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Wim den Braven

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Wim den Braven, Ames Research Center, Moffett Field, California

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Acronyms

ATC	air traffic control	MF	metering fix
cm	communications manager	PAS	Pseudo-Aircraft System
CTAS	Center/TRACON Automation System	PSCN	Program Support Communications Network
DA	Descent Advisor	pvd	planview display
DCP	data-link control panel	RNAV	area navigation
DHP	data-link history panel	SSR	secondary surveillance radar
DNP	data-link numeric panel	STA	scheduled time of arrival
DSP	data-link status panel	TMA	Traffic Management Advisor
ETA	estimated time of arrival	TRACON	terminal radar control
FAST	Final Approach Spacing Tool	TSRV	Transport Systems Research Vehicle
FL	flight level	VHF	very high frequency
id	identity	WC	waypoint capture
KIAS	knots indicated airspeed	4D	four dimensional
LAN	Local Area Network		

For abbreviations concerning data-link applications, see table 1.

Design and Evaluation of an Advanced Air-Ground Data-Link System for Air Traffic Control

WIM DEN BRAVEN*

Ames Research Center

Summary

The design and evaluation of the ground-based portion of an air-ground data-link system for air traffic control (ATC) are described. The system was developed to support the 4D Aircraft/ATC Integration Study, a joint simulation experiment conducted at NASA's Ames and Langley Research Centers. The experiment focused on airborne and ground-based procedures for handling aircraft equipped with a 4D-Flight Management System (FMS) and the system requirements needed to ensure conflict-free traffic flow. The Center/TRACON Automation System (CTAS) at Ames was used for the ATC part of the experiment, and the 4D-FMS-equipped aircraft was simulated by the Transport Systems Research Vehicle (TSRV) simulator at Langley. The data-link system supported not only conventional ATC communications, but also the communications needed to accommodate the 4D-FMS capabilities of advanced aircraft. Of great significance was the synergism gained from integrating the data link with CTAS. Information transmitted via the data link was used to improve the monitoring and analysis capability of CTAS without increasing controller input workload. Conversely, CTAS was used to anticipate and create prototype messages, thus reducing the workload associated with the manual creation of data-link messages.

1. Introduction

An air-ground data link is expected to play an increasingly important role in air traffic control (ATC). Not only will it improve the exchange of information between air traffic controllers and pilots, but it will also allow for integration of aircraft and ATC system capabilities. In May 1991 the 4D Aircraft/ATC Integration Study was performed to investigate such air-ground integration issues. This study, a joint simulation experiment of NASA's Ames and Langley Research Centers, focused on airborne and ground-based procedures for handling aircraft equipped with a 4D Flight Management System (FMS) and the

system requirements needed to ensure a conflict-free traffic flow. The scenarios that were investigated considered arrival traffic in Center airspace, from en route cruise until handoff to the TRACON. For the ATC part of the experiment the Center/TRACON Automation System (CTAS) at Ames was used. The 4D-FMS-equipped aircraft was simulated by the Transport Systems Research Vehicle (TSRV) simulator at Langley. A data-link system was developed to allow the exchange of digital data between the simulated aircraft and ATC.

The need for a data-link capability was already indicated by a previous experiment on air-ground integration, performed in July 1989 (refs. 1 and 2). Datalinking has the potential to increase the efficiency and clarity of air-ground communications, and in addition will allow communication of the minimum data the ground system needs to analyze an aircraft's preferred trajectory and to check for potential conflicts. Thus, for the 1991 experiment, an air-ground data-link system was developed that would support not only conventional[1] ATC communications, but also the communications needed to accommodate the 4D-FMS capabilities of advanced aircraft. However, the experiment did not involve all the elements of an operational air-ground data-link system. It was assumed that an air-ground data-link network, based, for example, on VHF-radio, satellite, or secondary surveillance radar (SSR) mode S, will be developed that provides the means to actually transmit messages. In this case the focus was on those elements of the air-ground data-link system that are related to the message contents, rather than to the actual transmission of the messages. In addition, none of the characteristic performance parameters of a real data-link system, such as communication capacity limitations, communication delays, and reliability were modeled. These parameters are assumed to be unrelated to the message content, and therefore less relevant for this experiment.

The purpose of this report is to describe the design and evaluation of the ground-based portion of the air-ground

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*Ames Associate from the National Aerospace Laboratory NLR/Delft University of Technology, The Netherlands.

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[1]"Conventional" refers to currently used message types and dialogues, as opposed to potential ones. It does not refer to the medium (voice versus data link).

data-link system, as developed for the 4D Aircraft/ATC Integration Study. The main requirements for its design were that it should (1) support conventional ATC communications and also the communications needed to accommodate the 4D-FMS capabilities of advanced aircraft; (2) be acceptable for controllers; and (3) have the potential for easy change and evolutionary development.

Although several small-scale experiments were performed during the development process, the real acceptance test was the experiment performed for the 4D Aircraft/ATC Integration Study. A description of the results of that experiment constitutes a major portion of this report.

The structure of this report is as follows. The overall data-link concept is described in section 2, which also includes a brief description of CTAS, in which the data link has been integrated. The data-link protocol, specifying the general rules, formats, and procedures for data-link communications, are described in section 3. This is followed in section 4 by a detailed description of the data-link design in terms of the data-link/controller interface, data-link applications, and CTAS/data-link synergism. Section 5 gives an overview of the setup and execution of the experiment and presents a description and analysis of the results. Finally, in section 6 some general conclusions are drawn, and recommendations for future study and development are made.

2. Data-Link Concept

Two important technological improvements in the present-day situation are prerequisites for integration of aircraft and ATC systems: improved automation of ground systems, and an air-ground data link. In this experiment, which focused on the aircraft/ATC integration, the improved automation was provided by CTAS, the Center/TRACON Automation System, under development at Ames. The ground-side of the data link was developed as an integrated part of CTAS, thereby taking advantage of the advanced capabilities of that system. This section discusses some aspects of the general data-link concept, on which the data-link design was based. The basic elements of the data-link communication chain are discussed, an overview of CTAS is given, and a general description of how the data-link system was integrated into CTAS is presented.

2.1 Data-Link Communication

A data link is a means of transferring digital data between two or more end-users. An end-user is any function or process (not a human!) that requires data transfer, for example, an arrival planning function that sends a scheduled time of arrival (STA) to an aircraft. An air-ground

data link enables communication between ground-based ATC computer systems and airborne flight systems. Through these systems, it also allows communication between an air traffic controller and pilots, as with the current radio-telephony. For ATC, a data link has many potential applications, ranging from sending a simple heading instruction to supporting a complex profile negotiation process (ref. 3).

Three generic components can be distinguished in a data-link communication chain: the source (sender), the medium, and the destination (receiver).

The *source* is the end-user that initiates the message transmission process. Depending on the message type (application), a particular "application process" is invoked that will actually send the message. This invocation could be a simple software function call, such as "send_new_heading_to_aircraft (new_heading, aircraft_id)."

The *medium* represents the portion of the communication chain that provides the actual telecommunication connection. The medium may consist of one or more (aeronautical) telecommunication (sub)networks. Typically, there is a network linking processes within an ATC facility, linking facilities with aircraft, and linking systems on board the aircraft. A facility network is for example a Local Area Network (LAN) that connects the various CTAS tools (see next section). SITA's (Société Internationale de Télécommunications Aéronautiques) Satellite Aircom network is an example of an air-ground network.

The *destination* is the end-user that receives the message. An application process of the end-user uses the message to generate the data that will actually enter the receiving system. Such an application process can again be seen as a simple software function, such as "receive_message," triggered by the reception of a message from the medium.

Sources and destinations can be specified on different levels of detail, varying from a facility name (e.g., Denver Center) to the actual software function that has to process a message. For this experiment, the global level was used, whereby sources and destinations are identified by facility names on the ground side and by aircraft call signs on the airborne side.

The remainder of this section describes CTAS, and how the data link was integrated in CTAS to provide the ground-based source and destination for air-ground data communication.

2.2 Center/TRACON Automation System

This section gives a brief overview of CTAS, the Center/TRACON Automation System. This system provided the

advanced ATC capabilities for the experiment. For a more detailed description of the design and operation of CTAS, the reader is referred to references 4-6.

CTAS is an integrated set of automation tools that assist air traffic controllers in the efficient management and control of arrival traffic. It comprises three complementary tools: the Traffic Management Advisor (TMA), the Descent Advisor (DA), and the Final Approach Spacing Tool (FAST). Communications between these tools, and between tools and the "outside world," go through the communications manager (cm). This overall CTAS concept is illustrated in figure 1. The system has been implemented on a series of workstations, connected by a LAN.

The TMA includes algorithms, a graphical interface, and interactive tools for use by Center and TRACON traffic managers. It coordinates the traffic flow through the feeder gates to the final approach fix and generates landing and metering fix crossing schedules that minimize delays. The TMA broadcasts the schedules, through the cm, to all sectors equipped with DA or FAST. It also receives information from DA and FAST, such as estimated times of arrival (ETAs), needed to perform its scheduling task.

FAST assists TRACON controllers in sequencing and spacing aircraft onto the final approach path. It gives speed and heading advisories which allow the aircraft to meet the arrival time as scheduled by the TMA. Since the experiment focused on Center arrivals, FAST was not used for this experiment and will not be mentioned further.

The principal function of the DA is to assist Center arrival/descent controllers in accurately and efficiently controlling arrival traffic to the TRACON feeder gates, in accordance with the schedules broadcast by the TMA. The DA is based on a generic four-dimensional (4D) trajectory-generation algorithm, adaptable for different types of aircraft. For all arrival flights, the DA periodically synthesizes trajectory solutions, based on controller inputs, current aircraft state (from radar tracking), and the TMA schedule. The DA translates these trajectory solutions into controller advisories which include speed for cruise and descent, the top of descent point, and heading. The DA also has algorithms to predict potential future conflicts between pairs of aircraft, and a limited conflict-resolution capability was added for this experiment to solve such conflicts.

The controller interacts with the trajectory-synthesis, conflict-prediction, and conflict-resolution algorithms to plan conflict-free trajectories that meet the arrival time. Once satisfied with a particular solution for an aircraft, the controller can issue the corresponding arrival clearance, and switch the DA from the planning mode to the monitoring mode for that aircraft. In this monitoring mode the DA compares the actual aircraft trajectory with the last calculated solution, in order to determine deviations in the lateral and vertical directions and in time. This switching from the planning to the monitoring mode is referred to as "locking" a trajectory, and is one of many interactive functions that can be performed by the controller.

Figure 2 shows a typical DA planview display (pvd). The picture shows the high-altitude sector, as defined for this experiment. Besides some overflights, this sector handles arrivals from the north-east from en route until handoff to the low-altitude sector. Aircraft with green and yellow tags on the pvd are arrivals; those with white tags are overflights. The blue lines on the map are the arrival routes. On the left side of the screen is the so-called timeline, which gives information about the schedule for the metering fix. The blue tags, on the left side of the timeline, give the scheduled time of arrival (STA) for each arrival flight, as determined by the TMA. The green tags on the right show the estimated times of arrival (ETAs), as calculated for each aircraft by the trajectory synthesis algorithms. For each aircraft the difference between its STA and ETA indicates how well the aircraft is expected to meet its schedule.

The controller can "select" one or more aircraft by clicking on the aircraft symbol, the small diamond shaped symbol displayed at the aircraft's position. The aircraft symbol and the aircraft tag turn yellow, and additional information is displayed for that aircraft in the rectangular panel in the top-middle of the screen. In figure 2, aircraft COA213 has been selected by the controller. The timeline ETA-tag also turns yellow, and a speed-range bracket is shown to indicate the earliest and latest arrival times possible with speed control only. The picture also shows several data-link panels; these will be described extensively in section 4.

In order to be able to fulfill its specific display and advisory functions, each CTAS component keeps information on the aircraft in the airspace under consideration. In general, this information is referred to as the (CTAS, DA, TMA, or cm) aircraft data base. This data base plays an important role in the integration of the data link in CTAS, which is outlined in the next section.

2.3 Data-Link Integration in CTAS

Under CTAS, each Center sector is equipped with its own DA. Each DA keeps an aircraft data base containing all the information needed to perform its display and advisory functions for controlling the aircraft in that sector.

Each DA also handles input by and output to the controller. The cm handles all communications between sectors, and between sectors and the outside world (i.e., outside the CTAS system boundaries). A similar architecture was chosen for the ground-based portion of the data link: the data-link/controller interface is integrated in the DA and the link with outside communication networks is integrated in the cm. This architecture allows the use of information in the DA aircraft data base to create data-link messages, and the update of that data base from information sent and received by data link. This synergism was expected to improve significantly the combined operation of the DA and the data link, by the controller.

With this architecture, the general process of data-link communication through CTAS is as follows. For uplink, data-link messages are created in the DA, using information from the data base. Upon controller approval, a message is sent from the DA to the cm, and the DA data base is updated based on the information in the message. In the cm, the message is coded in the proper format for transmission and subsequently transmitted over the appropriate medium. For downlink, messages are received in the cm and decoded into an internal format. The cm does not have information on which sector(s) should process a message; therefore, it broadcasts each decoded message to all sectors. Based on specific rules, each sector determines whether a message should be processed or not, and subsequently processes or discards the message.

The coding and decoding of messages in the cm is necessary because data-link messages are handled internally (in CTAS) in a specific format. In general, this format is not suitable for transmission to the destination. Therefore, for messages to be uplinked, the CTAS format has to be coded into a transmission format, and downlinked messages received in the cm have to be decoded. This coding and de-coding in the cm makes it easy to adapt for different applications, transmission media, or destinations.

In summary, the following data-link functions were integrated into the DA

1. Display data-link information to the controller

2. Handle controller inputs

3. Retrieve information from the aircraft data base

4. Update the aircraft data base

5. Send/receive data-link messages to/from the cm

and the following data-link functions were integrated into the cm

1. Code messages for uplink

2. Decode downlinked messages

3. Send/receive messages to/from the DAs

4. Send/receive messages to/from the outside world

Data-link integration in the cm will not be discussed further. The implementation of the data link within the DA will be described in detail in section 4. First, the data-link protocol is described in the next section.

3. Data-Link Protocol

The data-link protocol is the set of rules, data formats, and conventions that determines the way data-communication takes place between elements in the communication chain. For example, it specifies how to use the data link as a complement to voice, and how dialogues between aircraft and ATC are structured. This section describes several aspects of the data-link protocol, as developed for operating the data link in the context of this experiment.

3.1 Data-Link Complementing Voice

For the design of the data link, a complementary protocol (ref. 7) for controller-pilot communications was adopted, wherein data link was used as the primary medium for selected applications and voice for others. The range of data-link applications was selected such that for standard situations, arrival traffic could be controlled entirely by datalinking. However, for each message to be sent, the controller could choose to use either the data link or voice.

A consistent procedure was established for the combined use of voice and datalinking under standard and nonstandard conditions. This procedure demands flight crew acknowledgment of all ATC messages, and also that each acknowledgment is given over the same medium (voice messages should be acknowledged by voice, data-link messages by data link). For nonstandard situations, for example, when a flight crew cannot comply with an ATC instruction, the (negative) acknowledgment has to be followed by voice contact to explain the situation and expedite its resolution.

Since this procedure depends on the use of voice for communication during resolution of nonstandard situations, it is necessary that, upon entry into a new sector, each flight establishes two-way radio communications. Therefore, the flight crew has to use voice to check into a sector. However, it is not necessary to check out by voice: the selection of the medium—voice or data link—for issuing the frequency-change instruction is at the controller's discretion. The flight crew simply has to acknowledge the message by using the same communication medium as that used by the controller.

An important aspect of using the data link for air-ground communications is to determine which controller (sector) has jurisdiction over communications with a particular aircraft, both for uplink message transmission and for downlink message reception. Unlike voice communication, the data link is independent of a sector frequency. Therefore, there must be a clear and unambiguous rule to determine, for each aircraft, the sector with data-link communication authority. For this experiment, we based the rule on specific information available in the aircraft data base of the ATC computer, namely, which controller "owns" an aircraft, that is, the controller who last accepted control of the aircraft. The rule was that only the controller who owned the aircraft, could send data-link messages to and receive messages from an aircraft.

However, on controllers' request, one clearly defined exception was made for sending the "frequency change" message to an aircraft (shipping). This message is sent after the transfer of control has been accepted by the next sector's controller and the "old" controller still has radio-contact with the aircraft, but no longer owns it.

The procedure for the handoff of an aircraft to the next sector is summarized as follows.

First, the controller-to-controller handoff:

1. Ground handoff is initiated by the sector that owns the aircraft. The handoff can be initiated by the controller by selecting the DA's "initiate handoff" menu-option for the aircraft under consideration.

2. New sector accepts the handoff and thus takes over "ownership." The handoff can be accepted by choosing the DA's "accept handoff" menu-option for that aircraft.

This is followed by the controller-pilot-controller handoff:

3. The old sector no longer owns the aircraft. The only message it is now allowed to send by data link is a change-frequency message. For each aircraft in the hand-off process this data-link message can only be sent once.

4. The response to this message (roger or unable), if sent by data link, is processed by both the old and the new sector. In the old sector the acknowledgment is used to close the communication loop; in the new sector the response is used to indicate that there is one-way data-link communication with the aircraft, and that the voice check-in can be expected.

5. The new sector should not send any data-link message until the pilot has checked in with the new sector *by voice.*

Several checks were built into the data-link software to ensure that the proper procedures were followed.

3.2 Data-Link Message Formats

A data-link message format specifies the structure of the information required to process or send a data-link message. The minimum information required for data exchange between end-users consists of the following items:

1. Destination id (identity), which determines where the message goes

2. Source id, which determines where a message comes from, and thus where the response to a previously received message should be sent

3. Message type, which determines the type and format of the information that is in the message text; it is also an indication of how the message should be processed (which application process)

4. Message text, which contains the actual information (the data) to be sent, specific to the message type

5. Message id, which allows for unique identification of each message; this can be a sequence number which, together with the source and destination id, uniquely identifies the message

As already mentioned in section 2.1, source and destination identities are given by aircraft call signs and facility names. Within a facility, the sector that must process a message from a particular aircraft, is determined by the aircraft call sign and the rules for data-link communication authority, described in the previous section.

The message text may have more than one version, for example, a readable and a coded version. The readable version is shown to the controller. The coded version is used for internal processing or for transmission. If the message text is coded for transmission, it has to be decoded at the destination, for display purposes and for handling by the receiving system.

The general structure of both the CTAS message format and the format used for transmission to the TSRV is shown in figure 3. The CTAS format was primarily designed for ease of internal handling of data-link messages. The transmission format, developed by NASA Langley, is more suitable for transmission and conforms to ACARS standards for air-ground data-link communication; the appendix contains a more detailed description of both formats.

3.3 Data-Link Dialogues

A data-link dialogue specifies the sequence of data-link messages that are exchanged for a common purpose. For

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example, the following elementary dialogue types can be distinguished.

1. *Clearance dialogue*, to issue a clearance. This dialogue consists of an uplinked clearance, followed by a downlinked acknowledgment (roger or unable).

2. *Information dialogue*, to send arbitrary information. This dialogue consists of an up- or downlinked information message, followed by an acknowledgment of receipt.

Both dialogue types are illustrated in figure 4, by means of time-sequence diagrams.

Several elementary dialogues can be connected to form more complex dialogues. As an example, figure 5 shows both the ground-initiated (uplink) and the air-initiated (downlink) request-for-information dialogues. The first response to a request is a confirmation (roger) or negation (unable). A confirmation, which in these dialogue types corresponds to the "standby" used in voice communication, will be followed by the requested information.

For this experiment, even more complex dialogues were developed for the air-ground profile negotiation process and to deliver a complete 4D-trajectory clearance. A general description of such dialogues can be found in reference 3.

4. Data-Link/Controller Interaction

This section discusses the design of the data-link system in terms of the data-link/controller interface, the selected data-link applications, and the synergism gained from integrating the data link with CTAS. All are aspects that determine the way the controller interacts with the data link. First, some general design guidelines are discussed.

4.1 Design Guidelines

The following general guidelines were used for developing a data-link system that would be acceptable for controllers.

1. The controller workload, associated with operating the data link for air-ground communication, should be kept to a minimum. This was achieved by minimizing the number of inputs (mouse button clicks, mouse movements, and keyboard entries) needed to create and send messages.

2. Workload increase related to data-link communications should be compensated by workload reductions for other tasks. This was achieved by including an automatic update of the aircraft data base, based on the information sent by the data link.

3. The data link should improve the situational awareness of the controller, certainly not reduce it. This was realized by displaying data-link status information, in particular of outstanding messages, and by keeping a history of the data-link messages sent and received.

With regard to the creation and monitoring of data-link messages, the data-link interface design allowed the controller to preview adaptable messages and to review all messages transmitted or received. The following guidelines were used for the design.

1. For adaptable messages, that is, messages that can be modified manually, the controller needs to be able to preview the message and to approve actual transmission of the message.

2. For nonadaptable messages, the controller does not necessarily have to preview the exact contents of the message, provided the information to be sent is available on the DA traffic display or can be retrieved by the controller from the aircraft data base. This is especially important for the lengthy and complex messages of the profile negotiation process (described in a separate document). However, it should be possible for the controller to review afterward what actually has been sent.

3. For nonadaptable messages, it is also not necessary that the controller approve each message that is sent. For example, certain messages may be grouped together and transmitted by one control action. However, it should be possible for the controller to review afterward what actually has been sent and when it was sent.

The next section describes how these guidelines have been applied to design the actual data-link/controller interface.

4.2 Data-Link/Controller Interface

The basic CTAS system uses advanced graphics and windowing techniques for display of information. A computer mouse and keyboard are used for input. The data-link interface, incorporated in the DA, uses the same means and methods for input and output and is completely integrated into the DA's controller interface. Four separate display panels are available for the data link. These panels are graphical overlay windows that can be positioned anywhere on the screen at the controller's discretion. Each panel has its own specific functions and features, which will be described later in this section. The design allows nearly all inputs to be made by using the mouse, that is, by moving the mouse to point at objects and clicking the mouse buttons to invoke certain events. The keyboard is used for entering free-text messages.

The data-link interface supports two main data-link communication tasks. The first is the invocation of data-link messages for uplink, the second is monitoring of ongoing data-link communications and dealing with replies. The general procedure for invocation of a data-link message for uplink comprises five steps:

1. Selection of one and only one destination (aircraft) by the controller

2. Selection of the application by the controller

3. Creation, by the data-link software, of a message proposal

4. Completion/adjustment of the message by the controller

5. Initiation, by the controller, of message cancellation or transmission

With the DA, there are three ways to select a destination: (1) move the mouse pointer over an aircraft symbol or tag (dwelling) and press a specific key on the keyboard; (2) use the mouse to bring up an aircraft menu and choose the data-link option; and (3) mouse-click on the *aircraft tag*.

To execute the other steps, two separate panels are available, the data-link control panel and the data-link numeric panel.

The *data-link control panel* (DCP) is used to select the data-link application, to view the corresponding message, and to actually invoke the transmission or cancel it. Figure 6 shows the general layout of the DCP. Its main elements are as follows:

1. Call-sign field, showing the aircraft to which the next message will be sent

2. Message field, showing the message text that will be sent

3. Send button, which invokes the actual transmission of the message (to the cm)

4. Cancel button, which cancels the process of data-link message creation

5. Application selection buttons, to select the application that will be used. Each button has one or more options which can be selected by repeatedly clicking the button (see sec. 4.3).

Furthermore, a pop/stay selection is available on the DCP to allow the controller to choose whether the DCP and DNP (described next) should stay up after sending a message ("stay" option) or that they should disappear until the next data-link invocation ("pop" option).

The *data-link numeric panel* (DNP) is used to modify numerical values in certain message types. It acts as an electronic numeric keypad. Figure 7 shows the general layout of the DNP. Its main elements are as follows:

1. Digit buttons 0-9 and a decimal (.) button, to enter decimal numbers

2. Clear button, to erase a decimal number, so that a new number may be entered

3. Increment/scroll up (+) and decrement/scroll down (–) buttons, to scroll through the values that are available for a specific message type; for example, to scroll through the Flight Levels (FLs), with a 10-FL increment below FL290 and a 20-FL increment above

4. Space (" ") button,[2] to enter a space prior to entering a value

Two other panels are available to assist the controller in monitoring ongoing data-link communication and to deal with replies: the data-link status panel and the data-link history panel.

The *data-link status panel* (DSP) displays a list of active messages: uplinked messages awaiting pilot response, recently received pilot responses, and other messages awaiting controller response. Figure 8 shows the general layout of the DSP. For each message there is a

1. Call-sign field, showing the aircraft that a message was sent-to or received-from

2. Message field, showing the message text sent or received

3. Status field, showing the status of the message. The available status options are

"sent," for a message just sent but not (yet) replied to

"ROGER," for a positive acknowledgment of a previously uplinked message

"UNABL," for a negative acknowledgment of a previously uplinked message

"rcvd," for a received downlinked message (not for a roger or unable)

"info," for a message that presents additional information to the controller, for example when a downlinked profile cannot be reconstructed

4. Elapsed time, which shows the time elapsed since the last change in message status

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[2]This button was not necessary, since the "clear" button clears only the value contained in the message text and leaves the space that separates a value from the preceding word.

5. Remove button (rm), allowing removal of messages from the DSP at the controller's discretion.

When a profile proposal is received from an aircraft, the DSP also shows an enter button (fig. 9), which, if selected, tells the DA to use the received profile parameters for its trajectory computations.

The DSP shows up to 10 messages, with the message that was sent or received most recently at the bottom. Additional messages are not shown until other messages have been removed, either manually by the controller or automatically. For example, messages with "ROGER" or "info" status disappear from the DSP automatically after 30 sec. The limit of 10 messages on the DSP, and the 30-sec display time, are just two of many data-link design parameters that can be easily adapted.

The *data-link history panel* (DHP) contains a history of all messages sent and received, even after their removal from the DSP. This panel can be invoked at the controller's discretion, for example, to check whether a certain message has already been sent. Figure 10 shows the general layout of the DHP. For each message sent or received the DHP shows:

1. The call sign of the aircraft to which the message was sent or from which it was received

2. The sequence number of the message, with a prefix U for uplinked and D for downlinked messages

3. The message text

For downlinked roger or unable messages the message field shows the sequence number of the message to which the reply was made (230358 in fig. 9). This sequence number allows the controller to correlate downlinked acknowledgments to a previously uplinked message.

The DHP also has a scroll bar which allows the controller to scroll through the entire list: different mouse inputs allow line-by-line scrolling, page-by-page scrolling, or jumping to a specific portion of the list.

Figure 2 illustrates the controller/data-link interface, integrated into the DA display. The picture shows the DCP and DNP in the upper right portion of the screen. The DSP is shown to the left of these panels. The picture, which was taken during one of the traffic scenarios of the experiment, also shows several other display features of the DA, such as the timeline on the left and the descent advisory panel in the upper middle of the screen. A general description of DA display features was given in section 2.2; a more detailed description can be found in reference 4. Note that the DHP is not shown in the figure: it is at the controller's discretion to show this panel.

4.3 Data-Link Applications

A data-link application specifies one particular use of the data link. In general, each application corresponds to one specific message type. For example, the application for issuing a heading instruction sends a heading message. However, there are exceptions in which the application requires more than one message type. An example is the application to issue a 4D arrival clearance, which consists of a route clearance message, a 4D arrival clearance message, and a profile constraints message (see the appendix).

The data-link applications were selected to enable full data-link control of arrival traffic in the Center airspace. No effort was made to include non-control messages, such as weather information messages. The available applications are grouped into the following categories, each with its own button on the DCP (fig. 6, from left to right):

1. Strategic messages (button 1), for the 4D and DA arrival clearance and the profile request

2. Tactical messages (buttons 2-4), with separate buttons for the heading, altitude, and speed instructions

3. Navigation messages (button 5), for the proceed-direct-to and route-intercept messages

4. Frequency-change message (button 6)

5. Free-text message (button 7).

The complete list of available applications on the DCP is given in table 1. The 4D and REQ types are complex applications dealing with the 4D-FMS equipped aircraft. The DA-type is a CTAS-specific arrival clearance: it corresponds to the descent advisory created by the DA (ref. 4), which specifies a top-of-descent and the required descent speed profile. The other types have an equivalent conventional voice message.

The full set of available message types, their internally used (CTAS) format, and the formats used for transmission to the TSRV, are presented in the appendix. The appendix also describes messages that were uplinked automatically (information, route, and profile messages), and the messages available for downlink.

An important aspect of the design of data-link messages is the exact meaning of those messages. Voice messages are often a combination of several pieces of information, such as "proceed direct to SMITY, resume own navigation." The resume-own-navigation is an essential part of the message. For this experiment, a proceed-direct-to clearance by data link was defined to include the resume command. For those cases for which the resume was not valid, the controller had to use voice. However, the software is easily adaptable to allow controller selection

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of appending messages, depending on the initial message selected.

Another example is "turn right 30 degrees, vectors for spacing." In this case the second half of the message gives an explanation. The current design gave the controller the option to send explanations as a free-text message by data link or by voice. The design may also be extended easily to include options for appending standardized explanatory comments to certain data-link messages.

4.4 CTAS/Data-Link Synergism

Major advantages were provided by the integration of the data link within CTAS. The information available in the DA aircraft data base was used to select and create proto-type data-link messages for the controller. Conversely, the information sent by data link was used to update that aircraft data base. Both ways facilitated a considerable reduction of the total number of controller inputs—and workload—required for operating both the DA and the data link, compared with independent implementation.

As soon as a data-link message is approved for transmission, the aircraft data base is updated. This gives the controller immediate feedback on the effect of a message on the DA trajectory analysis, as will be described below. The consequence of this procedure is that if an unable reply is received instead of a roger, the data-base update was not appropriate, and the old information in the data base must be restored. An alternative solution is to wait until a positive response (roger) is received from the pilot. This solution was rejected, since in that case the update of the aircraft data base lags behind with respect to the controller's actions.

An example of how the data-link benefits from CTAS is as follows. All uplinked data-link messages require that one destination (aircraft) is chosen; that the application is chosen; and that the message is approved for transmission. Without CTAS, this would amount to a minimum of three mouse clicks for sending a message by data link. However, because of the CTAS/data-link integration, in many cases only two clicks are required: upon selecting a destination by clicking on the aircraft tag or dwelling on an aircraft symbol, the data-link software tries to anticipate the application to be used. This educated guess is based on the information available in the aircraft data base, including information on the current advisories presented to the controller. The following simple rules were applied (from high to low priority):

1. If the aircraft is not owned by the sector (see sec. 3.1), select the frequency-change message (VF)

2. If the DA shows a speed-resolution advisory (to solve a potential conflict), select the speed message (SP)

3. If the DA shows an altitude resolution advisory, select the altitude message (AL)

4. If the aircraft is 4D-FMS equipped:

If there is a downlinked profile proposal, select the profile constraints message (PRO), which is part of the 4D arrival clearance application (see appendix)

Else select the profile request message (REQ)

5. If the DA shows a cruise-speed advisory for an aircraft, select the speed message (SP)

6. If the profile is locked (sec. 2.2), select the speed message (SP)

7. If the DA shows a descent advisory, select the DA arrival clearance message (DA)

8. Else select the heading message (HE)

In section 5 it will be shown that these simple rules were reasonably effective in anticipating the message type.

In addition to this automated mechanism for application selection, there are several shortcuts available to the controller to combine the selection of aircraft and application. For example, when a controller clicks on the altitude portion of the aircraft tag (the second line), the altitude message will be selected automatically; clicking on the speed portion (third line) auto-selects the speed message for that aircraft. In addition, when selecting an aircraft by use of the aircraft menu, a data-link suboption may be chosen to specify the desired application.

Additional advantages of the CTAS/data-link integration are presented below, for each of the application categories.

Strategic messages– When one of these messages is selected, the DA will create the message for the controller, based on the information available in the data base. Under normal circumstances, there is no reason for the controller to change the contents of any of these messages. When sending a DA or 4D arrival clearance via data link, the aircraft trajectory is automatically locked (sec. 2.2). If such a clearance was issued by voice, this must be done manually, by clicking on the aircraft's ETA-tag on the timeline (fig. 2).

Tactical messages– In general, the tactical messages HE, TRT, TLT, AL, and SP are initialized with the current aircraft heading, altitude, or speed, depending on the message type chosen. The use of current aircraft state information for an initial guess of the desired value in the message results in only minor adjustments being

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necessary to obtain the desired value. There are three major cases in which CTAS is used to make a better message proposal. First, when the DA calculates a cruise speed advisory, the speed message is initially selected, with the advised speed in the message. Second, when there is a speed or altitude resolution advisory, to resolve a predicted conflict, the corresponding message is initially selected with the advised value. Third, when the aircraft is in the waypoint capture (WC) mode, the target intercept heading for waypoint capture is initially selected for the heading message. Provided the controller accepts the proposed value, the workload associated with message creation is significantly reduced (see sec. 5.2).

An additional effect of sending tactical messages by data link is that locked trajectories are automatically unlocked (since a tactical clearance has precedence over a strategic clearance). Furthermore, a heading message sent via data link automatically puts the aircraft in the waypoint capture mode to ensure consistent trajectory analysis by the DA. An altitude assignment by data link tells the DA to enter the assigned altitude in the data block of the aircraft.

Navigation messages– In order to get proper DA-advisories for aircraft in the waypoint capture mode, the controller must select one particular "capture waypoint." This is a standard CTAS procedure (ref. 4). If the proceed-direct-to (PD) message is selected, the prototype message contains the name of that waypoint. No addi-tional inputs are needed (although the controller may change the name to one of any published waypoint). Like the tactical messages, the transmission of a PD message via data link unlocks a cleared trajectory and puts the aircraft in the waypoint capture mode. For the route-intercept (RI) message, the DA fills out the published name of the current or the next route segment, depending on whether the aircraft is on-route or off-route.

Frequency-change message– In the current CTAS system, the sector to which an aircraft will be handed off is determined by the sector number the controller has entered in the right field of the DA scratchpad, a two-field input area on the traffic display. In figure 2, the scratch-pad is shown on the bottom right of the display. For the frequency-change (VF) message, that sector number (sector 15 in fig. 2), is used to fill out the message with the facility name (e.g., Denver), the sector type (approach/center), and the frequency used by that sector. This is under the assumption that each sector has one primary voice frequency. Thus, no additional controller inputs are required for this message.

In the next section, the data-link related results of the experiment are discussed. It will be shown that the CTAS/data-link integration considerably enhances the

efficient use of the data link. But before doing so, a data-link example is presented.

4.5 Example of Data-Link Communication

Using the picture of figure 2 as reference, an example is given of how the data link is used by the controller. The example starts approximately 1 min before the picture was taken and ends about 2 min later. The figure shows COA213 on a delay vector. The controller's intention is to slow the aircraft down to 250 knots indicated airspeed (KIAS) and bring the aircraft back on route through a proceed-direct to SMITY, a waypoint previously selected by the controller.

To send the speed instruction by data link, the controller clicks on the third line of COA213's tag. This brings up the DCP and the DNP, in the upper right portion of the screen. The controller has positioned the panels there in order to avoid overlap with the sector's airspace.

The DCP comes up with a speed message proposal, the result of clicking on the third line of the tag. When the controller selected the aircraft for data link, the DA showed a speed advisory of 250 KIAS in the fourth line of the aircraft tag of COA213, similar to the advisory shown for COA788. As a result, the speed message will already contain the target value of 250 KIAS, so the controller only has to click on the "send" button to send the mes-sage. Had the intent been to send a different value, the controller could have used the DNP to change the value shown in the speed message.

When the message is sent, the DCP and DNP will disap-pear from the screen, unless the controller has previously selected the "stay" option, in the bottom right corner of the DCP. In that case the panels will stay on the screen. To show the message just sent, the DSP appears (unless it is already shown for previously sent messages), showing the message with the status indication "sent." The DSP keeps track of the time elapsed since the message was sent: 14 sec in figure 2.

The controller does not have to wait for the pilot to respond to the message before sending the next message to the same aircraft, or to another aircraft. In this case the controller clicks again on the aircraft tag of COA213, on the first line this time, and the DCP shows a proposal to send the DA arrival clearance. However, the intent is to send a proceed-direct instruction, so the controller clicks on the navigation button (WPCAP on the DCP) to select the corresponding message. The selected button is high-lighted, and the computer generates a message proposal: it looks for the selected capture waypoint (SMITY) and fills out the name in the message, as shown in figure 2. The

controller can send the message and it will be added to the DSP.

When the pilot's response to the speed message is received, the status indicator on the DSP will change from "sent" to "ROGER" or "UNABL," to show the pilot's reply. If it was an unable, the pilot is required to contact the controller by voice to explain and solve the situation; otherwise the transaction is completed. In both cases, after taking notice of the pilot's reply, the controller can remove the message from the DSP by clicking on the remove (rm) button.

5. Experimental Evaluation

5.1 Experiment Description

Although the data-link system is the subject of this report, it was not the main focus of the experiment. The primary objective of the experiment was to investigate issues regarding the integration of 4D-FMS-equipped aircraft in a 4D ATC environment. In order to provide the background information necessary for the analysis of the data link related results, this section gives an overview of the experiment design and the experimental conditions.

Experiment setup– As in a previous experiment (refs. 1 and 2), CTAS was used to create the 4D ATC environment, and the TSRV simulator was used to simulate the 4D-equipped aircraft. Both systems were linked through NASA's Program Support Communications Network (PSCN). Other air traffic was simulated with the Ames Pseudo-Aircraft System (PAS), a system for real-time generation of multiple aircraft trajectories (unreleased material, "Pseudo-Aircraft System Documentation Package," R. Weske et al., Ames Research Center, 1990). The PAS aircraft trajectories are controlled by what is known as pseudo-pilots, whose main task is to simulate the pilots' roles in air-ground communication. One pseudo-pilot handles several aircraft, using simple commands to control the aircraft in accordance with ATC instructions. For this experiment, PAS was provided with the capability for reception and acknowledgment of data-link messages.

Since the timeframe for implementation of systems like the one under investigation is of the order of 10-15 years, it was assumed that all the aircraft had RNAV (area navigation) capabilities. However, only the TSRV had the capability for accurate 4D navigation. The north-east Denver airspace (KEANN gate) was simulated with one high-altitude and one low-altitude sector. The traffic was controlled from en route cruise to the metering fix, where the aircraft were handed off to the TRACON. The overall experiment setup is shown in figure 10.

Controller subjects– Six active controllers from the Denver and the Dallas-Fort Worth Centers participated in the experiment. Four of the controllers had no previous experience with CTAS or a data link. For three consecutive weeks, teams of two controllers worked with the system (three teams). Depending on their experience with CTAS, they received 1.5 to 2.5 days of training on the DA, the data link, and the interaction with the 4D-FMS-equipped aircraft. The last 2 days of the week were used for the actual experiment, during which five test-runs were conducted. Each run involved approximately 1.5 hr of active control of traffic and included two flights of the TSRV.

Traffic scenarios– The main arrival traffic flow was provided by the PAS. The TSRV-piloted cab was injected into that flow at precise times to create the described situations for the 4D-FMS-equipped aircraft. The TMA (sec. 2.2) was used to set up realistic traffic situations that met specific criteria with respect to the amount of delay to be absorbed and the geometry of the predicted conflicts. Three cases were considered for small delays (up to 3 min), small enough to be absorbed on-route: (1) aircraft from different routes, merging during the descent phase, (2) aircraft on the same route (entrail), and (3) aircraft from different routes, merging while still in cruise. A fourth case was considered for moderate delays (up to 8 min), which required that the aircraft be vectored off-route to absorb the delay by means of path-stretching.

Controller procedures– The data link supported current ATC communication, as well as the advanced communications required to deal with the 4D aircraft. It was assumed that all aircraft were data-link equipped. Since the main interest was in the profile negotiation process, the controllers did not have to use the data link for conventional ATC operations, but they were encouraged to do so.

The following general strategy for controlling the arrival traffic through the high-altitude and low-altitude sectors was adopted. The high-altitude sector controller would try to set up a conflict-free traffic flow and absorb most of the delay, whereas the low-altitude sector controller would merge the traffic and control their descents. Delay would be absorbed by speed control and, if necessary, also by vectoring aircraft off-route (path-stretching). The handoff from the high to the low sector was prior to SMITY (fig. 2). For aircraft at lower cruise altitudes (FL310 and lower), the low-altitude sector issued the arrival clearances. For aircraft at higher cruise altitudes the high-altitude sector could issue the arrival clearance or descend the aircraft to altitudes that allowed the low-altitude sector to issue the clearance.

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Data collection– During the 3 weeks of the experiment a total of 16 controller hours with data link were recorded, during which 19 successful TSRV flights were made. All data-link-related controller inputs and all data-link transmissions were recorded. For the pseudo-aircraft, the pseudo-pilot commands were also recorded, both during the data-link runs and during 8 hr of simulation with voice only. At the end of each week, both team members filled out a questionnaire which contained several questions related to the data link.

In the following sections the results obtained from the recorded data will be presented first, followed by the results of the questionnaire. Finally, some observations that were made by the experimenters are discussed. The analysis of the results focuses on the more "conventional" use of the data link. Advanced features, such as multiple-message sequences, processing of downlinked messages and automatic message transmission, will be discussed in separate documents.

5.2 Analysis of Recorded Data

Information was extracted from the recorded data for the following data-link parameters:

1. Message rates, that is, the number of data-link messages uplinked per controller per unit of time (minutes)

2. Message creation times, that is, the time elapsed between selection, by the controller, of an aircraft for data-link transmission and the actual transmission of the message

3. Transaction times, that is, the time elapsed between transmission of a message and the reception of its reply (roger or unable)

An overall summary of these data is shown in table 2. For each message type in the table the total message count, average message rate, mean creation time, and mean transaction time is given. The table shows that some of the message types were used infrequently and, therefore, provide insufficient data for further analysis. These latter types were (1) the tactical messages TRT, TLT, TR, TL, SPI, and SPD; (2) the navigation message RI; and (3) the free-text message FT.

Three remarks need to be made, regarding these types:

1. The tactical messages TRT, TLT, TR, TL, SPI, and SPD are all message types that would never be selected by the automatic application selection algorithms. This means that the DCP would never show any of these messages as the initial selection. The infrequent use can mean two things: the HE and SP messages provide suffi-

cient flexibility to be used most of the time, or it is too cumbersome to select and modify the other types of heading and speed messages. This has not been investigated and there have been no controller comments with regard to this issue.

2. The controllers never used the route-intercept message (RI) through the data link, although they did use it a few times with voice communication. The controllers took advantage of the RNAV capabilities of the aircraft, in combination with the waypoint capture mode of CTAS, to let aircraft capture their original routes and resume their own navigation.

3. The free-text message (FT) was never used. Controllers used voice for messages that were not available as standard data-link messages, and, in some cases, for example, for explanatory messages (sec. 4.3), they did not send the message at all.

For the remaining message types (DA, 4D, REQ, HE, AL, SP, PD, and VF), the data-link parameters are discussed in more detail. Some of these parameters are not only a function of the application (message type), but also of the controller or flight crew and the type of sector (high or low altitude). Controller crew dependency may be related to differences in controller preference for voice or data link, different strategies for controlling traffic, and differences in proficiency. The sector dependency may be due to the fact that there is a division of tasks between sectors: in this case the high sector would set up a conflict-free traffic flow and do most of the delay absorption (vectoring), whereas the low sector would merge the traffic and issue most of the arrival clearances. The transaction times are dependent on the flight crew and not on the controller crew, since those times reflect how long the flight crew takes to respond to uplinked messages. Both for controller and pilot crews, the data are presented as the average of both crew members.

In the next sections, the different data-link parameters will be analyzed. First, analysis of the message rates is used to confirm that the general strategy for controlling the traffic through the high-altitude and the low-altitude sector was indeed as intended. Second, the creation times are analyzed to show the significant benefit of data-link integration in CTAS for the controller. Finally, the transaction times the controllers had to deal with, are discussed. Figures 11 through 13 are used to illustrate the results. Except for figure 12(a), the vertical axis in these figures shows the parameter of interest; the horizontal axis shows the various message types (applications) under consideration, in the following order: strategic (DA, 4D and REQ), tactical (HE, AL, and SP), navigational (PD) and frequency change (VF).

Message rates– The message rate is the average number of messages uplinked per controller per unit of time (minutes). To compensate for different simulation times, the totals of the message counts (for each message type, controller crew, and sector) were divided by the elapsed time. The results are presented in figure 11. Figure 11(a) shows the message rate for each message type. In figure 11(b) these rates are given as a function of the controller crew (weeks 1-3), and the sector (high or low).

The results for the strategic, tactical, and navigation messages confirm that the way the arrival flow through the high and low sector was handled was indeed as intended (see sec. 5.1): the high-altitude sector tried to set up a conflict-free traffic flow and absorb most of the delay, whereas the low-altitude sector merged the traffic and controlled their descents (by means of the arrival clearances). For each message category a brief explanation is given below.

   Strategic messages: The rates for the 4D and REQ message are much lower than the rate for the DA message: the 4D and REQ messages were used only for the TSRV, whereas the DA message was used for all other aircraft. The DA and 4D rates in figure 11(b) show that most arrival clearances are issued in the low-altitude sector. However, more requests are sent in the high-altitude sector. Reference 3 gives a detailed description of the use of the 4D and REQ message, as part of the profile negotiation process. Note in figure 11(b) that the first controller crew never issued a 4D clearance in the high altitude sector.

   Tactical messages: Of the tactical clearances, speed instructions are issued most often (fig. 11(a)): twice as often as altitude instructions and three times as much as heading instructions. This is related to the fact that CTAS always tries speed adjustment first to meet an arrival time. Altitude and heading are used by the controller to make up delays above that absorbed by speed change, or to resolve conflicts. The high-altitude sector issued most of the tactical clearances (fig. 11(b)).

   Navigation messages: The high-altitude sector issued most of the PD commands, to bring aircraft back on route after a path-stretch maneuver. The actual merging of aircraft into one main arrival flow took place in the low altitude sector.

   Frequency-change message: The number of frequency-change messages is roughly the same for both sectors. This is not surprising, since all of the arrival traffic under consideration went through both sectors.

Figure 11 also shows that the second controller crew issued fewer heading and altitude instructions by data link. They had a slight preference to use voice for these messages, probably related to the way these messages are created, which is discussed in the next section.

Creation times– Creation time is defined as the time elapsed between selection, by the controller, of an aircraft for data link and the subsequent transmission of a message to that aircraft. It covers the time the controller needs to select the application, modify the message (if necessary), and approve its transmission. Creation times are an indication of the time the controller spends communicating by data link. However, they should be interpreted with care: between selection of an aircraft for data link and approving the message for transmission, a controller may perform some tasks that are not related to the creation of the message.

Figure 12(a) shows the distribution of the message creation times. The frequency distribution shows a clear peak at 2 sec creation time. The cumulative frequency distribution shows that 61% of the messages were created and sent in less than 5 sec; 95% in less than 17 sec. The data show no clear upper limit for the creation time. A relatively high percentage (3%) of messages has a creation time of more than 20 sec. For longer creation times it is likely that as already mentioned above, the controller performed other tasks in parallel with the message creation process.

Table 3 and figure 12(b) present creation times for each message type separately. The creation times are presented as the sum of the mean time required for selection, modification, and approval of a message. These three components are discussed separately below. They show that the integration of the data link into CTAS, as described in section 4.4, has provided a considerable benefit for the use of the data link by the controller.

   Application selection: The selection times give an indication of the quality of the automatic application selection algorithms and the design of the DCP (sec. 4.2). There are some interesting issues; for example, does the DCP come up with the desired application when an aircraft is selected for data link, and how many inputs are required and how long does it take to select a particular application on the DCP. It was found that for 64% of the messages approved by the controller, the DCP came up with the proper application. This includes the shortcuts that were available to select the AL and SP message (see sec. 4.4).

For the selection times, the following information can be retrieved from table 3 and figure 12(b). The selection time was zero for the VF message: the DCP always came up correctly when this message was required. The mean selection time was only 0.2 sec for the DA message, which means that the software anticipated most of the DA

messages correctly. The mean selection time was the longest (4.9 sec) for the PD message: this message always required one manual input for selection, since it was not included in the automatic selection algorithms.

Message modification: When not satisfied with the message text presented on the DCP, the controller can modify the contents of that message. An example is changing the target value of a heading instruction. Fortunately, as a result of the integration of the data link into CTAS, many messages can be approved without modification. This is illustrated in figure 12(b) and table 3(b), which show that only tactical messages (HE, AL, and SP) required modification. For the nontactical messages, the message text is automatically created from the information available in the aircraft data base. In this experiment, the nontactical messages comprised 55% of the total number of messages sent by the controllers. However, also for the tactical messages, it is possible that the DA provides the desired target value, for example, when there is a DA cruise speed advisory (see sec. 4.4). In this experiment, only 54% of the HE, AL, and SP messages required additional inputs. In total, for 75% of the messages the controller directly used the initially proposed message text.

Table 4 presents a more detailed overview of message creation times for the HE, SP, and AL messages. The table shows the significant difference between messages that did and did not require modification. For the tactical messages that did require modification, an average of 5.2 modifications per message (i.e., the number of entries in the DNP or keyboard to enter the proper value) was recorded, at a mean creation time of 10.4 sec per message. Only 3.5 sec, and zero inputs, was recorded for the tactical messages that did not require modification.

Message approval: The mean time required to approve a message was 3.1 sec. This approval time is the time between the last selection or modification of a message by the controller and clicking on the "send" button on the DCP. Higher values for the 4D, REQ, and PD messages can be accounted for by what was mentioned at the beginning of this section: after selecting the aircraft, controllers performed different tasks (such as reviewing the traffic situation) before they actually approved the message for transmission.

Figure 12(c) presents creation times as a function of crew and sector. The results indicate that there is no clear relation between creation times and these parameters. For example, the tactical-message creation times for the first crew are longer in the high- than in the low-altitude sector; the second and third crew show the opposite. Of the nontactical messages, the VF message shows longer

times for the low-altitude sector, whereas the PD message shows the opposite.

Transaction times– Transaction times are measured as the time difference between sending a message from a sector and receiving the reply at the same sector. They cover the time required for uplink of the message, the time the pilots need to review and respond to the message, and the transmission time of the reply. Since no data-link delays were modeled in this experiment, the transmission times were relatively small.

Transaction times describe the speed with which uplinked messages are acknowledged. The controller has no influence on these times, but must deal with them. They are analyzed in detail for the 4D-FMS-equipped aircraft only, since that was the only aircraft in the experiment that was simulated by a cockpit simulator (the TSRV) and flown by operational pilots as a real aircraft. Unfortunately, the flight crews only received half a day of training, so that they were not fully proficient with the data link.

The mean transaction time for tactical messages was 9.4 sec for the TSRV. In reference 7, which combines several data-link studies, 10 sec is given as a mean value (not including transmission times). By comparison, the mean transaction time for the aircraft simulated by the PAS and controlled by the pseudo-pilots, was only 3.9 sec.

Figure 13(a) shows the mean transaction time per message type for the TSRV. In figure 13(b) the results are given per flight crew and control sector. Note that data are presented for the first and second flight crew only. Data for the last crew were discarded, because that crew chose to conduct real-time discussions with the observing engineer before responding to most of the data-link messages. The DA message is not included in the analysis: for the TSRV, only the 4D message was used to issue arrival clearances. "Missing" bars in figure 13(b) (for example, for the speed-message for the second flight crew in the low-altitude sector) indicate that for the 4D-FMS-equipped aircraft the corresponding message type was never used by the controller crew in that sector.

Overall, the transaction times are not very sensitive to the message type. The data indicate a slightly larger response time for the strategic messages (4D and REQ) than for the tactical (HE, AL, and SP) and navigational (PD) messages. Strategic messages are more complex and lengthier than the other messages and are likely to take more time to be reviewed by the pilots.

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5.3 Analysis of Questionnaires

All six controllers filled out a questionnaire with several questions related to the data link. There were two types of questions: subjective ratings and short answers. The data-link-related results, which give an indication of controller acceptance, panel ratings, data-link advantages, and several other aspects of the data link, are summarized below.

On a scale of 1 to 6, the controllers rated their preference of data link compared to voice (1 = data link preferred; 6 = voice preferred) for different applications. In figure 14 the results are summarized for tactical (HE, AL, and SP), navigational (RI and PD) and strategic (DA, 4D, REQ) message categories. The horizontal axis represents the rating scale, with preference for data link on the left and voice preference on the right. The vertical axis shows the number of controller responses for each rating. With all ratings on the left, the results show that data link is strongly preferred for all categories, with a slightly higher rating for the strategic messages. Strategic messages are complex and lengthy, but nevertheless very easy to send by data link.

The controllers were also asked to rate, on a scale of 1 to 6, each of the data-link panels, DCP, DNP, DSP, and DHP (see sec. 4.2). The ratings, which considered usefulness, clarity, ease of use, and need for further improvement, are presented in figures 15(a)-15(d). Again, the rating is on the horizontal axis, with the most favorable rating on the left; the number of controller responses for each rating is on the vertical axis. From figure 15(a) it is clear that the controllers find the data-link panels easy, if not very easy, to use. The ratings for usefulness and clarity show similar results (figs. 15(b) and (c)). Nevertheless, the controllers also indicate that there is some need for further improvement (fig. 15(d)), although the only concrete suggestion was to highlight certain information in the message text on the DCP. One controller never used the DHP, and therefore did not rate it.

The controllers agree, or strongly agree (rating 1 or 2 on a scale of 1 to 6), with the following statements:

1.   It is easy to create a data-link message for uplink

2.   The DSP is a "good" way to keep track of the communication situation

3.   Using data link for air/ground communication does not increase workload (one controller agreed slightly)

4.   Using data link for air/ground communication does not distract from other tasks

5.   Data link should be the primary means for transfer of control to the next sector (sending the frequency-change message)

The controllers' opinions were more varied (varying or even opposite ratings on a scale of 1 to 6) on the following issues:

1.   The data-link interface should not be separated from the DA interface: on average the controllers agree (ratings vary from "slightly disagree" to "fully agree"). They find the CTAS/data-link synergism in terms of CTAS using data-link information and vice versa more important than an integrated data-link interface.

2.   It is acceptable that specific messages are automatically removed from the DSP (in particular rogered messages): some controllers agree, some disagree. This can easily be adapted to a controller selectable feature.

3.   The DCP should "stay" up after a message is sent: the replies indicate that this should be a controller's choice, which is currently the case.

The controllers confirmed that in many cases, the DCP comes up with a message type different from what they intend to send. Furthermore, they indicated that, in general, the initially proposed value for the tactical messages is not good. Actually, the recordings show that in 66% of the cases the correct message was automatically selected, and 46% of the tactical messages did not require modification (sec. 5.2). The controllers' opinions indicate, that they would like the automation to anticipate their actions even better. A thorough analysis of the cases in which the selection rules (sec. 4.4) failed is needed to determine how those rules can be improved.

In the responses to a short-answer questions on the main advantages of the data link, the controllers mentioned the following: reduced frequency congestion, fewer communication errors, and reduced overall workload. In reply to another question, on specific situations that required additional voice communication, the controllers indicated:

1.   When an aircraft had to report leaving an altitude

2.   When no response to a clearance was received within a "reasonable" time interval and the controller wanted to find out if the clearance had been received (see next section)

3.   When a pilot could not comply with a clearance ("unable" reply) and had to send an explanation

The controllers indicated that most data-link-related errors occurred when using the mouse and the DNP for input or adjustment of a new message value. This is confirmed by experimenter observations, discussed in the next section. There was only one suggestion for improving the use of

the data link and that was to provide some audio-feedback to support the visual information (e.g., sound a beep when a message is received). The general opinion was that the data link should be operationally available as soon as possible.

5.4 Experimenter Observations

During the experiment, a number of observations were made by the experimenters. Some of these could only be partially confirmed by the questionnaire or the data. The most significant observations are discussed below.

1. The way controllers handled data-link communications differed from the way they handled voice communications. With voice, the controllers usually waited for a pilot to reply to a message and used the reply to verify that the message was received properly, before they addressed another aircraft. With data link, this sequential process was replaced by a parallel process in which the controllers did not wait for a reply before they sent a message to the next aircraft. This difference is consistent with the results of other experiments, as described in reference 7. For this experiment, the data show that in 32% of the overall time there were one or more messages on the DSP for which a reply had not yet been received. In 28% of that time (i.e., 9% of the overall time) there were two or more messages that had not been replied to, with a maximum of five messages simultaneously.

Another difference between voice and data link was that the controllers spent very little time in dealing with the data-link replies. This is related to the fact that most replies are a mere "roger" and do not give any readback of the uplinked message. Only when there was an unable reply, or no reply at all, did the controllers have to take further action.

2. The controllers did not appear to be sensitive to transaction times, as long as those times did not exceed a certain limit. The lack of sensitivity is illustrated by the fact that there was no difference in dealing with the TSRV or with the other aircraft, even though average transaction times were 9.4 sec for the TSRV and 3.9 sec for the pseudo-aircraft (tactical messages only). However, if a reply was not received within approximately 40 sec, the controllers would start wondering (they verbally expressed their doubt about whether the message was actually received on board) and after roughly 1 min they would inquire by voice whether the message had been received. This occurred several times when the data-link connection between CTAS and the TSRV failed, and with the third pilot crew, which used exceptionally long times to respond to uplinked messages. The controllers indicated that it might be useful to have feedback on message

delivery, that is, as soon as a message is received at the destination, a signal should be sent back to indicate to the controller that the message was delivered. This "technical acknowledgment" is comparable to a "standby," used for voice communication. Also, if a message cannot be delivered, then the source should receive an indication of that problem, provided that the source can still be retrieved from the message.

3. Comparing the data-link runs with the voice-only runs, it became clear that data link provided a precise and concise exchange of information. The clarity of communication is illustrated by the fact that it was never required to send a data-link message twice because a pilot could not understand the message. This was not the case when voice communication was used. In particular, for the complex strategic messages it was much easier to use data link than to use voice. The strategic messages are lengthy and take much more time to communicate by voice (for issuance and readback). With data link, these messages are automatically composed and take comparatively little time to select and approve for transmission and, provided future data link has reliable message delivery, the lengthy verbal readback is avoided.

4. The experiment clearly showed a large reduction of frequency congestion. The percentage of messages sent by data link varied per controller team. The data indicate that between 50% to as much as 90% of the messages were sent by data link. The sound level in the control room was substantially lower for the data-link runs than for the voice-only runs.

5. The controllers always positioned the data-link panels on their traffic display such that these panels would not overlap their main area of interest. It was clear that they did not want to hide any of their radar information. This was the case even when they used the "pop" option on the DCP (sec. 4.2), which lets the DCP and DNP only on the controller display when they are actually creating a message. Figure 9 gives an example of how the datalink panels were typically positioned.

6. Most data-link-related errors occurred when using the mouse and the DNP for input or adjustment of a new message value. The consequence of such an error was either that the controller had to make additional inputs to correct the errors or, in a few cases, that the wrong value was uplinked. Fortunately, these errors are of a sort that can be recognized easily by a message-validation algorithm. For this experiment, such an algorithm was not available.

7. Some controllers used the DHP as electronic flight strips, since the DHP has information on all the clearances issued via data link. They invoked the panel to check

whether a specific message was sent or a reply received. Furthermore, on the DHP they could check the exact message text (in CTAS format) transmitted for the lengthy messages dealing with the 4D aircraft. For these messages, the DCP or DSP only showed a shortened version of the message text.

The overall results of the experiment, combining observations, recordings and questionnaires, are summarized in the next section.

6. Conclusions

An air-ground data-link system was developed to investigate integration of aircraft and ATC system capabilities. In the previous sections, the design and experimental evaluation of the ground-based portion of this data-link system were described. The results of the experiment allow several conclusions to be drawn with respect to the data link. These are summarized below, together with recommendations for further study and development.

The controllers responded favorably to the data-link capability. Furthermore, several technical advantages of data link were demonstrated, such as improved clarity of complex communications and reduced frequency congestion. Of greater significance was the synergism gained from integrating data link with CTAS. The information transmitted via data link was used to improve the monitoring and analysis capability of CTAS without increasing controller input workload. Conversely, CTAS was used to anticipate and create prototype messages, thus reducing the workload associated with the manual creation of data-link messages.

Overall, it was found that the initial design requirements, as set out in section 1, were clearly met:

1. The data-link system was able to support conventional ATC communications, as well as the complex communications developed to deal with the 4D-FMS capabilities of the TSRV.

2. The use of this data link was accepted by the controllers. The data link was useful, clear, and easy to use and for most applications data link was preferred to voice.

3. During the development process, the data-link system proved to be easily adapted and expanded.

Based on the outcome of this experiment, it is recommended that the data-link interface be improved and that new experiments be conducted, addressing, for example, the following:

1. Optimization of the data-link protocol

2. Determination of the optimal set of data-link applications

3. Optimal design for the various data-link panels

Furthermore, some operational aspects of the data link that have not been looked at for this experiment, should be investigated:

1. A mix of data-link equipped aircraft and aircraft not so equipped

2. Transmission delays in the air-ground data-link communication chain

3. Large-delays/heavy-traffic conditions

4. Two controllers working a sector

Despite these open issues, it is clear that integrating data link with an advanced automation system, such as CTAS, creates a large potential for development of an operationally suitable tool for air-ground data communication.

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7. Kerns, K.: Data Link Communication between Controllers and Pilots: A Review and Synthesis of the Simulation Literature. The MITRE Corporation, MITRE MP-90W00027, McLean, VA, 1990.

Table 1. Applications available on the Data-Link Control Panel

Button	Category	Code	Message text on the DCP
1	Strategic	DA	\<DA clearance> e.g., "DA RI 56 .70/280"
		4D	"Cleared \<arrival-procedure> at \<time>"
		REQ	"Request cross \<MF> at \<time>"
2	Heading	TRT	"Turn_right_to ..."
		TLT	"Turn_left_to ..."
		HE	"Fly_heading ..."
		TR	"Turn_right ... degrees"
		TL	"Turn_left ... degrees"
3	Altitude	AL	"Altitude ..."
4	Speed	SP	"Fly_speed ... knots," or
		SP	"Fly_speed ... " (Mach no.)
		SPI	"Increase_speed ... knots"
		SPD	"Decrease_speed ... knots"
5	Navigational	PD	"Proceed_direct_to ..."
		RI	"Intercept ..."
6	Frequency-change	VF	\<facility>\<type> on \<freq> e.g., "Denver center on 123.45"
7	Free text	FT	\<free text>

Table 2. Overview of measured data-link parameters: Total elapsed time 944 min

Message type	Code	Message count, all aircraft	Message rate, all aircraft, per min	Creation time, all aircraft, sec	Transaction time, TSRV only, sec
DA arrival clearance	DA	198	0.21	3.7	—
4D arrival clearance	4D	18	0.02	7.8	12.2
Request for profile	REQ	50	0.05	11.0	14.0
Turn-right-to	TRT	0	0.00	—	—
Turn-left-to	TLT	1	0.00	29.0	—
Heading	HE	93	0.10	10.7	10.0
Turn-degrees-right	TR	5	0.01	8.8	—
Turn-degrees-left	TL	9	0.01	13.6	—
Altitude	AL	160	0.17	8.7	8.8
Speed	SP	320	0.34	5.6	9.4
Increase-speed	SPI	4	0.00	13.3	—
Decrease-speed	SPD	2	0.00	31.5	—
Proceed-direct-to	PD	73	0.08	9.0	9.6
Route-intercept	RI	0	0.00	—	—
Frequency change	VF	382	0.40	2.9	12.0
Free text	FT	0	0.00	—	—
	Total	1315	1.39	Mean: 5.8	Mean: 11.9

Table 3. Message creation-time components and input counts

Type	Creation time components, sec				Input counts	
	Select	Modify	Approve	Total	Select	Modify
DA	0.2	0.0	3.5	3.7	0.4	0.0
4D	2.8	0.0	5.0	7.8	1.2	0.0
REQ	2.5	0.0	8.5	11.0	1.5	0.0
HE	2.7	4.7	3.3	10.7	0.9	6.6
AL	2.1	4.4	2.2	8.7	0.7	4.4
SP	1.5	1.7	2.4	5.6	0.5	0.9
PD	4.9	0.0	4.1	9.0	1.0	0.0
VF	0.0	0.0	2.8	2.8	0.0	0.0

Table 4. Differences in mean creation times for modified and unmodified tactical messages (Total number of messages considered: 1315)

Tactical message	Heading (HE)	Altitude (AL)	Speed (SP)	Total
Unmodified messages	6	14	242	262
Mean creation time, sec	6.8	2.7	3.5	3.5
Modified messages	87	146	78	311
Average creation time, sec	10.9	9.2	12.2	10.4
Mean no. of modifications	7.0	4.9	3.8	5.2
All messages	93	160	320	573
Mean creation time, sec	10.7	8.7	5.6	7.3

Center Controllers   **Traffic Manager**   **TRACON Controllers**

Descent
Advisor
(DA)

Traffic
Management
Advisor
(TMA)

Final
Approach
Spacing
Tool
(FAST)

communications
manager
(cm)

CTAS

Outside world

Radar, weather,
and flightplan data   Air-ground datalink
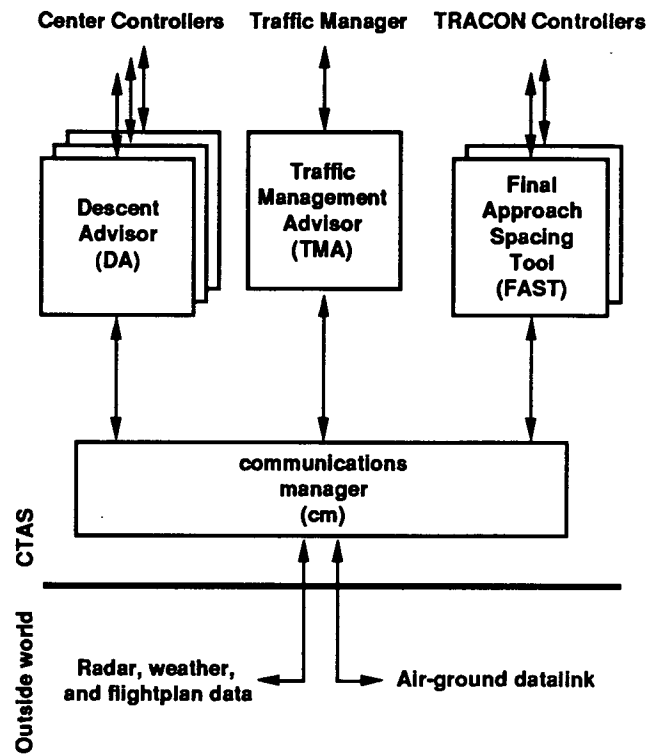
Figure 1. Center/TRACON Automation System (CTAS) concept.

Figure 2. DA planview display with timeline, DA advisory panel and several data-link panels.

Destination **Message** **Sequence**
ID **type** **number**

| 515 | ATC | TAC | HE230 | 120534 |

Source **Message**
ID **text**

(a)

Destination ID	NASA515
Source ID	ATC
Message type	343
Shown message text	Fly_heading 230
Message text	Hdg 230
Sequence number	120534

(b)
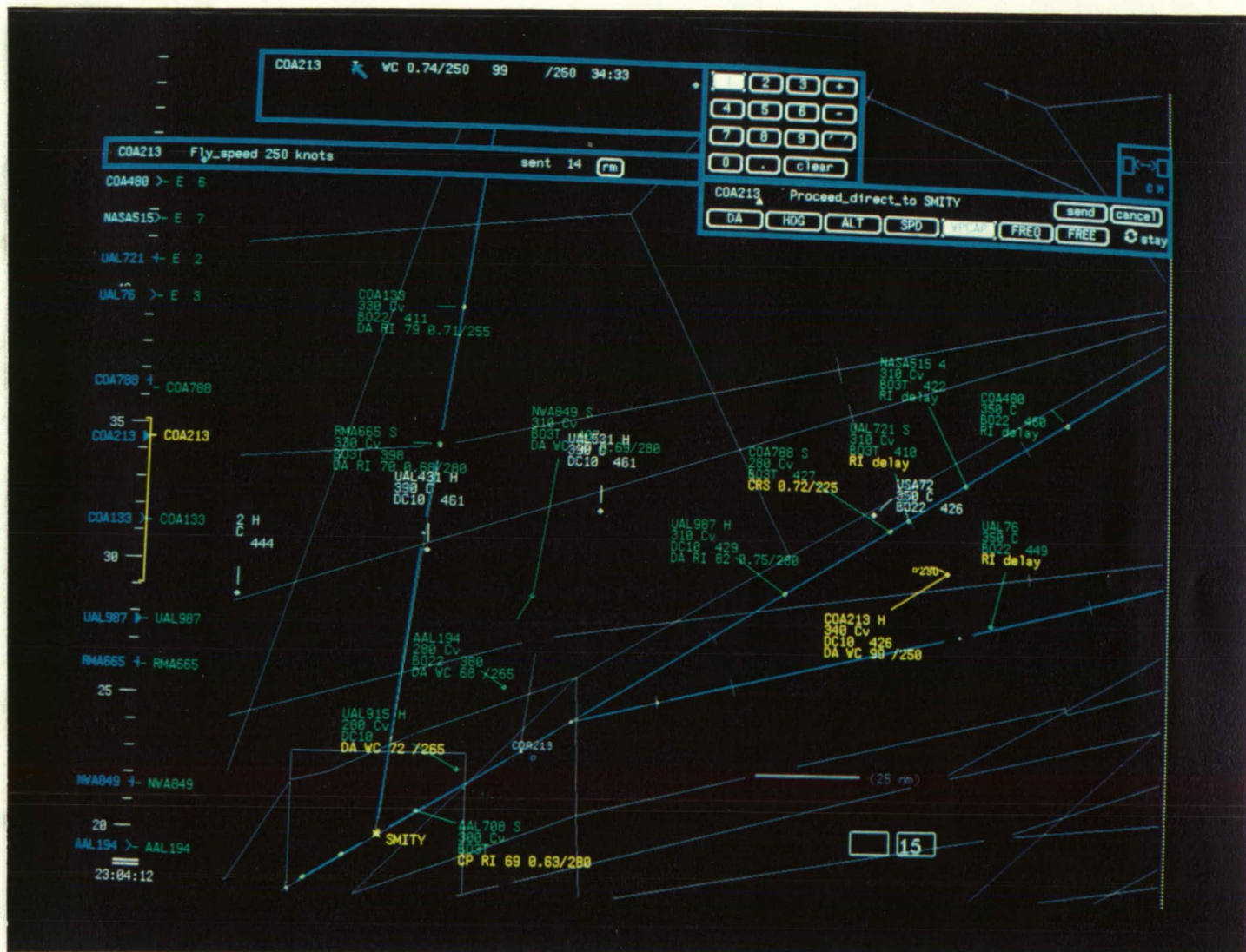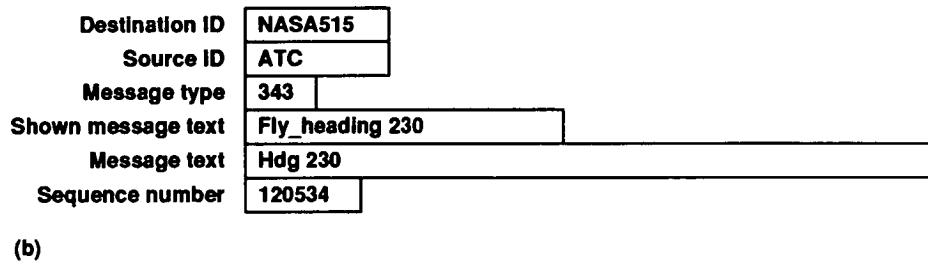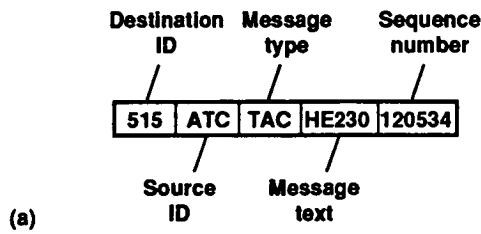
Figure 3. Comparison of CTAS and transmission message format structure.

GROUND **NETWORK** **AIR**

Clearance dialogue

Clearance

Acknowledgment

Information dialogue (Downlink)

Information

Acknowledgment

Information dialogue (Uplink)

Information

Acknowledgment
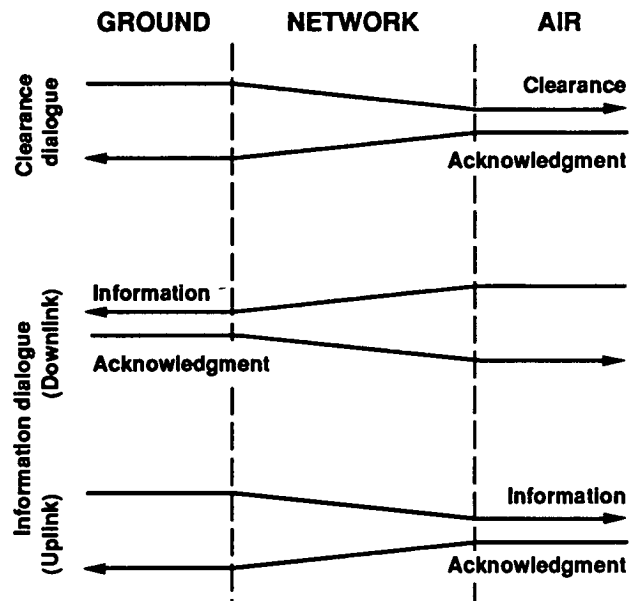
Figure 4. Clearance and information dialogues.
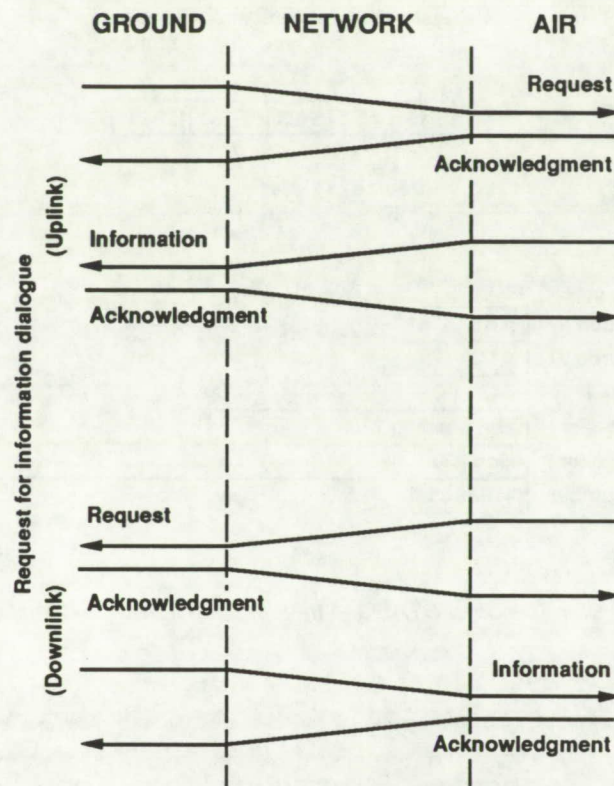
Figure 5. Request-for-information dialogue.
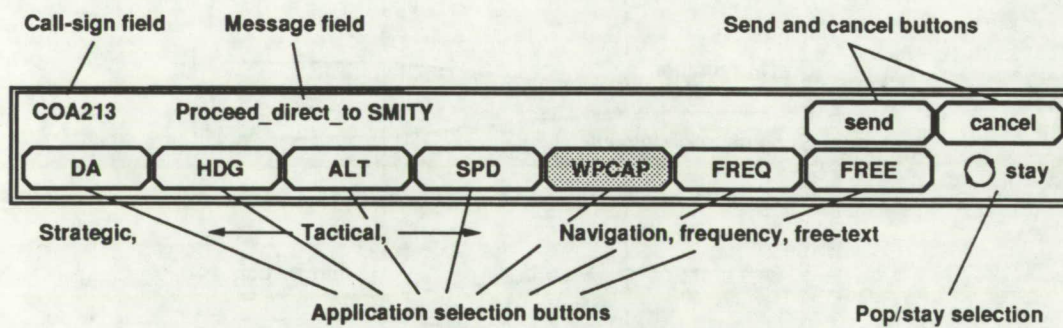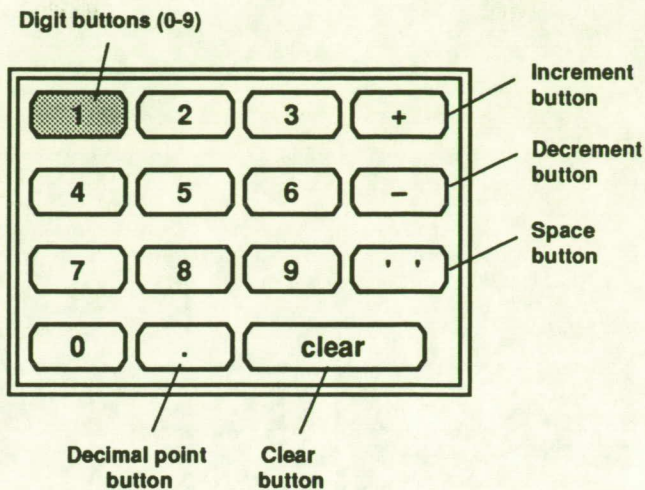

Figure 6. Data-link control panel (DCP).

Digit buttons (0-9)

Increment button

Decrement button

Space button

1	2	3	+
4	5	6	−
7	8	9	' '
0	.	clear	

Decimal point button

Clear button

Figure 7. Data-link numeric panel (DNP).

Call-sign field   **Message field**   **Status field**   **Remove button**

COA213	Proceed_direct_to SMITY	sent 14	rm	
NASA515	PROfile: 0.68/0.62 0 0.62/230	rcvd 9	rm	enter

Elapsed time   **Enter button**
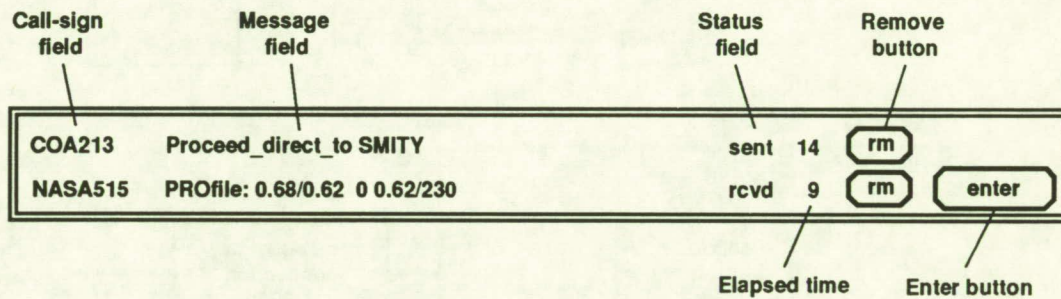
Figure 8. Data-link status panel (DSP).

Sequence number
U = Uplink
D = Downlink

Callsign   **Message**

COA213	U230358	Proceed_direct_to SMITY
NASA515	D230422	PROfile: 0.68/0.62 0 0.62/230
COA213	D230426	roger_down 230358

Scroll- bar   **Sequence number of uplink**
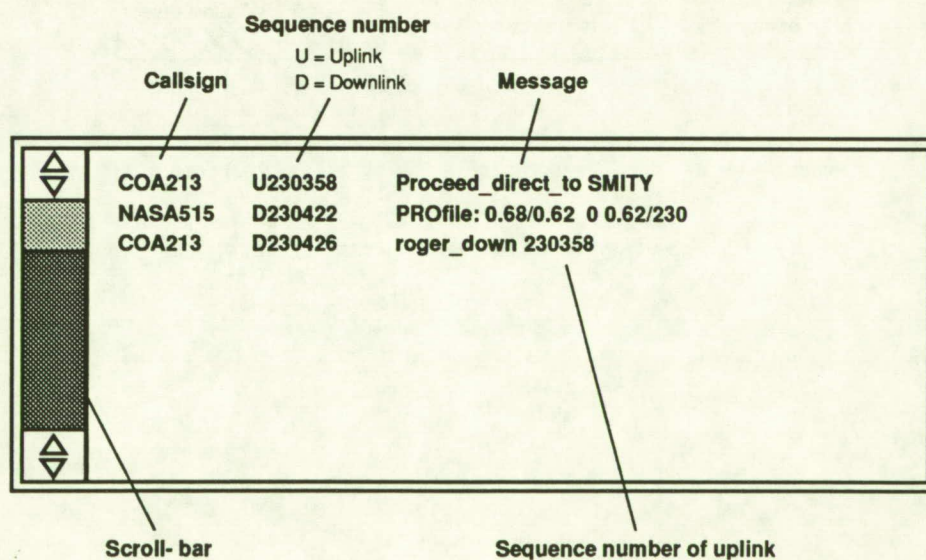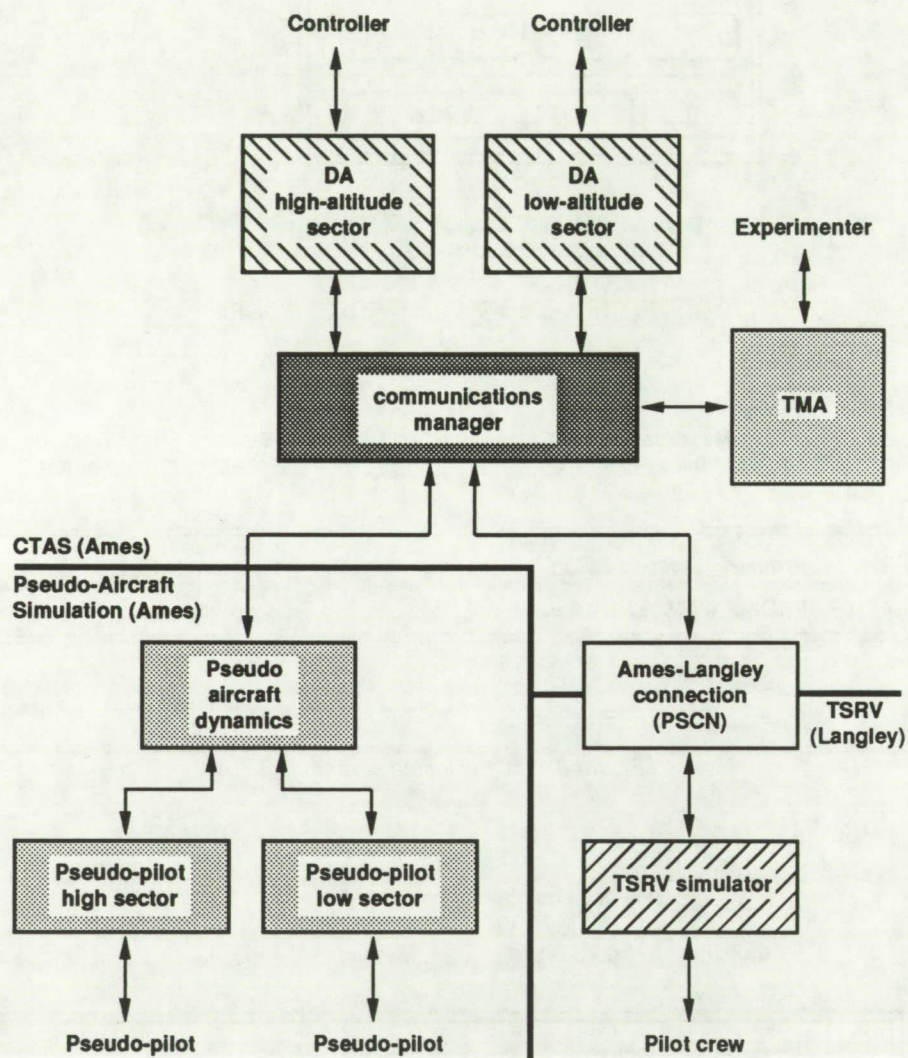
Figure 9. Data-link history panel (DHP).

Figure 10. Experiment setup for the 4D Aircraft/ATC Integration Study.
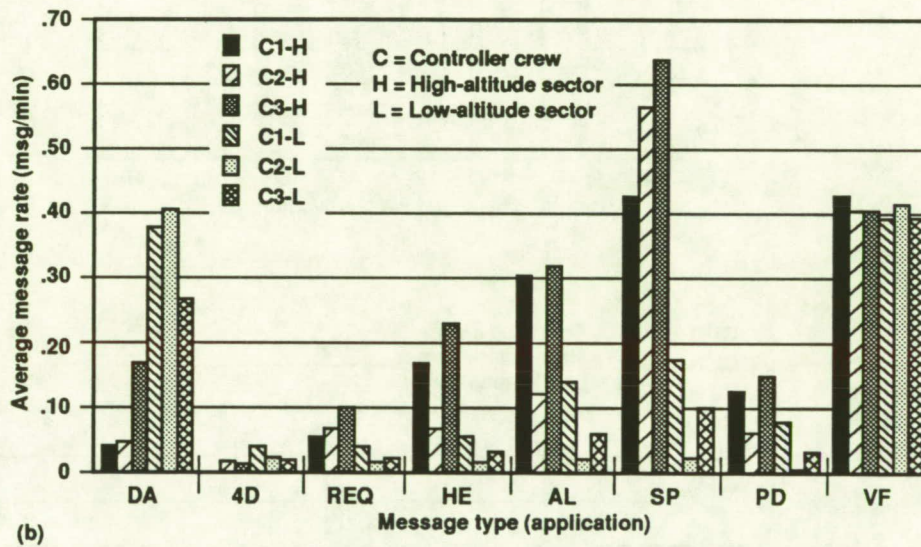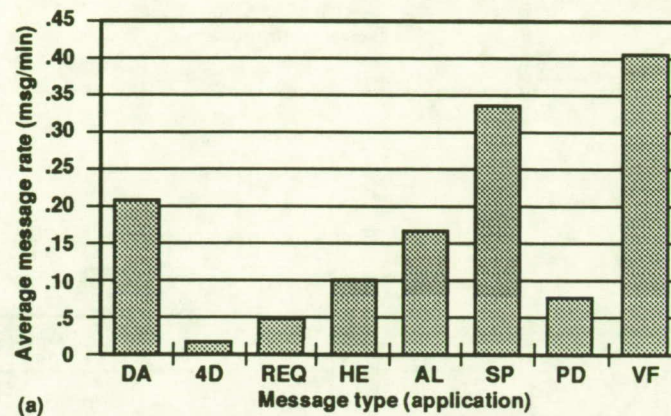
Figure 11. Data-link message rates (all aircraft). (a) Average message rate as a function of message type; (b) average message rate as a function of message type, controller crew, and sector.
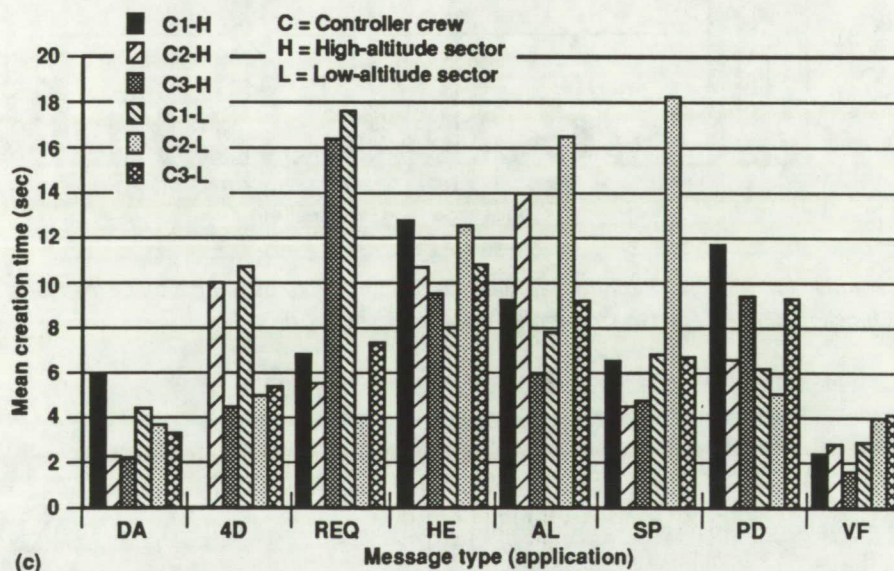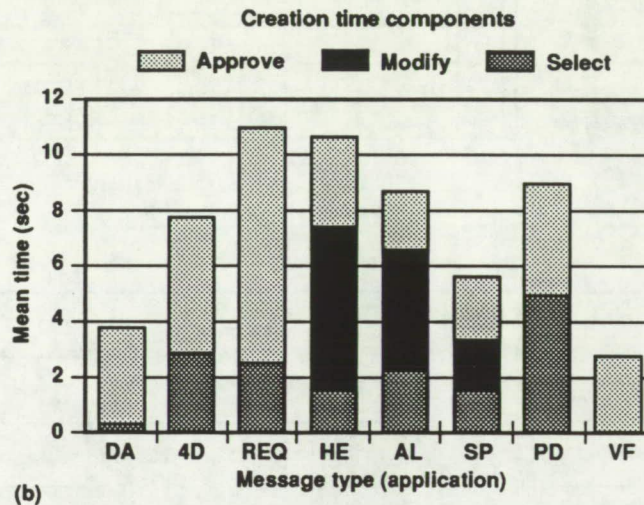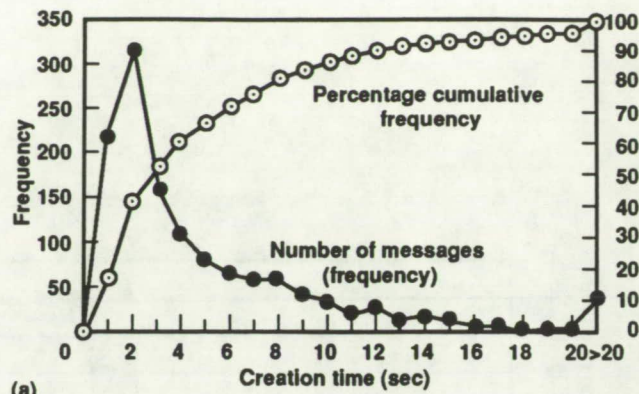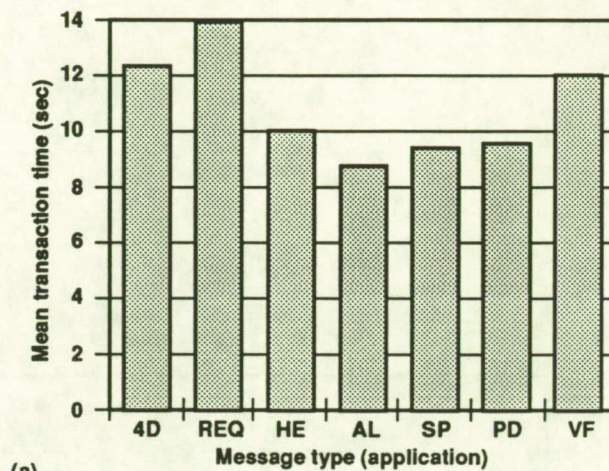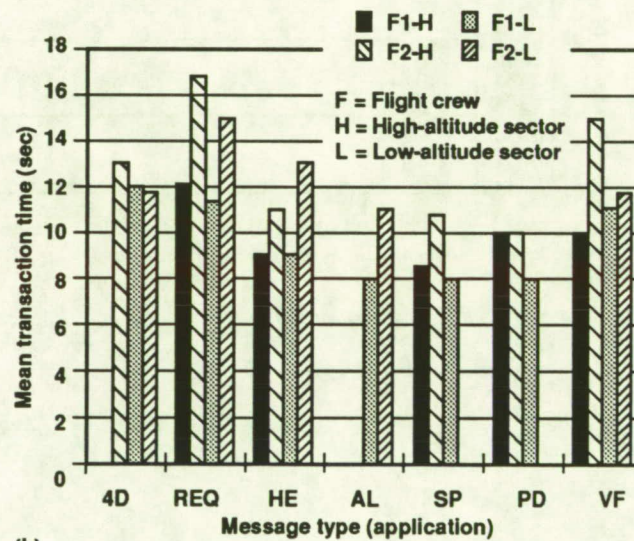
Figure 12. Data-link message creation times (all aircraft). (a) Message-creation time distribution; (b) mean message-creation time and time components as a function of message type; (c) mean message-creation time as a function of message type, controller crew, and sector.

Figure 13. Data-link transaction times (TSRV only). (a) Mean data-link transaction time as a function of message type; (b) mean data-link transaction time as a function of message type, controller team, and sector.
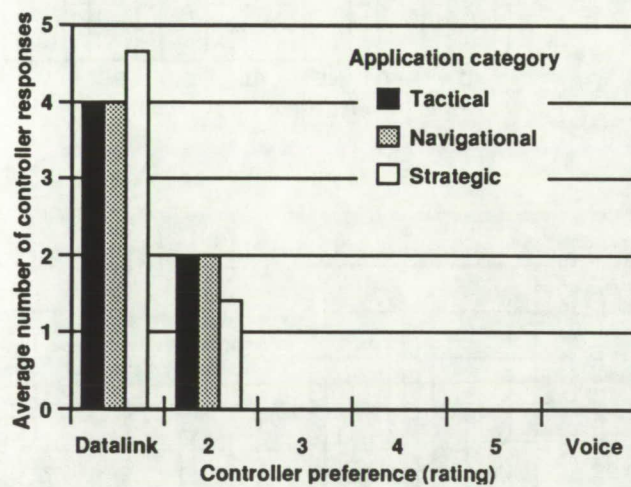
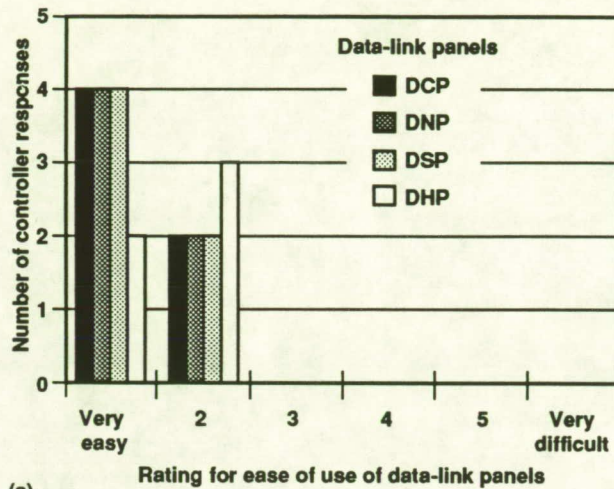*Figure 14. Controller preference of data link to voice for different categories of applications (six controller subjects).*
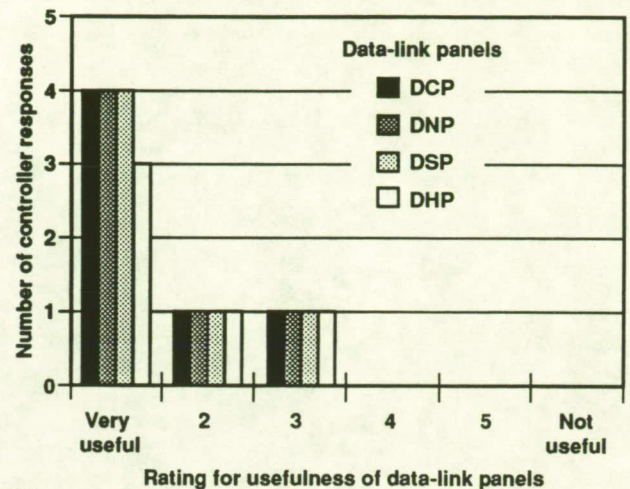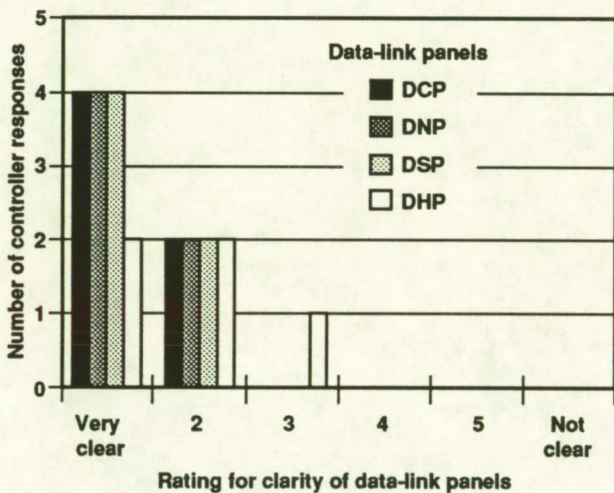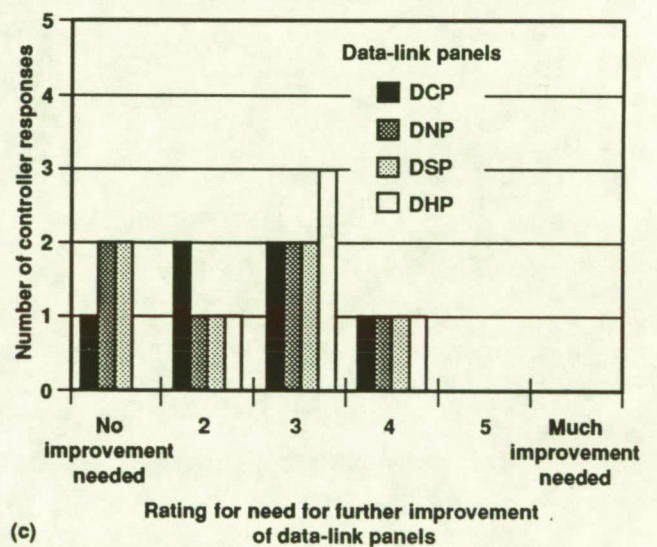
Figure 15. Controller ratings of several aspects of data-link panels (six controller subjects). (a) Rating for ease of use of data-link panels; (b) rating for usefulness of data-link panels; (c) rating for clarity of data-link panels; (d) rating for need for further improvement of data-link panels.

Appendix. Description of Data-Link Message Types and Formats

This appendix provides a description of the available data-link message types and the different formats used for coding the message contents in the message text (see sec. 3.2 of main text). For each message type used in the experiment, three different formats are described:

1. CTAS format, used for handling messages in the DA and for internal communication between DAs and the cm

2. Format used for transmission of messages to/from the TSRV at Langley

3. Format used for data-link communications with aircraft simulated by the Pseudo-Aircraft System (PAS) at Ames

For each message type the following information is given:

Code:	Description	
RT phraseology:	equivalent RT (voice) message	
CTAS:	CTAS format	CTAS example
TRX:	format for transmission	transmission example
PAS:	PAS format	PAS example

The "code" specifies the message type. Under CTAS, each message type is represented by an integer number. This message number is not included in the format description. For transmission, the message type is represented by a three-character code, included in the description. For PAS, there is no separate message type: the message text gives sufficient information for message processing.

The basic format for transmission to/from the TSRV is an ASCII string of up to 220 characters:

DDDSSSTTT:ccccc:HHMMSS:<CR>

with

DDD	destination;
SSS	source;
TTT	message type (TSRV specific);
ccccc	message text (variable length);
HHMMSS	sequence number (hr, min, sec);
<CR>	carriage return (decimal 13).

The transmission format description covers the portion TTT:ccccc.

The CTAS format has been generalized, which means that certain parts of the format can be changed without affecting the message processing. In the format description this is indicated by "word," which can be replaced by any suitable word. Uppercase items represent fixed-length fields; lowercase items are for variable-length fields. Items between parentheses are optional. Those parts of the general formats that are fixed are printed in bold.

The meaning of the various format descriptors is as follows:

word	any suitable word
#	one or more blanks (spaces)
C, c	character
D, d	digit
X, x	x-coordinate (n. mi. for CTAS; deg for transmission)
Y, y	y-coordinate (n. mi. for CTAS; deg for transmission)
K, k	speed, knots
M, m	Mach number
R, r	range or distance, n. mi.
NNNNNN, nnnnnn	message sequence number

HHMMSS, hhmmss   time in hours, minutes, seconds
N.A.   Not available

First, the message types that have a corresponding application button on the data-link control panel are described. They are followed by some additional message types for uplink and the message types for downlink.

Strategic Messages

DA: Arrival clearance with DA advised descent profile
RT phraseology: "Cleared for the <arrival-procedure-name> arrival, begin descent at <tod-dist> DME, descend at
                    (Mach .MM,) KKK knots indicated"
CTAS: word#CC#rrr#(m.mm#)kkk#ccc   DA RI 58 .70 280 GOLDN
TRX: **TAC:DARRRMMKKK:CLRccc**   TAC:DA05870280:CLRGOLDN
PAS: **DME#ccc#rrr#(Mmm#)Skkk**   DME GOLDN 58 M70 S280
remarks: CC can be RI - Route Intercept, WC - Waypoint Capture, PS - Path Stretch; ccc = arrival procedure name

4D: 4D arrival clearance
RT phraseology: "Cleared for the <arrival-procedure-name> arrival, (begin descent at <tod-dist> DME, descend at
                    (Mach .MM,) KKK knots indicated,) cross <meter fix name> at <time>"
CTAS: word#ccc#word#HHMMSS   Cleared KEANN at 190524
TRX: **TAC:CLRccc:MTHHMMSSccc**   TAC:CLRKEANN:MT190524SWEET
PAS: N.A.
Remark: if descent constraints are specified, this message is sent in conjunction with the profile (PRO) message, described under the additional messages.

REQ: Request for profile
RT phraseology: "(Expect direct to <waypoint name>,) (expect meter fix time of <arrival time>,) what is your profile
                    request?"
CTAS: (CC#ccccccc)(#hhmmss)   PS PONNY.J114.KEANN 170605
                  (CC can be PS - Path-stretch, PD - Proceed-direct, RI - Route-intercept, OR - On Route)
TRX: **REQ:RTccccccccc(:PS/:PDccccc)(:MTHHMMSS)**
                  REQ:RTPONNY.J114.KEANN:PSPONNY:170605
PAS: N.A.

Heading Messages

HE: Heading instruction
RT phraseology: "Maintain heading DDD"
CTAS: word#ddd   Fly_heading 50
TRX: **TAC:HEDDD**   TAC:HE050
PAS: Fddd   F50

TLT: Turn-left-to instruction
RT phraseology: "Turn left to DDD"
CTAS: word#ddd   Turn_left_to 240
TRX: **TAC:HETLTDDD**   TAC:HETLT240
PAS: Lddd   L240

TRT: Turn-right-to instruction
RT phraseology: "Turn right to DDD"

CTAS:	word#ddd	Turn_right_to 340
TRX:	**TAC:HETRTDDD**	TAC:HETRT340
PAS:	**Rddd**	R340

TL:	Turn-degrees-left instruction	
RT phraseology:	"Turn left ddd degrees"	
CTAS:	word1#ddd#(word2)	Turn_left 30 degrees
TRX:	**TAC:HETLDDD**	TAC:HETL030
PAS:	**Gddd**	G30

TR:	Turn-degrees-right instruction	
RT phraseology:	"Turn right ddd degrees"	
CTAS:	word1#ddd#(word2)	Turn_right 15 degrees
TRX:	**TAC:HETRDDD**	TAC:HETR015
PAS:	**Dddd**	D15

Altitude Messages

Altitude is given in hundreds of feet, both above and below transition-level/altitude. The translation to transmission format depends on the position of the target altitude relative to the current altitude.

AL:	Altitude instruction	
RT phraseology:	various (see below)	
CTAS:	word#ddd	Altitude 290
PAS:	**Addd**	A290
RT phraseology:	"Climb and maintain <altitude or FL>"	
TRX:	**TAC:ALCDDD**	TAC:ALC290
RT phraseology:	"Descend and maintain <altitude or FL>"	
TRX:	**TAC:ALDDDD**	TAC:ALD080
RT phraseology:	"Maintain <altitude or FL>"	
TRX:	**TAC:ALMDDD**	TAC:ALM350

Speed Messages

SP:	Speed instruction	
RT phraseology:	"Maintain kkk knots" or "Maintain Mach .MM"	
CTAS:	word#kkk or word#m.mm	Speed 250 or Speed .67
TRX:	**TAC:SPKKK** or **TAC:SP.MM**	TAC:SP250 or TAC:SP.67
PAS:	**Skkk** or **Mmm**	S250 or M67

Remarks: This message is used for CAS and Mach commands; for Mach: 0 < speed < 1.0

SPI:	Increase-speed instruction	
RT phraseology:	"Increase speed kk kts"	
CTAS:	word1#kk#(word2)	Increase_speed 20 kts
TRX:	N.A. (We used TAC:FTIncrease speed kk kts)	
PAS:	**Ckk**	C20

SPD:	Decrease-speed instruction	
RT phraseology:	"Decrease speed kk kts"	
CTAS:	word1#kk#(word2)	Decrease_speed 20 kts
TRX:	N.A. (We used TAC:FTDecrease speed kk kts)	
PAS:	**C-kk**	C-20

Navigation Messages

<u>RI</u>:	Route-intercept instruction	
RT phraseology:	"Intercept <route name>"	
CTAS:	word#cccc	Intercept J114
TRX:	**TAC:RIcccc**	TAC:RIJ114
PAS:	**INT#cccc**	INT J114

<u>PD</u>:	Proceed-direct-to instruction	
RT phraseology:	"Proceed direct to <capture waypoint name>, resume own navigation"	
CTAS:	word#ccccc	Proceed_direct_to SMITY
TRX:	**TAC:PDccccc:HERE**	TAC:PDSMITY:HERES
PAS:	**CAP#ccccc**	CAP SMITY

Frequency Change Message

<u>VF</u>:	Frequency-change instruction	
RT phraseology:	"Contact <facility name> <facility type> on <frequency>"	
CTAS:	word1#ccc#ccc#word2#1DD.dd	Contact Denver Center on 123.750
TRX:	**TAC:VFDDDDDcccCCC**	TAC:VF23750DENCNT
PAS:	**HO#ccc** (PAS sector identifier)	HO S9 (HO TRA for TRACON)

Free-Text Messages

<u>FT</u>:	Free text message	
RT phraseology:	any non-standard free-text message	
CTAS:	cccc (up to 51 characters)	Report current heading
TRX:	**TAC:FTcccc**	TAC:FTReport current heading
PAS:	**FT:#cccc**	FT: Report current heading

Additional Messages

General remarks:

1.   Under the current data-link procedures, a 4D clearance is issued as a sequence of three messages, sent when the controller approves the "4D" application on the DCP. The sequence consists of a route clearance (ROU), an arrival clearance (4D), and additional profile constraints (PRO). The route is sent only if the new route differs from the last cleared route.

2.   The information (INF) message is used only for low-priority, automatically generated information. For example, when the controller enters a downlinked profile message (PRO) into the DA's trajectory analysis, a "Profile receive, standby" is uplinked automatically.

<u>ROU</u>:	Route clearance	
RT phraseology:	"cleared for the route <route> (, proceed direct to (, at your discretion))"	
CTAS:	CC#ccccccccc	PD PONNY.J114.KEANN
TRX:	**ROU:RTccccccccccccc(:PScccc or :PDccccc)**	
	ROU:RTPONNY.J114.KEANN:PDPONNY	
PAS:	N.A.	

Remarks: The ROU message is always sent in conjunction with the 4D arrival clearance message (see before).

<u>PRO</u>:	Profile constraints	
RT phraseology:	(see 4D message)	
CTAS:	ccccc#hhmmss#xxx#yyy#m.mm#m.mm#kkk#rrrr#rrr	
	GOLDN 170515 234.34 456.20 .72 .72 295 0764 58	
TRX:	**PRO**:ccccc:HHMMSS:NXXXXXXXWXXXXXXX:.MM:.MM:KKK:RRRR	
.PRO:	GOLDN:170515:N0404507W1024915:.72:.72:295:0764	
PAS:	N.A.	

Remarks: The PRO message is always sent in conjunction with the 4D arrival clearance message (see before).

<u>INF</u>:	Information message	
RT phraseology:	any non-standard informative message	
CTAS:	ccccc (up to 202 characters)	Profile received, standby
TRX:	INF:ccccc (up to 202 char.)	INF:Profile received, standby
PAS:	Info:#ccccc	Info: Profile received, standby

Downlink Messages

<u>PRO</u>:	Profile proposal	
RT phraseology:	"Request to cruise at Mach .mm and descend at (Mach .mm,) kkk knots indicated"	
CTAS:	ccccc#hhmmss#xxx#yyy#m.mm#m.mm#kkk#rrrr#rrr	
	GOLDN 170515 234.34 456.20 .72 .72 295 0764 58	
TRX:	**PRO**:ccccc:HHMMSS:NXXXXXXXWXXXXXXX:.MM:.MM:KKK:RRRR	
PRO:	GOLDN:170515:N0404507W1024915:.72:.72:295:0764	
PAS:	N.A.	

<u>INF</u>:	Information message	
RT phraseology:	any non-standard informative message	
CTAS:	cc (up to 202 characters)	This is an info message
TRX:	INF:cc (up to 202 char.)	INF:This is an info message
PAS:	N.A.	

<u>ROG</u>:	Roger	
RT phraseology:	"roger"	
CTAS:	nnnnnn	123456
TRX:	**ROG**:NNNNNN	ROG:123456
PAS:	nnnnnn	123456

<u>UNA</u>:	Unable	
RT phraseology:		
CTAS:	nnnnnn	170623
TRX:	**UNA**:NNNNNN	UNA:170623
PAS:	nnnnnn	170623

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Wim den Braven*

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13. ABSTRACT *(Maximum 200 words)*

The design and evaluation of the ground-based portion of an air-ground data-link system for air traffic control (ATC) are described. The system was developed to support the 4D Aircraft/ATC Integration Study, a joint simulation experiment conducted at NASA's Ames and Langley Research Centers. The experiment focused on airborne and ground-based procedures for handling aircraft equipped with a 4D-Flight Management System (FMS) and the system requirements needed to ensure conflict-free traffic flow. The Center/TRACON Automation System (CTAS) at Ames was used for the ATC part of the experiment, and the 4D-FMS-equipped aircraft was simulated by the Transport Systems Research Vehicle (TSRV) simulator at Langley. The data-link system supported not only conventional ATC communications, but also the communications needed to accommodate the 4D-FMS capabilities of advanced aircraft. Of great significance was the synergism gained from integrating the data link with CTAS. Information transmitted via the data link was used to improve the monitoring and analysis capability of CTAS without increasing controller input workload. Conversely, CTAS was used to anticipate and create prototype messages, thus reducing the workload associated with the manual creation of data-link messages.

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