. Control-By-Exception (Full Data Block, Vosyn)

A very promising eighth mode (Full Data Block - Single Command - Vosyn) was not considered because it required extensive modifications in the M&S software that was to be used in the follow-on testing.

TEST CONDUCT.

Twenty-one air traffic controllers, each with over 10 years of field experience, served as test subjects in 91 separate simulation runs. Each run lasted for 1 hour and was preceded by a 1-hour training run. The runs were watched by other controllers who were permanently assigned as test observers. The test sequences were arranged to balance out controller experience derived from their earlier runs and the effects of different traffic scenarios that were used with each of the seven modes under consideration.

The data recorded for each run consisted of controller questionnaire responses and real time quantitative measures in the form of communication delays and counts of various events (numbers of separation violations, tag repositionings, and controller manual overrides of the M&S commands). During the preparatory stages of the data analysis, five task areas were covered:

1. Immediate review of the questionnaires and end-of-run printouts revealed that seven test runs were invalid and had to be repeated. Only two of these were due to major errors in controller operation, the remainder being caused by equipment malfunctions.

2. Statistical analysis disclosed that the measured data was highly heterogeneous and, therefore, required a high significance level in the interpretation of the results. A 0.99 confidence factor was generally applied in order to avoid overstatements.

3. A characterization of the time for a complete message transaction as a function of traffic density was made possible through the choice of a ramp density profile. The profile was selected to increase linearly up to a high count of 11 instantaneous aircraft (44 approaches/hour), thereby making the instantaneous load proportional to the test run time. It was felt that a running record of the controller's message transaction delays would show a sharp increase as they approached the limit of their traffic-handling capability. However, the actual delay variation was linear with delay increases that were generally less than 30 percent.

4. A real time conflict detection program revealed a total of 10 separation violations in the 91 hours of testing. This number was considered low in the face of the requirement for reduced separation criteria (2 nmi except for a 5-nmi fantail behind heavy jets) and the 91 conflict situations that were deliberately inserted (one in each test run).

5. Slight modifications to the questionnaires were made after the completion of the first series of tests in which an equal number of voice and data link aircraft were employed (50-percent mix). These tests marked the half-way point when it was learned that the remaining computer time would be curtailed. This led to the design of abbreviated test groups for 20- and 80-percent mix levels.

SUMMARY OF RESULTS.

In terms of the objectives of this simulation, the implications of the final analysis of the accumulated data can be expressed in four task areas. The objectives were to:

1. Compare the performance of the seven candidate modes with each other to obtain an overall ranking.

2. Compare combinations of modes to indicate preferences for each of the design alternatives:

a. Full data block (FDB) versus tabular list (TAB);
b. Single versus multiple command;
c. Voice versus Vosyn; and
d. Control-by-approval (CBA) versus control-by-exception (CBE).

3 Determine whether the performance is improved as the percentage of data link aircraft is increased (20-, 50-, and 80-percent mixes).

4. Provide other information on performance and procedures that will be helpful to follow-on data link programs.

Within each of these task areas, a combined examination of the controller questionnaries and the quantitative data is summarized as follows:

RANKINGS. The results of the analysis showed (a) the best modes were CBE, FDB-Multiple-Vosyn, and TAB-Single-Vosyn; and (b) the worst modes were FDB-Multiple-Voice, and TAB-Multiple-Voice.

The CBE mode resulted in much lower communication delays (message transaction times, queue lengths, etc.), but caused some controller concern over its potential susceptability to blunders. The FDB-Multiple-Vosyn mode was given the highest overall ranking after the controllers were exposed to all modes, but its quantitative performance was the worst because of the delays of the trackball action. This action was not required in the TAB-Single-Vosyn modes, which was also aided by a blinking target symbol for target correlation with the active command. In addition to the trackball action, the low rankings of the FDB-Multiple-Voice and TAB-Multiple-Voice modes were caused by the requirement for different voice and data link procedures for servicing the commands. The servicing consisted of an identification of an asterisk (*) character for data link aircraft and a subsequent depression of a DISPATCH (data link) or ADVANCE (voice link) function key. This time-consuming and annoying procedure was not required for the single key operation in the Vosyn modes.

DESIGN ALTERNATIVES. In terms of the design alternatives, the following results were found:

1. Subjective data favored FDB, and quantitative data favored the tabular list.

2. Single command modes were strongly preferred over multiple command modes (mainly due to the elimination of the trackball action).

3. Vosyn modes were mildly preferred over voice modes (mainly due to procedural simplicity).

4. The CBE mode was subjectively preferred over all but one of the CBA modes and was strongly preferred over all modes by the quantitative data.

The contradiction in the subjective and quantitative comparisons of FDB-Multiple with TAB-Multiple modes was due to differences between the delay measurements and the questionnaires. Although the TAB modes minimized the motion of the trackball, the controllers customarily worked with the FDB and valued the close proximity of the command to the target symbol.

The preferences for single over multiple commands and the Vosyn over voice strongly suggest that the FDB-Single-Vosyn mode would have performed extremely well if it had been tested. The Vosyn option has been selected here because it was favored by the controllers. Moreover, even though the Vosyn was less flexible and slower than voice communications, the delay measurements indicated that a busy controller would look ahead to the next command during a Vosyn transmission.

IMPROVEMENT WITH A DATA LINK. Extrapolation of the data indicates that if all of the aircraft in the simulation scenario were data link-equipped, the controller's message transaction times at maximum load would compare to a purely voice link operation as follows:

1. CBE; 57-percent improvement from 12.2 to 5.2 seconds per message;

2. TAB-Single-Vosyn; 46-percent improvement from 15.5 to 8.3 seconds;

3. FDB-Multiple-Vosyn; 25-percent improvement 19.5 to 14.6 seconds; and

4. All other modes; improvements ranging from 14 to 37 percent.

The overall conclusion from the above comparison is that a data link capability can definitely improve the controller's communications efficiency. This was especially true for the CBE mode where the delays in the initiation of a command were effectively eliminated. CBE therefore permitted a much faster operation in a predominantly data link environment and was ranked best at the 80-percent mix by the controllers. The improvements in most of the other modes are also significant and were substantiated by the results from the questionnaires. The controllers generally accepted a data link as an operational benefit. They also preferred the automatic generation of M&S commands over their current procedures for manual vectoring, provided that the simulation scenario contained a majority of data link aircraft.

OTHER INFORMATION. Other results of this simulation study indicate the following:

1. The majority of the controllers indicated that only 1 to 3 hours of additional training would be necessary to make them feel comfortable with the operational procedures.

2. A 3-second holdover of a "W" character to indicate pilot compliance on the data link is satisfactory but not absolutely required. However, pilot noncompliance and data link failures should be prominently displayed until the controller resolves them.

3. Voice commands should be held over in a nonblinking state for 20 seconds, in case the pilots request a repeat of the message.

4. Eighty-five percent of the controllers felt that the workload at the maximum density (44 approaches per hour) was at (22 percent) or below (63 percent) their maximum capacity. Controllers indicated that it was also relatively easy to maintain a "picture" of the traffic situation and monitor for conflicts at the reduced 2-nmi separation. However, if the M&S and the data link parts of an ARTS system failed, even though a hazard would not exist, the maximum load could not be handled indefinitely.

5. The variation in controller message transaction delays did not show a sharp increase as the traffic density steadily increased to the maximum value of 11 instantaneous aircraft. The actual variation was linear with delay increases that were generally less than 30 percent of the delays at light loads.

6. The display presentations (formats, video map, etc.) and function key operation were considered adequate by a large majority of the controllers. The preorientation of the full data block was particularly helpful in reducing the repositionings to within two to five per hour.

7. Eighty-one percent of the controllers felt that Vosyn operation was less tiring than voice.

8. Measurements of arrival time errors at the inner fix indicated that prompt delivery of the last heading command was critical to a timely arrival of aircraft on the runway. Since the delay of commands in the message queue will vary with aircraft load, the command lead-time for a given mode should not be a fixed constant, but should be adjusted on-line automatically to compensate for queue delays and for the processing speed of each individual controller. If constant lead-times are used, the specific values recommended for each mode are:

a. CBE, 2 seconds before desired execution time,
b. TAB-Multiple-Voice, TAB-Single-Vosyn, and FDB-Multiple-Vosyn, 9 seconds lead time,
c. TAB-Multiple-Vosyn, TAB-Single-Voice, and FDB-Multiple-Voice, 10 seconds lead time.

9. The real-time conflict detection program revealed a total of 10 separation violations in the 91 hours of testing. This number is considered low because the conflict situations were deliberately inserted in each test run.

CONCLUSIONS.

Results of the simulation indicate that if ATC approach control commands are automatically generated by an M&S system with a data link communications channel then:

1. A CBE mode (with computer-generated speech on the voice channel) is by far the most efficient mode tested, but it raises some questions on blunder susceptibility. This mode had message transaction times between 28 and 50 percent lower than the other modes tested and resulted in the lowest number of queued messages.

2. If a CBA mode were implemented, the best operation, on the basis of both efficiency and controller acceptance would have been achieved with computer-generated speech and one-at-a-time activation of commands displayed in the ARTS III full data block (FDB-Single-Vosyn). Two other favored modes confirmed in the tests, also include computer-generated speech and are ranked as follows:

   a. Single command display in a separate tabular list, and
   b. Multiple command display in the full data block.

3. If all of the aircraft in the airspace were equipped with a data link, the controller's message transaction times would decrease between 14 and 57 percent (depending on the mode employed). The data link would also produce significant improvements in the precision and timeliness of message delivery.

4. The optimization of display formats and operating procedures has a significant effect on communications efficiency and the controller's ability to provide separation assurance in dense traffic.

RECOMMENDATIONS

It is recommended that further investigation of a data link be accomplished in the following areas:

1. Simulation with the prototype version of the ARTS III M&S system involving computer-generated speech with the CBE, FDB-Multiple, and TAB-Single modes of operation. If it is possible to modify the current M&S software, the FDB-Single mode should also be investigated.

2. Verification of adequate failure recovery and traffic-monitoring capabilitites if a CBE mode is to be implemented in future systems. Particular attention should be addressed to the possibilities for dual-mode operation to insure continued controller familiarity with backup manual vectoring procedures. One suggested method involves the use of CBA when the traffic density is low, and a shift to CBE during peak loads.

3. Optimization of the throughput and intelligibility of computer-generated speech, particularly as it relates to speech rates, tone, and standardization within the ATC system.