NASA Contractor Report 3461

A Flight Investigation of Simulated Data-Link Communications During Single-Pilot IFR Flight

Volume I – Experimental Design and Initial Tests

James F. Parker, Jr., Jack W. Duffy,
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FOREWORD

This is a human factors study of single-pilot IFR flight in which a Flight Data Console presents ATC information through a simulated digital data link. The study was conducted for the NASA Langley Research Center under the direction of Dr. John D. Shaughnessy, Mr. Hugh P. Bergeron, and Mr. David Hinton. We would like to thank them profusely for their excellent suggestions and guidance.

Mr. Donald Dawson, of K&W Electronics, and Mr. James H. Sanders, of BioTechnology, were instrumental in the design and fabrication of the Flight Data Console. Mr. Arthur Paul Barker, of BioTechnology, played a key role as inflight console operator.

Finally, a particular note of appreciation must go to the subject pilots for their most important contributions:

Allan E. Carr
Catherine C. Connor
John E. Dettra
Sam Griffith
Mike McDermott
Julian Morrison
Gregory L. Schwob
James H. Thornbro
Kenneth R. Yenni

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INTRODUCTION

Aviation in the 1980s – The Vistas of Technology

The history of civil aviation in America has been one of rapid growth, partly in response to an increasing population and partly as a result of an overwhelming increase in manufacturing capacity during World War II. The extent of this growth is shown in a comparison of operations over the two decades from 1958 to 1978. The airlines of the United States, in 1958, flew 39.5 million passengers on domestic routes, while another 4.2 million were carried in international service. A milestone also was achieved in this year when, for the first time, more people crossed the Atlantic from the United States by air than by steamship (Canby, 1963). By 1978, an amazing growth was seen. In this year, 254 million passengers were carried within the United States and an additional 20.7 million on overseas routes. This is an increase of over 640 percent in our domestic air transport operations.

The complexion of the national aviation system has changed a number of times during its growth, mainly to accommodate new procedures and equipment. The first air traffic control started at Newark, New Jersey, in 1935 to provide weather information to aircraft and also for limited guidance during terminal area operations. The feasibility of two-way radio installations made this possible.

World War II produced many advances in aviation, a most important one being the use of radar to monitor the flight path of an aircraft. This military technology became part of civil aviation in the 1950s, initially to provide positive guidance during instrument landing operations. A mid-air collision between two commercial airliners over the Grand Canyon in 1956 served as an impetus for the addition of long-range surveillance radar to the air traffic control system, soon allowing positive separation during flight over most areas in the continental United States. It was widely recognized at this time that improved radar coverage had given new dimensions of sophistication and safety for commercial flight operations. What was hardly noticed, however, was that a few hardy general aviation pilots had noticed the new system and were beginning to move from Sunday afternoon pleasure flights to all-weather business trips from one city to another. However, the system continued to focus on commercial flight and, to the extent that it acknowledged the presence of the few general aviation planes operating in IFR weather, treated them mostly as noise on the radar scope. No allowances were made for the meager skills of the pilot or his woefully inadequate avionics equipment.

There is no question but that the initial development of the National Airspace System was directed toward the commercial air carriers. And no one can fault this. The rapid and safe movement of large numbers of business and pleasure travelers obviously is a most important national priority. But somehow, although not given much in the way of Federal attention, general aviation has shown a healthy growth rate for well over twenty years. Avionics manufacturers, ever alert to the emergence of a new market, soon developed greatly improved radio and navigation equipment. By 1976, an aviation publication was describing the route by which general aviation avionics had assumed the role of innovator formerly held by airline avionics (Klass). General aviation aircraft kept pace. They became more complex, had greatly improved flight capabilities, and certainly were more expensive.

The position gained by general aviation as a user of the National Airspace System, at the end of the 1970s, is shown in Table 1. At airfields with FAA towers, there are five times as many operations by general aviation aircraft as by air carriers. There are one and one-half times as many instrument flight operations. In fact, since 1975 general aviation has been the largest single user of the instrument flight system. Table 1 also shows the number of active airman certificates as of 1978. Of interest is the significant number of pilots who now hold instrument ratings.

Table 1

General Aviation Operations
(1978)

	Air Carriers	General Aviation
Total Operations (Fields with Towers)	10,063,259	50,798,779
Total IFR Operations	10,421,496	16,310,259
Active Airmen Certificates:	798,833	
Instrument Ratings Held:		
Private Pilot	32,470	
Commercial Pilot	145,268	
Airline Transport Pilot	55,881	

Source: *FAA Statistical Handbook of Aviation* (1978).

Best estimates are that the growth of general aviation will continue unabated in the coming decade. Federal Aviation Administration (FAA) forecasts for 1985 predict a 25 percent increase in the number of active pilots, to just under one million. Of these, some 360,000 are expected to hold instrument ratings. By far the majority of these instrument-rated airmen will operate in the general aviation fleet.

It is clear that general aviation is far and away the fastest growing segment in American aviation. It also has become a national resource—an integral part of our national transportation system. In 1978, some 29 percent of the people who traveled intercity by air did so in general aviation aircraft. Recent sales figures for corporate aircraft would indicate that this percentage will be larger by 1985.

How well will general aviation function as a major component in a national system for the transport of passengers and goods? Will the typical general aviation pilot benefit in the same manner as an airline pilot from the technological changes now taking place in aviation and in air traffic control? Certainly we are entering a decade of major advances in aviation systems. Wiener and Curry (1980) describe how modern microprocessor technology and display systems make it entirely feasible to automate many (if not all) of the flight-deck functions previously performed manually. Whether or not such total automation will take place, or is even desirable, is another issue. Certainly automation now can be used where it provides a demonstrable benefit. However, before considering problems of the general aviation pilot in a technologically advanced world, it would be well to review how well he is doing with present systems.

General Aviation Safety

There is hardly any better way to examine the efficiency with which general aviation operates as a component in the national aviation system than by an examination of its accident rate. It is not unreasonable for a passenger boarding a small aircraft to expect the pilot to be fully qualified, the aircraft to be airworthy, and the flight itself to be pleasant and safe. Unfortunately, these expectations are not always fulfilled.

A comparison of the accident rates for general aviation and for the commercial air carriers is shown in Table 2. During 1978, general aviation had 4,609 accidents—a lot—compared to the 26 accidents suffered by the airlines. This gives general aviation an accident rate which is 34 times as high as that for carrier operations. Any reaction to the magnitude of this difference should be tempered, however, by a realization that this is based on *all* general aviation flights. The accidents include those instances (hopefully rare) in which a pilot decides his flying skills, or his courage, are better after two martinis. The numbers also reflect cases in which a pilot swoops low over his girlfriend's house and stalls into the ground while looking over his shoulder to see if she came out to wave. Finally, there are the cases where an inexperienced pilot presses on into weather, sometimes with icing, for which neither he nor the airplane is fully prepared.

A more reasonable comparison between commercial and general aviation operations is on the basis of safety during instrument flight. Here, one can presume that the horseplay element is gone. The demands of instrument flight require a professional approach—the full time and attention of the pilot must be on completing the flight safely. Yet even here general aviation does not fare too well.

Table 2

General Aviation/Air Carrier Accident Rates

All Accidents – 1978	Air Carriers	General Aviation
Number	26	4,609
Rate (100,000 Aircraft Hrs.)	0.37	12.59
Difference: GA is 34 Times Higher		
Instrument Approaches – 1974/1975		
Number of Approaches	1,553,698	1,512,817
Accidents	4	66
Rate/10,000 Approaches	0.026	0.436
Difference: GA is 17 Times Higher		

Sources: NTSB Aircraft Accident Data Reports, CY 1974, 75.
FAA Statistical Handbook of Aviation, 1975.

Table 2 also shows accidents experienced by the two segments of aviation while making instrument approaches during a recent two-year period. While the number of approaches flown was almost identical for the two groups, the accidents were not. General aviation had 66 accidents during IFR approaches, while the airlines had only four. This gives general aviation an accident rate which is 17 times as high as that of the carriers.

Examining the problem from a different perspective, Forsyth and Shaughnessy (1978) reviewed the general aviation accident files of the National Transportation Safety Board for a 12-year period (1964 through 1975). It was found that over this time, 72 percent of the IFR landing phase accidents involved single-pilot operations. Of these, 87 percent were attributed wholely or in part to pilot error. The study also found, as seen in Figure 1, that single-pilot pilot error accidents increased at a rate of 3.5 accidents per year, while dual-pilot pilot error accidents increased at only one-third this rate.

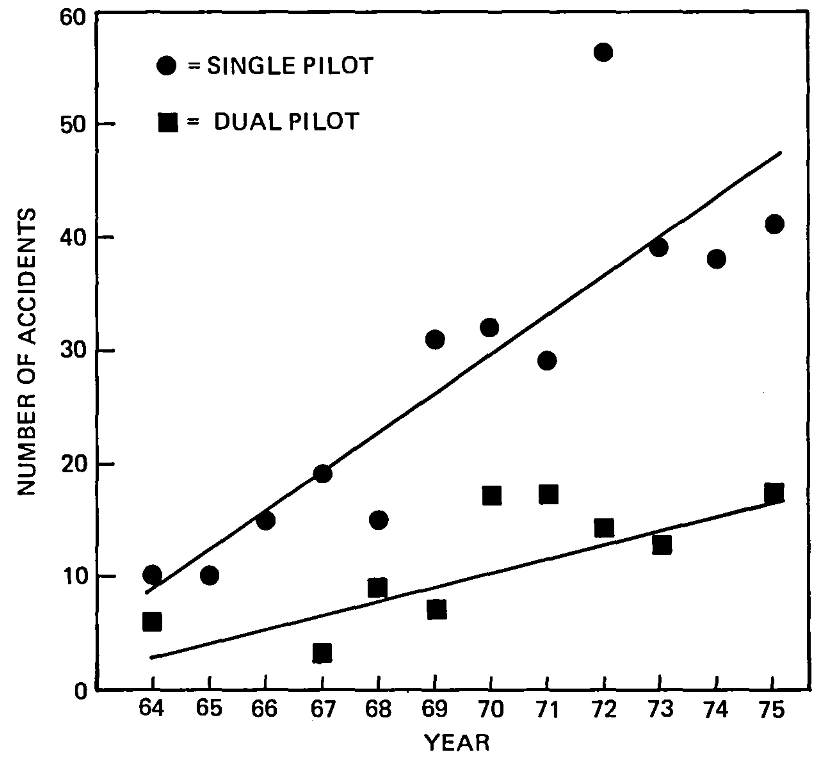


Figure 1. General aviation landing phase accidents (adapted from Forsyth and Shaughnessy, 1978).

The General Aviation Flight Deck

The comparisons just presented lead to two conclusions. First, the accident rate for general aviation operations, including instrument flight, is high—certainly higher than one would desire. Second, IFR flight with a copilot seems to be safer than when only a single pilot is present.

The accidents experienced in general aviation, especially when flight is conducted under instrument rules, can logically be attributed to a number of factors, all subsumed under the broad but somewhat misleading rubric "pilot error." First, there is the issue of *recency*. The Federal Aviation Administration states that "No pilot may act as pilot in command under IFR . . . unless he has, within the past six months, . . . logged at least six hours of instrument time under actual or simulated IFR conditions, including at least six instrument approaches, or passed an instrument competency check." In the extreme instance, this means that a pilot may not have flown IFR for five months and 29 days, yet he is legal in filing for an airport showing a 60.96-meter (200-foot) ceiling and 0.8 kilometers (one-half mile) visibility. Whether he will be able to complete an approach on arrival at the airport should be a matter of concern. If his proficiency six months earlier was excellent, the approach may be fine. If his earlier proficiency was marginal, the approach could be quite a hazardous matter.

The second issue affecting IFR performance is that of *training* and *initial proficiency*. While the FAA does spell out training requirements and objectives for instrument flight, there is no way in which one can equate the scope, quality, and intensity of this training in general aviation with that given airline pilots. The task, however, remains the same. During instrument flight conditions, the Air Traffic Control system must, by necessity, treat a general aviation pilot with 300 hours no differently than an airline crew with a combined total of 30,000 flight hours.

The final problem, and the one of most consequence for the present effort, is that of cockpit *workload*. Single-pilot instrument flight, particularly without an autopilot, is about as difficult as any kind of flying that exists. The pilot must fly the airplane; handle all communications, including numerous frequency changes; navigate with precision, using the many necessary charts; comply with all ATC procedures; and periodically monitor the performance of fuel and electrical systems. In an aircraft which might cruise at 170 and approach at 120 knots, much can happen while the pilot is dealing with one of his many tasks.

The second of the comparisons made in the previous section shows that most of the IFR landing phase accidents experienced by general aviation involve single-pilot operations. This comparison of single- versus dual-pilot IFR operations suggests a number of things. Although general aviation flights are not organized with a clear delineation of crew duties as is found in air carrier operations, it is obvious that a copilot does contribute something. He may lighten the workload of the pilot by handling all radio communications. He also might assist by calling out airspeed and on-course information, as well as by reminding the pilot as he approches Decision Height. He also can leave the pilot free to deal only with the cockpit instruments by looking outside for runway lights during the final stages of the approach.

A summary statement of a copilot's duties might well be that he assists in *data management* in the cockpit. He helps to acquire information (ATC communications), to verify critical data items, and to assist in the storage of data until needed. All this is of considerable value, as the reduction in the accident rate when two pilots are aboard testifies. This also suggests that proper data management in the cockpit might well be a most important factor influencing the safety of an IFR flight.

When a copilot is not present, all data management tasks fall on the pilot. During periods of high workload, his capability to perform these many tasks, while he is busy flying the airplane, may become degraded to a point of real concern.

Data Management and Information-Processing Qualities of the Human Operator

Much research in the field of human factors engineering has been conducted on the capabilities of a human as an information-processing component in a man/machine system. In the broadest sense, this research covers topics such as visual and auditory sensory capabilities, learning, short and long-term memory, decision making, fatigue, and motor responses. For present purposes, the focus will be on the ability of a human operator to receive a number of items of information and to use these items appropriately within a short period of time. Of particular interest is the effect of stress and high workload on pilot performance as measured by speed and accuracy of response.

The following are the key features of the information-processing literature relevant to the conditions of single-pilot IFR flight:

1. ***Channel Capacity***. Since the late 1940s, there has been considerable interest in studying the properties of man as an element within a man/machine control system. To the extent that his capabilities can be defined in engineering terms, the system can be designed to incorporate these capabilities in a manner tending to optimize total system function. While the goal of a strict engineering specification of man's capabilities has not been achieved, much has been learned concerning how man operates in a system.

A useful concept which engineering psychology has borrowed from the communications engineer is the notion of a channel used to describe the means by which data are conveyed to the central mechanism (Murrell, 1971). Of the sensory organs used as channel transducers for external stimuli, the visual and auditory channels are most important. However, the term "channel" is not necessarily synonymous with "sensory modality." Visual information alone, for example, can be presented through a number of channels.

In a review of human information processing, Senders (1970) notes these broad conclusions concerning man's channel capacities:

a. The operator is a single-channel system.

b. The channel has a fixed capacity.

c. The capacity has a single metric by which any task can be measured.

Murrell (1971) cites evidence tending to show that, at the highest decision-making level, man acts as a single-channel mechanism and that the rate at which decisions can be made is strictly limited. Once a piece of data enters the channel, there is a psychological refractory period which inhibits the receipt of further data. This refractory period is in the order of 0.5 seconds, meaning that about two pieces of data can be passed through a single channel per second. Murrell concludes that if two pieces of data arrive almost simultaneously, one will be passed through the channel but the other may be delayed or lost altogether. If the data arrive absolutely simultaneously, however, it is possible that they can be coded and passed through the channel as one piece.

The concept of a single-channel limitation for man, while undoubtedly possessing real validity, is by no means absolute. Wierwille et al. (1979) note that a great deal of laboratory research exists on empirical tests of various ramifications of the single-channel concept. For example, data are available on the possibility of multi-channel processing; procedures for switching attention among channels; various points of conflict or bottlenecks in the human information-processing channel; and variations in upper channel limits due to factors of stress, emotional state, fatigue, and effort. In short, single-channel operation is the rule, but this rule shows all the variability which characterizes any form of human behavior. Even so, Murrell concludes that "Designers should accept the general principle that under no circumstances should equipment be designed or a machine cycle be evolved which requires the operator to make two simultaneous decisions, whether through one or more sense modality."

2. ***Information Storage.*** By information storage we refer to the short-term memory process. Human memory has been studied extensively in the laboratory, but it remains a long step to apply the detailed laboratory findings to an operational situation such as instrument flight. For the moment, it will suffice to note that in a review of the literature, Craik (1979) comments that short-term memory apparently is not "one thing" but is an aggregate of mechanisms and skilled processes.

A particularly relevant study was accomplished recently by Loftus et al. (1979). Even though done in the laboratory, the study used an aviation context, which makes it easier to apply its findings to the operational scene. Communication between ground controllers and pilots was simulated in a short-term memory task in order to explore sources of error. Subjects were asked to repeat messages containing place/frequency and transponder code information following a retention interval lasting for up to 15 seconds. A typical message was "Contact Seattle center on 128.9. Squawk 7126." In a low information-load condition, place/frequency or transponder information was given alone. The high-load condition used place/frequency combined with transponder data.

Figure 2 is a forgetting curve which shows that under both low load and high load there is a demonstrable loss of information by 15 seconds. Most important, however, is that under the high-load condition information (place/frequency plus transponder code) can be recalled correctly in only 50 percent of the trials after 15 seconds. The authors conclude that the two major determinants of error are (1) amount of information that the pilot has to process in a given time and (2) retention interval between the time information is transmitted from the controller and the time it is acted on (recalled) by the pilot.

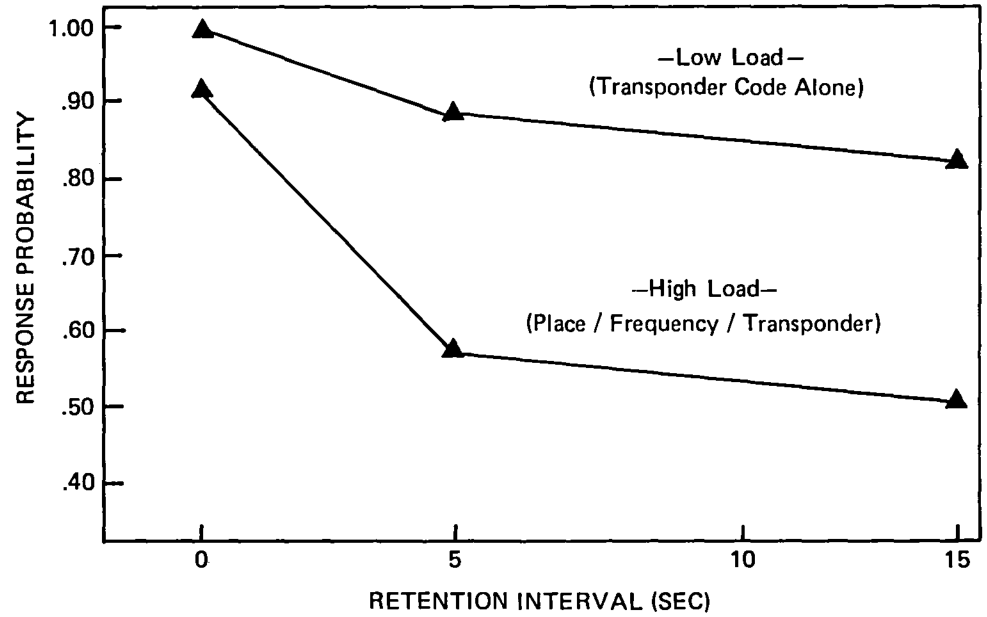


Figure 2. Retention of ATC information under low and high information load conditions (adapted from Loftus et al., 1979).

3. ***Recall Interference.*** It is well established that the short-term memory system can retain only a limited amount of material at any one time. For instance, in only about 50 percent of trials can subjects correctly repeat back a number of random digits when the number reaches seven to eight. Welford (1968) notes that this number is reduced if the subject shifts his attention to other material during the period between presentation and recall. Any number of studies have shown that the introduction of other information during the time of retention will reduce the accuracy of recall. The nature of the interpolated information also is important. The more similar the interpolated information is to that which one is trying to recall, the less accurate will be the recall. Thus, if one is trying to remember a series of digits, the introduction of additional digits during the retention period will cause more errors than if letters were to be introduced. In aviation terms, an ATC command for a heading change, followed by an altitude change, and completed with a frequency change, represents a situation which will tax the accuracy of short-term memory to its limit.

4. ***Workload.*** The workload placed on a pilot during an instrument landing approach can be high and it can affect performance. These are subjective aphorisms–their experimental proof is not easily come by. The principal problem is one of specifying just what workload is. Wierwille (1979) states that "There is no single, agreed-upon definition of mental workload, and there is no single, universal metric of it. Mental workload is a theoretical construct, and as such, might best be defined operationally. Clearly, it is related to factors such as operator stress and effort, but these concepts also require operational definitions." In a separate report, Williges and Wierwille (1979) reviewed 14 general approaches to the problem of developing behavioral measures of aircrew workload. They conclude that no single technique can be recommended as the definitive behavioral measure of operator workload. They note, however, that the strongest research support exists for using subjective opinions and task analytic methods involving task component/time summation. In other words, as the number of independent task activities increases and as the pilot reports heavier workload during landing approach, we can legitimately describe that as a high-workload condition.

High workload impairs man's ability to manage and to process information. To determine the particular characteristics of high workload which are important, Goldstein and Dorfman (1978) investigated the effects of speed and load stress where operators responded to moving stimuli presented in each of three visual displays. The task was representative of complex man/machine systems in which an operator is required to respond to multiple information sources that produce large numbers of signals in a short period of time. The authors note that in tasks which require response to multiple sources (load stress), timing and anticipation of response is an important aspect of human performance, and one which can be disrupted. In tasks with speed stress, the number of signals can be expected eventually to reach channel capacity. Also, speed stress can result in situations where the signals are bunched together within a short period of time and result in a "crisis" situation with significant disorganization of response.

Goldstein and Dorfman found that increasing the load stress by requiring the operator to monitor two or three displays rather than a single display resulted in a significant decrease in performance. On the other hand, increasing speed stress, where the operator was monitoring only one display, had no appreciable effect on performance. It was possible to increase the number of signals per minute from 24 to 72, with the observers continuing to be able to time their responses equally well. However, the most important finding of the study is that an increase in speed stress, where the operator is working under a load stress represented by two or especially three displays, causes a considerable disruption of performance. Figure 3 shows the delay in response, or latency, as signal speed increased for the three load conditions. The authors conclude that performance in this type of continuous time-sharing task is most negatively affected by load stress, especially in conditions which combine high load stress with speed stress. Comparisons certainly can be made between the conditions of this experiment and those which exist during the single-pilot instrument landing approach.

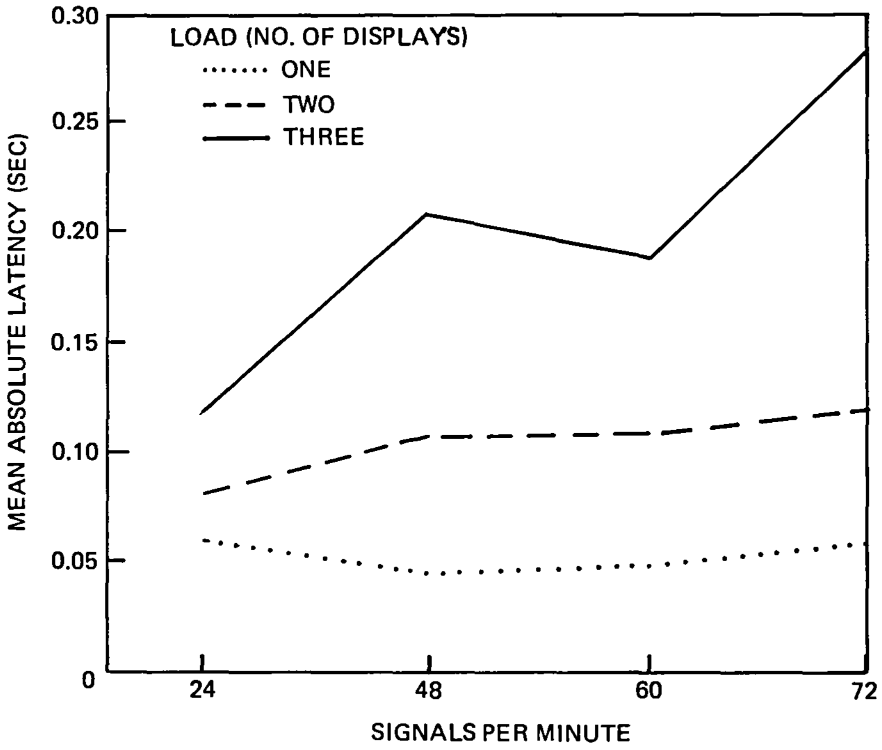


Figure 3. Response delay as a function of speed and load stress (from Goldstein and Dorfman, 1978).

Conclusions

One of the principal roles of a human operating in a man/machine system is to manage data and process information. Much has been learned of man's capabilities and limitations to perform in this role. The design of a man/machine system, if it is to operate efficiently and accurately, must take these capabilities and limitations into account.

Single-pilot IFR flight represents a man/machine system in which the task is imperfectly matched to the operator. During the approach-to-landing phase, and indeed at other points, critical information is presented simultaneously (and rapidly) through both the visual and auditory channels. The *simultaneous* presentation impacts the operator's tendency to function as a single-channel device.

The fact that multiple items of information are presented in rapid bursts of communication from ground controllers means that certain items must be stored until they can be acted upon. This storage requirement, particularly if it reaches 10 to 15 seconds, can introduce a rather significant error factor. Experimental results would indicate that where the message contains place/frequency/transponder code items, the error rate in setting the transponder display could reach 50 percent. Also, the fact that most items of ATC information are in the form of numbers can increase the extent of recall interference.

Finally, humans do not work with extreme precision under heavy workload. Experimental results indicate that a combination of high load, as represented by information received from several displays, when combined with an increasing speed of presentation can seriously disrupt performance. This is very much the situation during an instrument landing approach, when the pilot is monitoring as many as six displays while receiving command information from an air traffic controller. To make matters worse, the speed of information presentation on one display (the Course Deviation Indicator of the VOR/ILS display) increases in sensitivity during landing so that there is an increase in the speed at which information concerning position change is presented. This adds to operator workload in a manner almost designed to reduce accuracy of performance.

PROJECT OBJECTIVES

This is a human factors study of single-pilot IFR flight. An examination of the typical general aviation instrument flight, particularly during the approach-to-landing phase, indicates that the workload imposed by data management is quite heavy and may be a key factor underlying the high accident rate. Wiener (1977), in a review of landing accidents in commercial airline operations, says that "the message is clear–it is high time to take a fresh look at the problem of cockpit workload, procedures, and fatigue." If this is true for the professional world of commercial aviation, it certainly is true for general aviation.

The premise of this study is that cockpit workload can be reduced and IFR proficiency improved with a better match between the requirements of the system and the capabilities of the pilot. To accomplish this, the following changes appear warranted:

1. The pilot should be allowed to control the rate at which he deals with incoming Air Traffic Control instructions. During a critical period of flight such as an instrument approach, the tasks should be self-paced to the extent possible. This is in keeping with the concept of the pilot as a single-channel processor in which he maintains some control over channel flow rate. Pacing of activities controlled entirely by the system will add both to workload and to psychological stress.
2. Critical items of flight data should be stored until they have been acted upon by the pilot and he clears the data himself. The human memory system is entirely too fallible to be relied on completely during periods of heavy workload.
3. An appropriate alerting signal should be given whenever a condition bearing on safety of flight is entered. Functioning as a single-channel operator, the pilot may find it difficult to remain continuously aware of his entry into this boundary condition. It should not be left to the pilot to develop the *principal* warning scheme on his own.
4. The signal-to-noise ratio of ATC communications should be maximized. There should be no opportunity for communications intended for other aircraft to be received or for such communications to be blocked by transmissions from other aircraft. There should be no requirement for the pilot to serve as a communications filtering device.
5. The labor associated with the current communication system (handling of microphone, read-back of clearances, etc.) should be reduced.

It is clear that the above objectives cannot be met simply through refinements to the existing ATC/aircraft communications system. Billings (1980) recently reported on a summary of over 23,500 incidents submitted to the NASA Aviation Safety Reporting System. Well over one-half of these ASRS reports were found to involve a problem in the handling of information. Billings notes that, though much aeronautical information is highly dynamic, the problem is not usually that the information is incorrect. It almost always is correct at its point of origin. The problem is more likely to be in the transfer from its origin to a point where it must be used in decision-making.

Information is communicated from ATC to pilots currently through a VHF radio link, a link which is relatively free of static and other simple noise. Billings further notes that VHF channels are often congested, however, and the universal use of simplex communications poses potential, and sometimes very hazardous, problems due to blocking of one transmission by another. Blocking was thought to be a factor in the Tenerife accident; it appears to be a frequent problem in ASRS reports. To reduce the misunderstanding of verbal communications, most clearances now are read back after being received. The ASRS data show, however, that even an incorrect readback can be misperceived by an ATC controller and acknowledged as correct.

Bergeron (1980) recently examined ASRS reports which specifically dealt with general aviation single-pilot IFR operations. He cataloged the incidents into five major problem areas, one of which was "ATC and pilot communication problems." Bergeron found that the communication problems were of the following four types:

- Misunderstanding of instructions
- Frequency congestion
- Excessive frequency changes
- Excessive/impeding procedural requirements.

These represent some of the specific problems which must be addressed in attempting to improve the match between pilot and system.

Project Plan

The plan of this project is to evaluate an alternative to the current VHF voice link for pilot/ATC communications. Many studies show this to represent a key pilot/system mismatch. As an alternative, one would turn to a system which could provide the pilot with the necessary information for flight control through a non-voice data link. In other words, the requisite flight information should simply appear on a display in front of the pilot, thereby allowing him to deal with it in a timely and orderly fashion.

All of this implies use of a digital data link for communications. Indeed, the FAA has been working for some time on just such a system, the Discrete Address Beacon System (DABS). The DABS system will be discussed in some detail later in this report. For the moment it is sufficient to say that its current configuration does not include the presentation of ATC command information (heading changes, altitude changes, etc.) nor has the system been evaluated for its human factors implications such as reduction of workload and acceptance by pilots.

In this project, a prototype system, termed a Flight Data Console (FDC), was developed to allow simulation of a digital communications link. While much project effort went toward hardware development, the thrust of the study was a human factors evaluation of the extent to which such a system might reduce cockpit workload, improve flight proficiency, and be accepted by general aviation pilots.

The plan for this project involved four principal phases, as described in the following sections.

Study Problems of Data Management During General Aviation Single-Pilot IFR Flight

A number of instrument approches to facilities in the Washington, D.C. area were recorded for study. These included ILS, localizer back course, VOR, NDB, and ASR approaches. For purposes of study, key points in some of these approaches were transcribed onto Flight Data Logs. The purpose here was *not* to conduct a systematic study of cockpit workload during instrument approaches. These recordings were made simply to obtain information which might serve as a comprehensive base for the development of the Flight Data Console. We wished to be certain that the console could present all of the key items of information required by a general aviation pilot during the various types of instrument approach.

Design and Construct a Cockpit Flight Data Console (FDC)

A cockpit display was designed and developed which would allow, through appropriate inflight simulation, the presentation of both reference and command data from Air Traffic Control. Use of this sytem was designed to remove the pilot completely from the ATC voice loop. The intent was to construct a device which would allow a general aviation pilot to fly a complete instrument approach, including landing, with no voice communications from ATC whatsoever.

Conduct an Inflight Study

A human factors study of the Flight Data Console was conducted inflight using general aviation pilots. The purpose was to see that the study included realistic conditions of cockpit workload and reasonable inflight stress. Four types of approaches were flown into Washington Metropolitan Area airports. The performance of subject pilots, as well as problems encountered by them, was recorded by a safety pilot. Extensive interviews were conducted with subject pilots at the completion of the flights.

Prepare Recommendations

The final phase of the project involved the preparation of recommendations, as presented in this report, dealing with three topics:

1. Avenues for the improvement of data management in general aviation aircraft during instrument flight. These recommendations were not to be restricted simply to ways for optimizing the use of a device such as the Flight Data Console.
2. Use of a digital display such as the Flight Data Console for presenting ATC information. These recommendations deal with the information to be presented, techniques for display of the data items, the placement of such a display in a general aviation cockpit, and ways in which a system such as this should be included with other cockpit instrumentation.
3. Use of an FDC-type system in a future Air Traffic Control environment. The FAA at this time is considering digital data link systems for future ATC operations. For these systems to achieve their full potential (which is large), human factors issues concerning their use and incorporation as a major part of air traffic control should be solved in advance.

PROCEDURES

Record Instrument Approaches

The first step in the design of a cockpit display for presenting ATC information is to decide upon the specific data items to be shown. In order to define the data items and to insure that no important ones were missed, tape recordings were made of ATC/pilot voice communications during a number of instrument approaches. The approaches were made into facilities in the Washington area, and included Dulles International Airport, Baltimore-Washington International Airport, Hagerstown Airport, and Manassas Airport (Harry P. Davis Field). Some approaches were made specifically for recording purposes while at other times the recordings were incidental to a business trip. The purpose was to cover as wide a range of approaches as possible. Recordings were made of ILS, VOR, localizer back-course, ASR, and NDB approaches.

Certain of the approaches were transcribed for detailed study, as shown in Figure 4, while others merely were reviewed to check the instructions given to the pilot by ATC. It was found that these instructions, for a standard approach, generally involve the following data items:

- Heading change, including direction of turn
- Altitude change
- Frequency change
- Altimeter setting
- Clearance (cleared for approach, cleared to land).

Design and Construct a Flight Data Console

Description

A cockpit display system for presenting Air Traffic Control information was designed and constructed. The system is capable of simulating a digital data link with ATC, thereby allowing a pilot to fly an actual instrument approach with no voice communication between the aircraft and the ground controller. The system also is capable of storing information until acted upon by the pilot and of providing certain warning signals.

FLIGHT DATA LOG

Type of Approach: ILS Location: Dulles International Page: 1

Mission phase	Approx. Time	Communications		Cockpit Activities	Remarks
		ATC	Pilot		
Vectoring	:00	Aztec 76Yankee is radar contact, expect vectors, ILS runway 1 right.			
			76Yankee	Approach chart selected; ADF, Mkr Bcn on; ILS frequency set on VOR; fuel pumps on. Verify each navigation frequency identification code.	Start of landing check list.
	1:00	Aztec 76Yankee, turn right heading 190 degrees, maintain 2,000 feet.			
			Heading 190, maintain 2,000, 76Yankee		
Initial Approach	4:00	Aztec 76Yankee, turn right heading 340 degrees, six from the marker, cleared for an ILS approach runway 1 right, wind 330 at 12.			

Figure 4. Sample page showing log used for transcription of recorded instrument approach.

The Flight Data Console is made up of three principal parts: a front seat display and data entry panel for use by the pilot, as shown in Figure 5, a rear seat display and data entry panel whereby a console operator serves as a transducer for ATC instructions (entering ATC commands and immediately transmitting these commands to the front seat display), and a battery power unit which makes the system independent of the aircraft. Figure 6 shows the hook-up of the three principal components of the system. Although every effort was made to keep these units as small as possible, considerations of legibility and ease of operation dictated that they be larger than most items of cockpit instrumentation. The display unit was 22.9 x 14 x 57 cm in size, while the entry keyboard was 13.3 x 12.7 x 3.2 cm. These dimensions played a key role in determining where the Flight Data Console could be installed in the project aircraft.

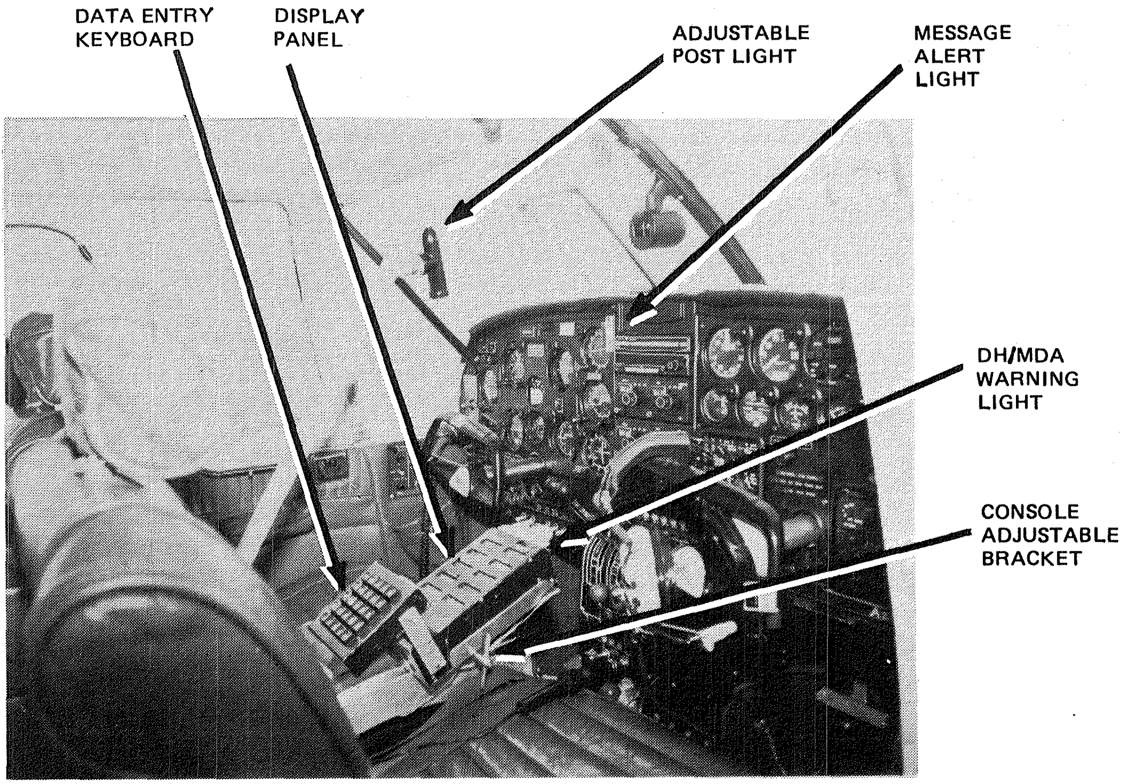


Figure 5. Flight Data Console front seat installation.

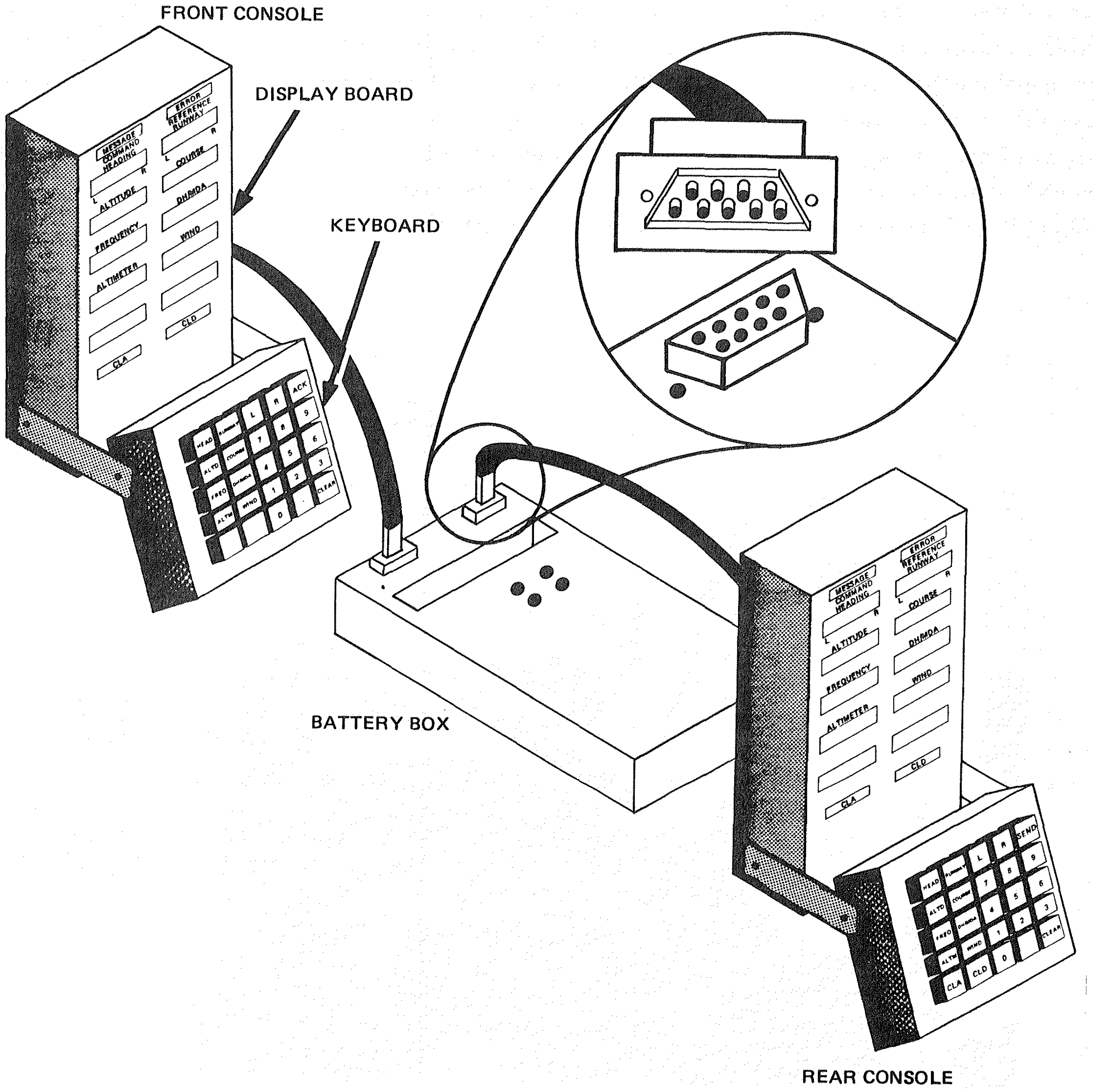


Figure 6. Principal components of Flight Data Console.

The unit which presents ATC information uses liquid crystal displays, each of which can present up to eight digits. These were chosen because of ease of legibility during daylight conditions. For night flights, a small floodlight, using a 12-volt bulb, illuminates the display panel. The pilot's entry keyboard uses a standard telephone-type touch system, with approximately one-quarter inch movement required for switching.

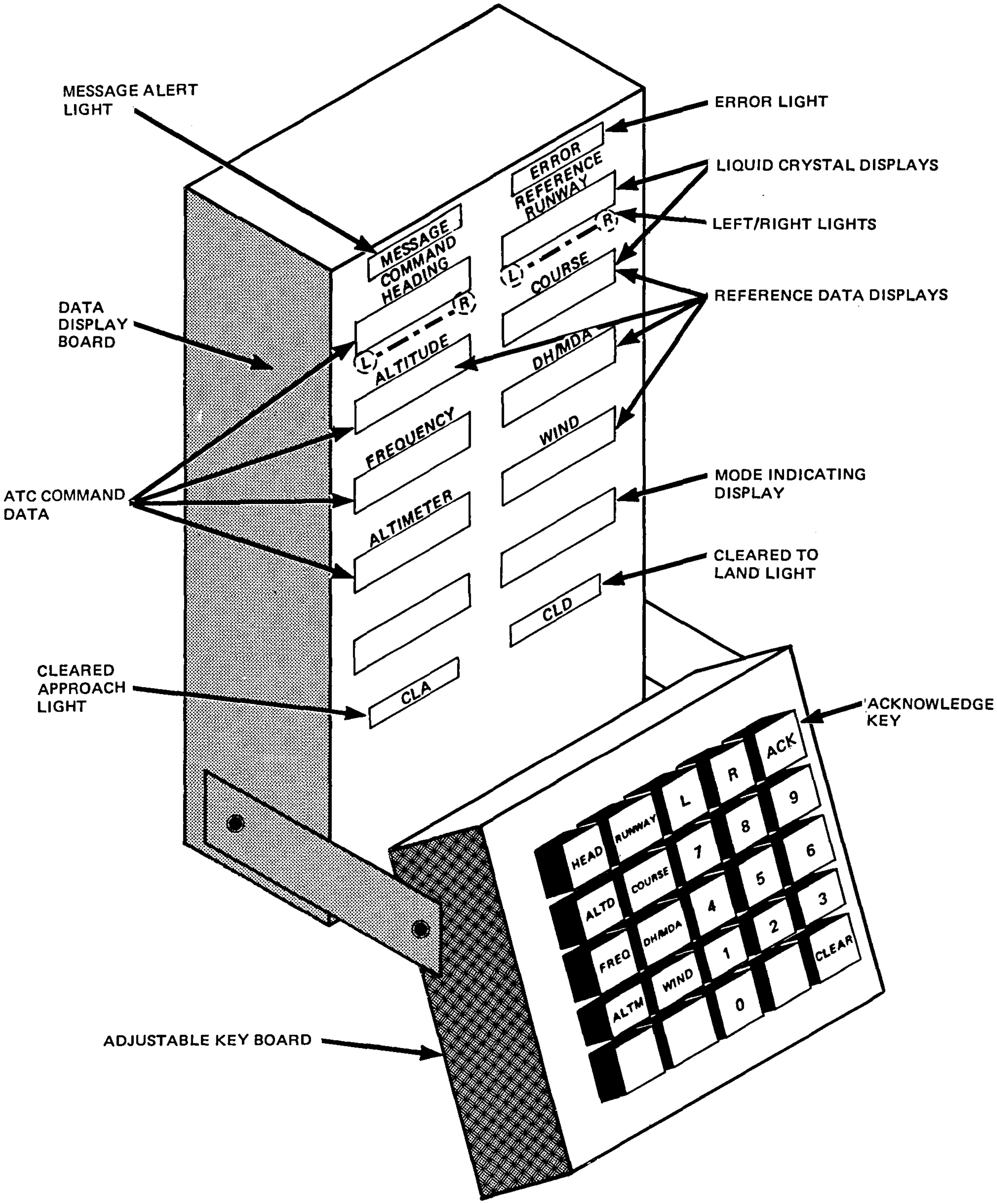
Operation

The Flight Data Console has two modes of operation. In Mode 1, the system presents and stores flight data items as entered by the pilot. The FDC in this mode serves as a memory aid and, in essence, takes the place of a paper-and-pencil kneepad. In Mode 1, most information items (reference data) appear in the right column of the display (Figure 7), although the pilot may enter information in the left column if he desires. For the most part, the information to be entered as reference data will be that obtained from the Automatic Terminal Information Service (ATIS) when the airplane is some distance from the airport.

When operating in Mode 2, the Flight Data Console receives command information from Air Traffic Control and presents it principally in the left column of the display (Figure 7). This includes instructions for changes in heading (including direction of turn), changes in altitude, new frequencies, updated altimeter settings, and, as shown in the bottom two display windows, "cleared for approach" and "cleared to land" instructions. When the pilot receives this information from ATC, he depresses the acknowledge key, completes the instruction, and presses another key to indicate completion.

In actual operation, an ATC instruction is received by the console operator in the rear seat. He enters the information in his entry keyboard and views it on his display, both of which are essentially identical to the front seat system, the only difference being that the front seat "acknowledge" key is now a "send" key. After the data are entered, the console operator depresses the send key, thereby transferring all information to the front seat display. At this time the command data item (heading change, for example) and the message light, mounted on the front panel, both blink to indicate arrival of a new ATC transmission. The character "M" in each of the activated command data displays illuminates to indicate which displays have changed. The pilot then depresses the acknowledge key to indicate receipt of the message. The M character remains on until he depresses the appropriate display key to indicate not only receipt of the message but accomplishment of it. At this time, the message light and the M character both are off, but the items remain on display until replaced by new entries.

As an approach continues, new command data are acquired as needed to continue the approach.



FRONT CONSOLE

Figure 7. Features of pilot's display and keyboard.

As the pilot descends to within 30.5 m (100 ft) of his Decision Height or Minimum Descent Altitude, a red light mounted at the top of the FDC holding bracket begins to flash as a warning for the pilot to monitor carefully his descent altitude.

The two display windows located just above the clearance lights were not used in this study, although the right window does show a number indicating in which mode the system is operating. These spare display windows were provided in order that the system might be expanded for future use by the NASA Langley Research Center.

Conduct an Inflight Study

Simulator Pretest

The Flight Data Console was pretested during two hours of simulator flight using the NASA Langley General Aviation Simulator. This served the dual purpose of examining the operation of the console as well as testing the adequacy of data-collection instruments. The principal problem noted during the simulator runs was one of alerting the pilot as new information is presented on the FDC. As a result, a blinking red "message" signal was placed on the pilot's instrument panel adjacent to the ADF indicator and directly within the pilot's primary scan pattern. Subsequent testing showed this to be a successful solution.

Another problem noted during the simulator pretest was the inability of a subject pilot to receive unusual ATC commands such as "Make a 360-degree turn for spacing." Since in any later operational use of the FDC concept, it is presumed that there will always be a backup voice channel, it was decided to simulate such a channel for the evaluation flights. A one-way intercom system was installed which allows the safety pilot, in the right seat, to transmit unusual ATC commands to the subject pilot through the intercom set. However, except for atypical commands which could not be programmed through the FDC, the subject pilot was unable to hear any ATC communications.

Aircraft Installation

The Flight Data Console was installed in a twin-engine Aztec aircraft. This aircraft was selected since it has adequate interior dimensions to allow installation of the console, is stable in flight, and can be mastered rapidly by multi-engine rated pilots with no prior flight time in the aircraft. The Aztec also is a popular twin and is considered typical of the general aviation fleet.

Figure 5 shows the installation of the Flight Data Console in the front-seat area of the Aztec aircraft. The front console ideally would be located at some point on the instrument panel or on the pilot's control yoke so it might be incorporated easily within the instrument scan pattern. The final positioning behind the throttle quadrant was accepted as a compromise to avoid costly and time consuming aircraft redesign approval and retrofit of such equipment.

Both the front and rear seat consoles are mounted in adjustable brackets, with the power unit contained within the copilot's seat-back pocket, as seen in Figure 8. The mounting brackets lock into the aircraft front and rear seat runners, using special attachments. Figure 8 also shows the location of controls for the message alert light, the DH/MDA warning light, and the intercom system.

The location of the rear seat console between the two seats, as seen in Figure 9, permits operation from either side. Both fore and aft console mounting brackets provide adjustable post lights for night operation. Power for these lights is obtained through a temporary installation using the aircraft electrical system. The message alert light and the DH/MDA warning light also are operated from this source.

The primary message alert signal is located on the aircraft instrument panel (Figure 5). This light, which flashes concurrently with the sending operation, is activated by the console operator through a control box located beneath the rear console (Figure 8). There also is a warning light on the front of the front seat console mounting bracket which is flashed, by the console operator in the rear seat, as the aircraft reaches an altitude of 30.5 m (100 ft) above the DH/MDA altitude.

Subject Pilots

Nine pilots were used in the project, one for pretest and eight for evaluation flights. All subjects possessed either a private or commercial license and all had multi-engine and instrument ratings. With one exception, all pilots were obtained through informal contacts at the Manassas, Virginia, airport.

Appendix A shows the flight experience of the subject pilots. One pilot, a test pilot from the NASA Langley Research Center, was atypical in terms of flight experience, having 7,000 hours of total flight time. The remainder ranged from 350 to 1,700 flight hours. Again with one exception, instrument flight time ranged from 20 to 225 total hours. As a measure of currency, instrument time in the last six months was obtained. This averaged to 13.6 hours for the group. Of the eight subject pilots, four were found to have had previous flight time in an Aztec/Apache type aircraft.

Evaluation Flights

The inflight evaluation phase consisted of four flights. The first flight was preceded by an indoctrination session, lasting about one hour, during which the operation of the Flight Data Console was demonstrated and an introduction given to the Aztec aircraft. The four flights were:

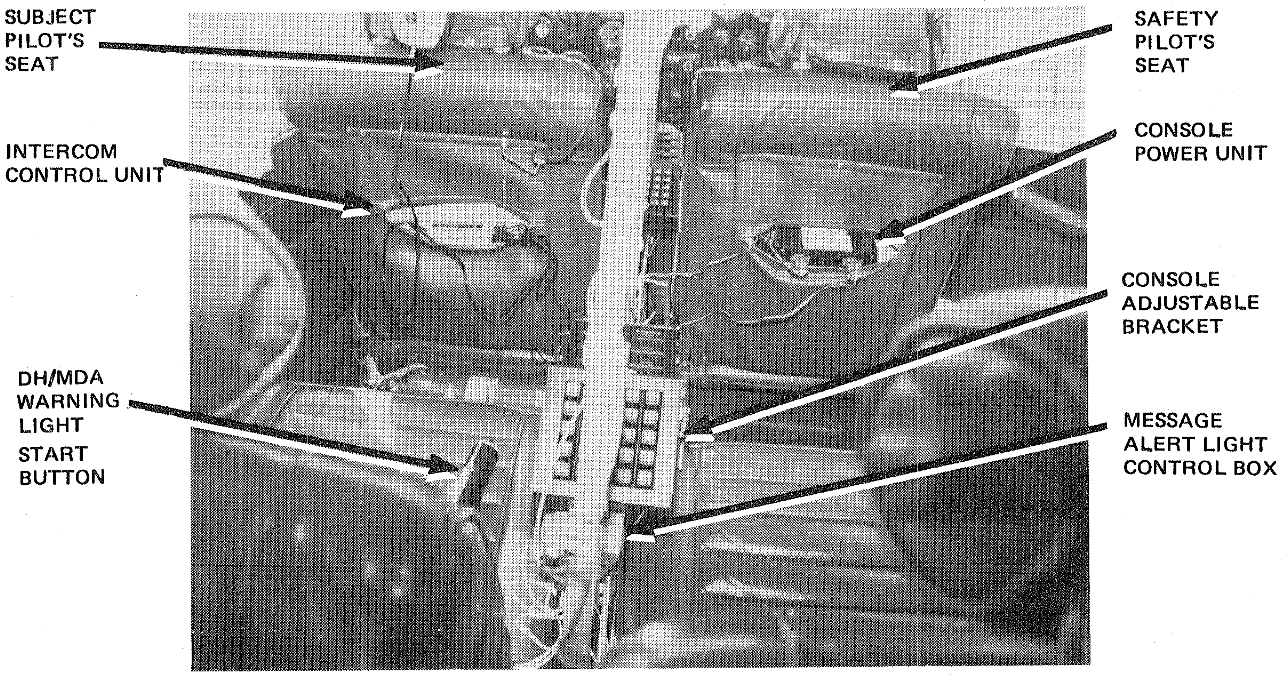


Figure 8. Location of ancillary controls for the rear-seat FDC operator. (Photograph taken from rear of aircraft cabin facing forward.)

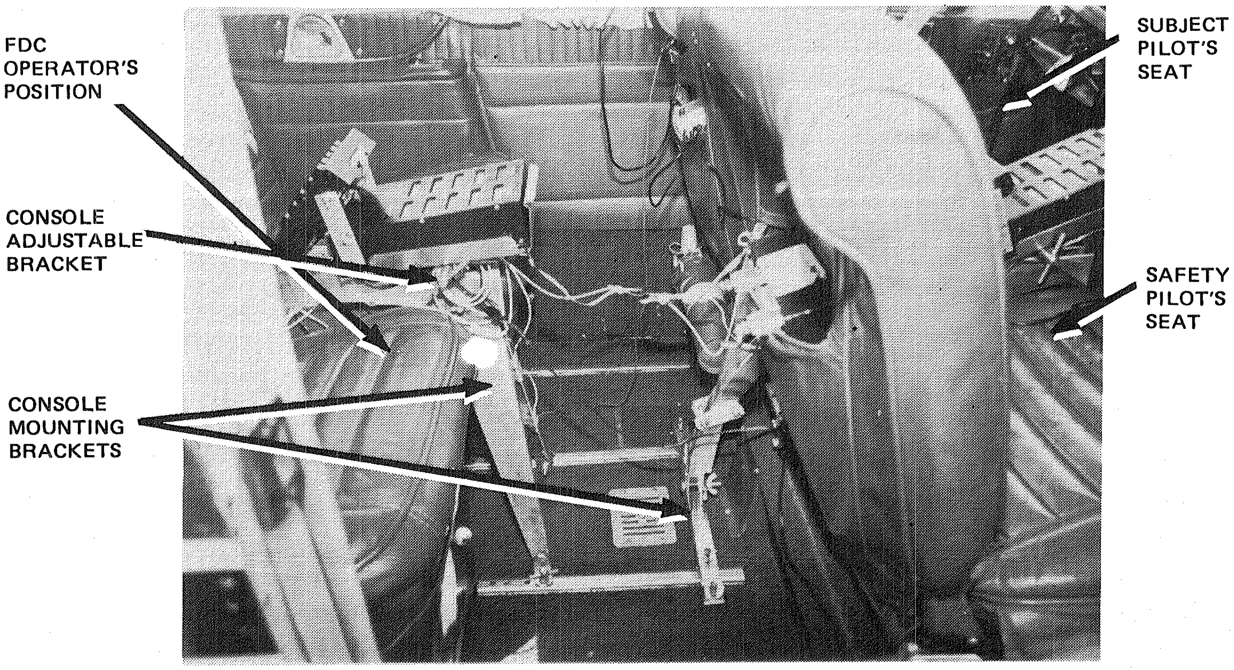


Figure 9. Installation of rear-seat Flight Data Console.

Flight A (two pilots)—In this flight, the subject pilot flew with an instrument-rated copilot and was free to use the copilot in any way he desired. In order not to bias the subject pilot, specific ways for use of a copilot (communications, chart handling, etc.) were not mentioned. The only restriction was that the copilot could not actually fly the aircraft. Flight with a fully qualified instrument-rated copilot was considered optimum in terms of reducing workload and making the flight as proficient and safe as possible. Therefore, this flight was intended to provide a baseline against which other flights might be compared.

Flight B (one pilot-FDC/memory)—Here the pilot was alone, in the sense that the safety pilot did not participate. The subject pilot used the Flight Data Console as a data storage system (memory aid) to assist during each instrument approach.

Flight C (one pilot-no FDC)—This is the customary single-pilot instrument flight. No special aids were available to the pilot and again the safety pilot did not participate. This is the type of flight which apparently needs improvement if the accident rate is to be reduced.

Flight D (one pilot-FDC/ATC)—In this flight, all approaches were flown using Air Traffic Control information provided through the Flight Data Console.

Flights A and B both were flown under daylight conditions in the late afternoon. The order of flight was counterbalanced, with half of the pilots flying an A/B program and half flying a B/A program. A comparison of these two flights was intended to indicate how a formalized data storage system, such as the FDC, might serve to provide some of the same kind of help obtained from a copilot.

Flights C and D were flown at night, on some occasions under actual instrument conditions. In any event, they were all flown as instrument flights, although a hood was not used. A comparison of these two flights, the order of which again was counterbalanced, should indicate the extent to which an ATC-interactive Flight Data Console could improve the single-pilot IFR flight situation.

Standard Flight Plan

Each of the four flights lasted for approximately one and one-half hours and included four instrument approaches. Each flight was flown on an IFR flight plan out of Manassas airport (Harry P. Davis Field). To the extent that traffic conditions allowed, a standard flight plan was followed, as shown in Figure 10. Departure course was to the Casanova VOR. However, ATC quickly vectored the aircraft toward Dulles airport for an ILS approach. This was followed by an NDB approach back to Manassas, and then a VOR approach to the Warrenton-Fauquier airport, operating from the Casanova VOR. Next, an ASR approach was made back to Dulles, followed by a VFR return to the Manassas airport. All approaches were made to minimum altitude except in the rare instance when ATC required a landing. The reason for the fixed flight plan, as opposed to a randomized order for making the approaches, was that this sequence was found to be most economical in terms of time and fuel and was most logical in terms of Dulles approach procedures.

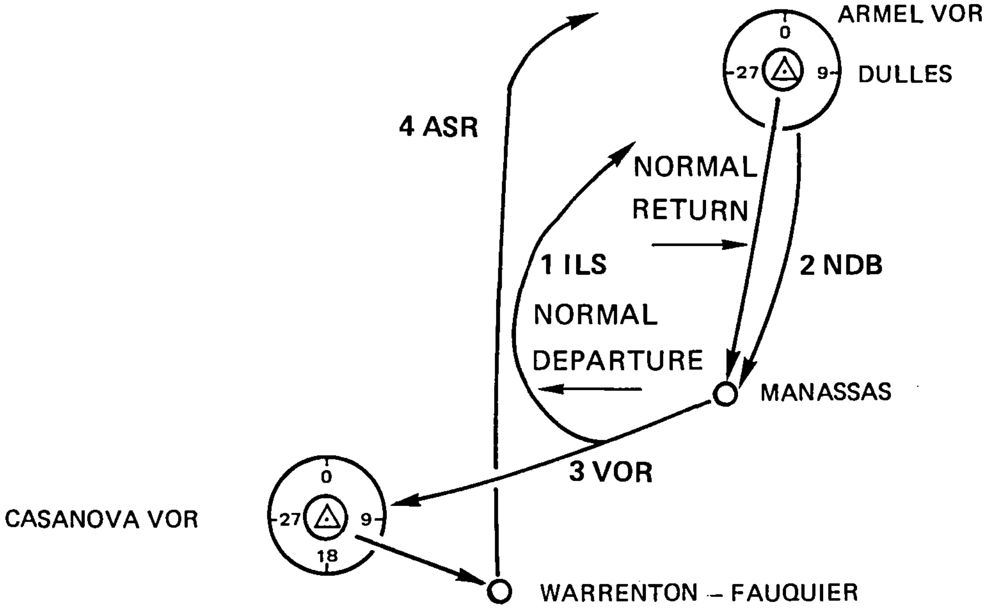


Figure 10. Standard flight plan for evaluation flights.

Data Collection Procedures

Data recording forms were prepared for completion during and after each evaluation flight. The three classes of information collected were:

Objective Measures. Measures of flight proficiency were recorded by the safety pilot during each approach. These measures included:

- Missed instructions
- Instructions followed improperly
- Response time, in seconds, from completion of controller message to start of flight maneuver
- Flight path deviations including changes in heading and altitude
- Descent below Minimum Descent Altitude.

Safety Pilot Ratings. The safety pilot rated the adequacy of flight proficiency at the end of each approach, using a ten-point rating scale which extended from "unsatisfactory" to "excellent." He also added comments concerning any unusual aspects of the approach.

Subject Pilot Ratings and Comments. At the conclusion of a flight, the subject pilot was asked to evaluate his performance for each of the four approaches made during that flight (ILS, VOR, NDB, and ASR) using the same ten-point scale as employed by the safety pilot. He was asked to make two such evaluations, the first dealing with the adequacy of the approach and the second covering the workload experienced during the approach. This was followed, again, by general comments on unusual problems.

Specific questions were asked which pertained only to specific flights. For Flight A, the question concerned the extent to which the copilot was of help. For Flight B, the question dealt with the help provided by the Flight Data Console while serving as a memory aid, its good and bad points, and the extent to which it served as a copilot. For Flight D, the question concerned the help provided by the Flight Data Console when it served as a replacement for ATC voice communications, and its good and bad points in that mode of operation.

Following the completion of all flights, the subject pilot was asked to rank, using a scale ranging from one to four, the four flights according to how safe a flight was felt to be, the workload imposed by the conditions of the flight, and the personal preference (or acceptance) of the pilot for each flight.

RESULTS AND DISCUSSION

There are two features of this project which influence how the results are presented and, more important, how they should be interpreted. The first is that this is a *proof of concept* study. It is not a field evaluation of a new item of cockpit instrumentation. The second is that it is a *field study*. As such, it is subject to all the advantages and disadvantages of such investigations.

A proof of concept study validates an idea or an approach to a solution. The setting, procedures, and equipment needed to present the concept are not legitimately part of the evaluation. The only reasonable question is "Does the concept appear to work?" In this study, the evaluation is concerned primarily with the extent to which the introduction of a digital data link system for ATC communications might reduce single-pilot workload and thereby improve general aviation safety. Additional considerations were to determine pilot acceptance for such a change and to identify human factors issues which would influence the effectiveness of a digital data link system, as represented in this instance by the Flight Data Console. The adequacy of the engineering design of the FDC as a cockpit instrument is of little concern.

The fact that this project was conducted in the field has considerable bearing on interpretation of results. The principal advantages of a field study, and these are major ones, are twofold. First, realistic stresses and contingencies automatically are built into the experimental plan. Second, the results can immediately be applied to operations in the real world. There is no question concerning the accuracy of extrapolation, as often is found with results from simulation work.

The opposite side of the coin presents certain disadvantages for field studies. There is the obvious lack of total control over the conduct of the experiment. If Air Traffic Control, faced with a deluge of DC-10s and 747s, asks you to land just as you are preparing to measure missed approach proficiency, you land. That's all. There also is a noticeable loss of experimental precision during field work. The ability to measure flight path deviations during moderate turbulence inflight, for example, is a far cry from what can be done in a simulator. Therefore, one finds that certain measures simply cannot be made inflight and that the accuracy of measurement for what can be done often is poor.

Use of Copilot

The roles of crewmembers and their working interrelationships are carefully delineated for airline operations. In general aviation, since so much flying is done with a single pilot, little if any attention has been given to crewmember roles and, in particular, to the way in which a copilot might be used. Yet, a copilot can make a real contribution to flight safety by assuming some of the cockpit tasks and lessening the workload on the pilot. This is especially true during instrument flight. But the potential contribution of the copilot is wasted if the pilot chooses, by virtue of preference or flying style, not to use his services in any way.

In this project, the eight subject pilots were asked, just prior to Flight A, how they normally used a copilot and whether such use made IFR flight easier, reduced the workload, or made it safer. Results are presented in Appendix B. This shows that a copilot is most frequently used to aid with communications and radio work. It is of interest that not all pilots felt that use of a copilot makes an IFR flight any safer or reduces the workload.

Appendix B also presents results of a question concerning the most difficult aspect of single-pilot IFR flight. The responses of the pilots encompassed seven items, with radio work/communications *not* being one of the items. For whatever reasons, the services of a copilot do not seem to be applied to those tasks which are considered most difficult.

At the completion of Flight A, pilots were asked "How was the copilot of most help to you?" Responses are presented in Table 3. These results closely match those obtained with the preflight questionnaire. Again, the principal use of a copilot is to assist with radio communications. Although not shown in these responses, the safety pilot reported that only one of the eight subject pilots asked for altitude call-outs during Flight A, even though four instrument approaches to altitude minimums were made during this flight.

Table 3

Crew Activities
—Use of Copilot—

Assist With	Number
Radio Communications	6
Radio Navigation	1
Navigation Charts	1
IFR Procedures	1
Missed Approach Procedures	1
Aircraft Familiarization	3

The above results show great disparity in the manner in which different pilots use the services of a qualified copilot during IFR flight. The most frequent use, presumably to reduce the workload of the pilot, is with radio communications. In one use with obvious importance for flight safety, that of providing altitude call-outs during instrument approaches, the services of the copilot are rarely employed. This infrequent use of copilot services undoubtedly is due to training, i.e., general aviation pilots typically are not trained in dual pilot operations.

Objective Measures of Performance

The use of objective measures of performance, taken inflight, was considered most desirable. Such information could augment the questionnaire responses of subject pilots and the safety pilot and aid in the evaluation of the different flight regimes. The objective measures sought included missed instructions, instructions followed improperly, response time following receipt of an ATC command, flight path deviations in heading and altitude, and descent below minimum altitude.

For a number of reasons, the attempt to obtain objective measures was discontinued during the project flights, with one exception. It was soon discovered that obtaining a systematic and accurate measurement record for each of the variables considered would require extensive pretesting of procedures, additional training for project personnel, additional flight time, and better cockpit recording equipment. All of this was beyond the resources of the project. In addition, there was no real feeling that these measures would add appreciably to an evaluation based on the systematic reports provided by subject pilots and the safety pilot.

An example of the problems encountered is found in the measure of "Time to respond" following a command from a ground controller. When the command was given through the voice channel, almost invariably the pilot began the maneuver before the command was completed. Thus for the command "Turn left to a heading of 210 degrees. Descend to and maintain 1,700 feet" the aircraft usually was well into a left roll before the instruction was completed.

When the Flight Data Console was used to provide ATC commands, the procedures required of the pilot were much different. In this case, he needed to observe the message light, check the display panel for the instruction, depress the acknowledge button, and start the maneuver. However, frequently pilots began this maneuver prior to pushing the acknowledge button. Again, this made precise measurement of response time essentially impossible.

Problems such as these introduced so much error into the objective measurement scheme that the process was soon abandoned. This, of course, does not mean that objective measures of performance cannot be obtained inflight. It merely points to the complexity and difficulty of the task and makes it quite clear that when such measures are needed, obtaining them must be of central concern. This was not the case here.

One objective measure was pursued through all flights. This was the recording of instances of descent below Minimum Descent Altitude during the various approaches. Table 4 presents the results of these recordings. During all flights, there were five instances in which a pilot continued his descent below the MDA. Surprisingly, two of these instances occurred when the subject pilot was free to use the safety pilot as a copilot. Had the copilot been requested to call out descent altitudes, these two instances could have been avoided. This clearly points out that general aviation pilots do not have the training or insight to use a copilot to full advantage.

Table 4

Descent Below Minimum Altitude

Flight	0-50 ft	51-100 ft	101-150 ft
A (Copilot)	√	√	
B (FDC/Memory)	√	√	√
C (Single Pilot)			
D (FDC/ATC)			

√= One Event

There were three instances of descent below MDA when the Flight Data Console was being used as a memory aid. These violations occurred even though the Minimum Descent Altitude was clearly shown on the display. Obviously, if the FDC is to be used in this mode, more attention must be given to including it in the instrument scan during the approach.

Since only eight pilots served as subjects and since there were only five instances of unauthorized descent, one must exercise caution not to make too much of these results. However, two conclusions, one firm and one tentative, might be drawn. First, general aviation pilots should know how to use a copilot when one is aboard. Commercial air carriers have required altitude call-outs from the copilot for years. Second, the altitude warning signal provided by the Flight Data Console *seems* to be effective in preventing pilots from descending below minimum altitude during an instrument approach.

Workload and Performance

Workload, when it exceeds manageable limits and particularly when it is combined with speed stress, can disrupt performance. The definition of workload, as noted in the earlier review, is tenuous. The limits of workload manageability depend on the individual, his training, the task, the work context, and a host of other variables. However, one may still conclude that workload stress will impair performance. In aviation, high workload conditions occurring at a time when precision in flight is required will increase the likelihood of an accident. During a single-pilot IFR approach, it is most important that workload not be high, particularly not so high that the pilot feels it as a stress factor.

The measurement of workload was considered of such importance that it was approached in two ways in this project. In the first procedure, each pilot was asked to rate his workload, on a scale from one to ten, for each of the four approaches flown during that flight. Averaging these, a single rating of workload conditions was obtained following each of the four flights. Figure 11 shows the results. The averaged ratings indicate higher workload for Flights A and B than for Flights C and D (see Appendix C for complete ratings). This may reflect the fact that Flights A and B (in counterbalanced order) always were flown before Flights C and D (in counterbalanced order). The reduction of workload for the latter flights thus could be attributed simply to increased familiarity with the airplane and the experimental situation.

In the second procedure, pilots were asked, at the completion of the full-flight program, to rank order the four flights in terms of the workload imposed by each. Figure 12 shows the results (see Appendix D for complete rankings).

The averaged workload rankings shown in Figure 12 present a different picture than is seen in Figure 11. Here, Flights A and D are judged to have significantly less workload than Flights B and C. Since these rankings were made at one point in time, the temporal effects reflected in Figure 11 should be reduced. These rankings are believed to be a more valid indicator of actual workload conditions.

A consideration of flight conditions indicates that Flight A (copilot present) and Flight D (FDC interactive with ATC) should impose less workload than the other two flights. Certainly, whatever help a copilot provides will serve to decrease the workload, especially since the pilot was free to call on the copilot at any time he felt pressed. In Flight D, the requirement to manipulate microphones and read back clearances, as found with voice communications systems, was removed. This certainly should decrease the workload. The post-flight rankings indicate that it does.

The performance level attained during each flight was rated, on a zero (unsatisfactory) to ten (excellent) scale, following the flight by both the subject pilot and the safety pilot. Each rating represents an average of the performance on the four types of instrument approach made during the flight. Then the ratings were combined for the eight subject pilots. Results are shown in Figure 13.

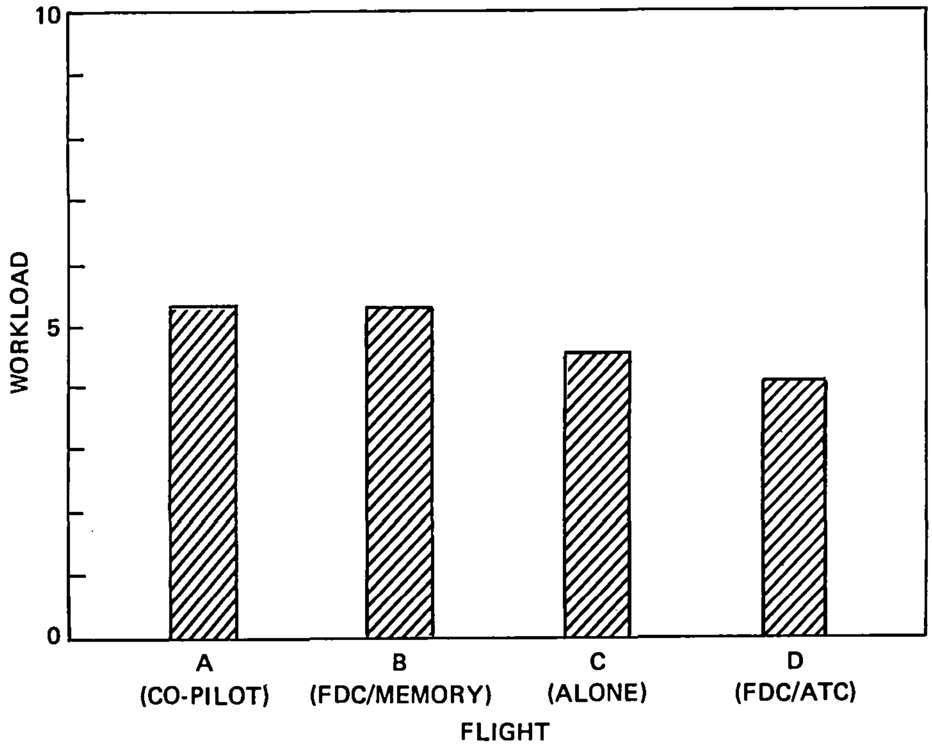


Figure 11. Average workload ratings obtained after each flight (0 = light, 10 = very heavy).

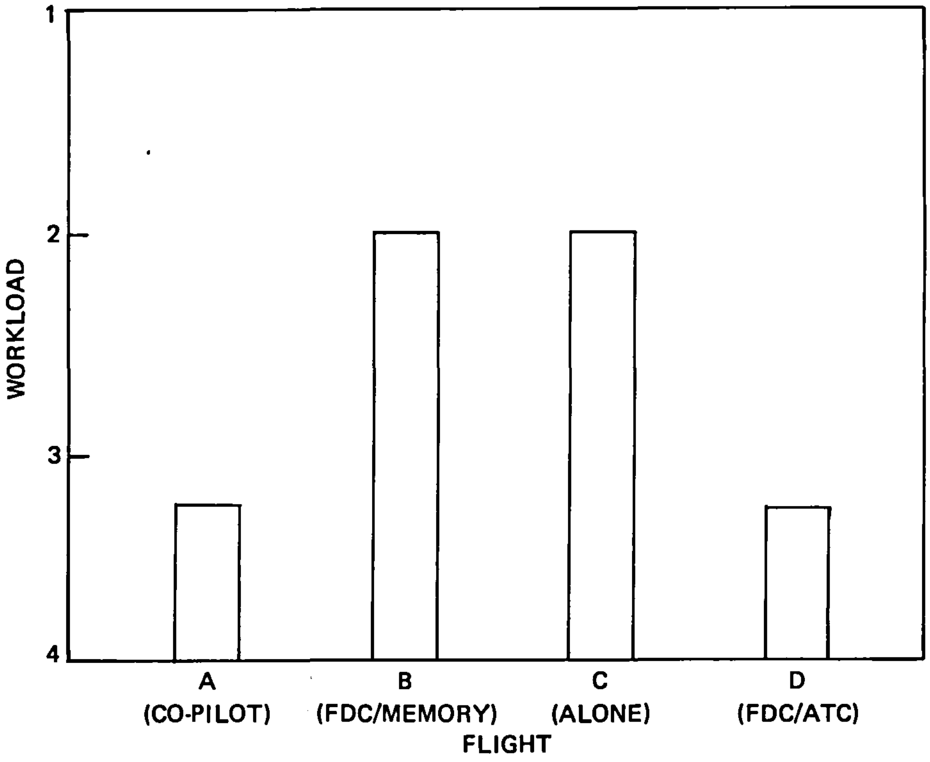


Figure 12. Average workload rankings obtained following completion of all flights (1 = heavy, 4 = very light). Note that ranking scale is inverted to allow direct comparison with Figure 11.

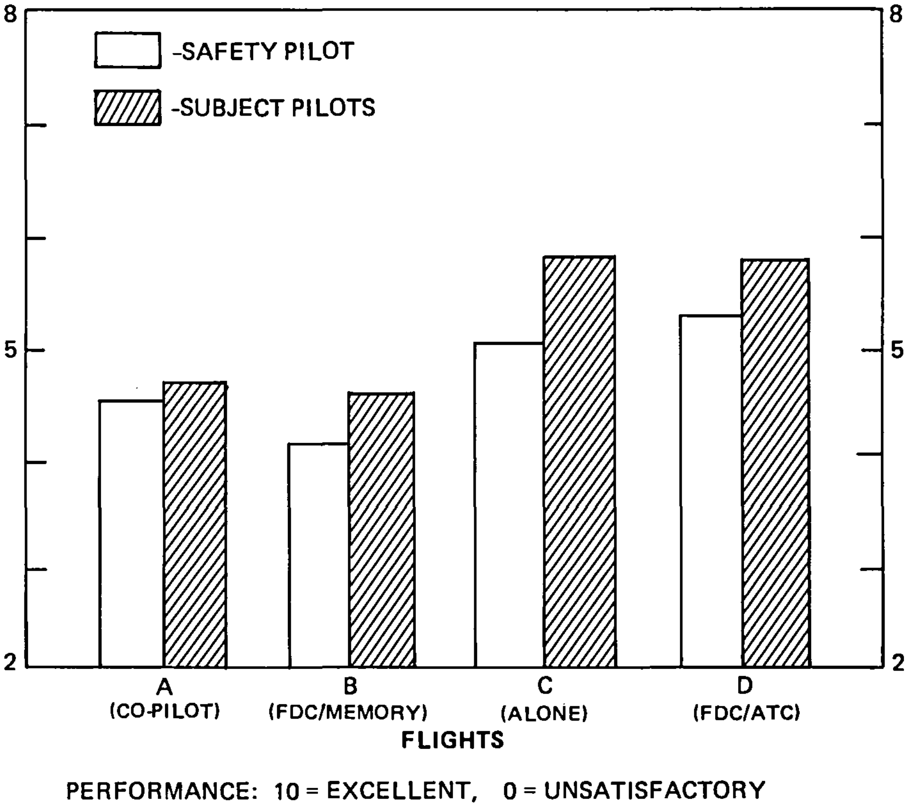


Figure 13. Judgments of flight performance by the safety pilot and by subject pilots following each flight.

Performance on Flights C and D was judged, both by subject pilots and by the safety pilot, to be better than that on Flights A and B. Again, however, an order effect might be operating. Flights C and D always occurred after Flights A and B. The simple fact that pilots were more familiar with the airplane in later flights could account for the apparent improvement in performance.

The fact of increasing experience does not affect comparisons between Flights A and B and between Flights C and D, since in these instances order of flight was counterbalanced. Half of the subject pilots flew Flight D before Flight C, for example. The counterbalancing therefore allows realistic comparisons to be made in the two cases of most interest. The results show that use of the Flight Data Console as a memory aid (Flight B) does not change performance over that found in Flight A, in which the subject pilot had a qualified copilot at his disposal. Comments by the safety pilot indicate that this lack of difference may have nothing really to do with any underlying merit of the Flight Data Console. In Flight A, most subject pilots made little if any use of the copilot. In Flight B, they were insufficiently skilled in the operation of the FDC to get any real benefit from its presence. Therefore, Flights A and B became in effect training flights for the final half of the experimental program. This is one interpretation. The fact that workload was judged higher in the FDC/Memory mode than with a copilot (Figure 12) may lead to another interpretation. The equality in performance could simply reflect the additional reserve capacity called on by pilots flying the FDC in order to maintain an acceptable level of performance.

The performance comparison of most interest is between Flight C (single-pilot IFR) and Flight D (FDC providing ATC commands). Again, there is no real difference in judged performance levels. Proficiency of flight is considered to be about the same when flying alone and using the customary voice radio procedures, or when flying with the FDC providing ATC information through a digital link. However, referring to Figure 12, we see that the workload is considered to be much higher when pilots are flying alone. This situation therefore may be one which reflects the observation by Roscoe (1979) that changes in handling and workload are not always reflected in changes in performance. Roscoe cites the comment by Spiker et al. "An evaluation procedure which relies exclusively on performance measures is inadequate. That is, a pilot with one configuration may work twice as hard as he does with another, yet achieve equal performance with both." What is seen in the comparison of Flights C and D may reflect this ability of pilots to maintain a performance standard while "compensating" for much different workload conditions. The compensation may be at a price, however, which increases the accident potential. Although performance standards were maintained under the conditions of these flights, the higher workload found under the conditions of single-pilot IFR (Flight C) could take its toll were additional tasks or emergency conditions to be introduced suddenly. Certainly the considerable increase in workload seen in single-pilot IFR, when compared with workload during use of a copilot, offers a very reasonable explanation for the fact that many more landing phase accidents occur with a single pilot operating than when two are present.

Safety and Acceptance

There are two questions, involving purely psychological dimensions, which a pilot may ask in evaluating a new flight system. These are: "Does use of the system seem to make flight any safer?" and "Would I like to use the system in my airplane?"

The dimensions of safety and acceptance obviously are correlated. No rational aviator is going to prefer a system if he feels it reduces safety of flight. Yet each of the two judgments contributes something different to a comprehensive evaluation of a flight system. Therefore pilots were asked to rank the four evaluation flights separately along each of these dimensions. The results of these rankings are presented in Appendices E and F.

The safety rankings show exactly what one would expect. There is a significant difference in the rankings for the four flight conditions, with Flight A, use of a copilot, being considered the most safe. There is an obvious measure of security in knowing that the person sitting next to you is a fully qualified instrument-rated pilot.

The acceptance rankings did not present nearly as clear a picture as was found for safety. Statistically, there was no difference among the flights in terms of pilot acceptance. However, the data do indicate a tendency for Flight B (use of the Flight Data Console as a memory aid) to be less preferred than any of the remaining three flights. Of particular interest are the rankings shown in Appendix F for Flight D (FDC used for ATC communications). Here we see that two pilots selected this system as most preferred, while another two chose it as least preferred. The next section explores some of the reasons underlying this ambivalence.

Acceptance Comments

Many factors influence the acceptance of new systems. Hopefully, the utility of the system is a primary factor, but many others, such as appearance, location, size, uniqueness, etc., may be important in establishing a final level of acceptance. Since acceptance is of such consequence in determining how equipment will be used and, in large measure, the extent to which design objectives can be achieved, every effort was made to allow pilots to express opinions concerning good and bad features of the Flight Data Console. These opinions were reviewed and placed into a limited number of categories. The following sections present typical comments, shortened somewhat for this report, and show the classification scheme used.

Positive Comments

Communications Effectiveness

"There is no confusion as to who the instruction from the ground is for."

"You can hardly miss a call."

"No misunderstanding or forgetting numbers."

Workload Reduction

"No fumbling with pencil, kneeboard, mike, or volume control."

"I found the FDC/ATC to be very easy to use and (it provided) much relief of workload."

Cockpit Conditions

"I like the quiet of the radio-free environment."

Negative Comments

Human Engineering

"Position of FDC is horrible. Could use it better if more forward."

"Position of FDC detracts from instrument scan."

"Difficult to read in daylight."

"Every time I used it, I had to screw my body into a weird contortion."

Information Restriction

"I would feel most comfortable with the FDC used in conjunction with a radio."

"Voice security blanket is significant."

"Not able to question ATC."

"FDC tends to force greater reliance on ATC than I'm ready to give."

In summary, the comments indicate that a digital data link system, as simulated by the Flight Data Console, may represent an improved ATC channel with good prospects for reducing cockpit workload. However, for the system to achieve its potential, it must be located for ease of view and operation and it should incorporate a voice channel as backup.

Air Traffic Control Implications

Development programs are underway at this time which will cause the air traffic control environment five to ten years from now to be much different. The impact for change is coming from a combination of traffic saturation, altered patterns of air travel, and significant advances in electronics and control systems engineering. Microprocessors, electronic displays, and voice-activated data entry systems will make the communications link between aircraft and Air Traffic Control a much different matter in future years.

The NASA Ames Research Center has been supporting a Demonstration Advanced Avionics System (DAAS), a development program accomplished by Honeywell Avionics Division and King Radio Corporation. The purpose is to develop the technology for an integrated avionics system for use in general aviation in the coming decade. The system uses data bussing, distributed microprocessors, and shared electronic displays. Such a system is very advanced, very expensive, and shows what the future holds in store. One part of this system includes a display whereby ATC communications can be presented to a general aviation pilot in much the same manner as was done with the Flight Data Console in this project.

The Federal Aviation Administration is supporting the development of the Discrete Address Beacon System (DABS). This system, scheduled to become operational in the mid-1980s, will provide an automatic data link connecting Air Traffic Control and other data sources to aircraft in a two-way digital transmission loop. The advantages of the DABS concept are many. It will provide more accurate tracking of aircraft than is obtained now with transponder and raw radar returns. It will be able to communicate with one aircraft to the exclusion of all others. It also will offer a pilot a broader range of routine information than he now receives, including enroute weather and enhanced terminal information. Finally, the FAA believes use of DABS will lead to improved cockpit data flow and reduced workload both for controllers and for pilots.

In its initial installation, DABS will not provide Air Traffic Control command instructions, as were presented with the Flight Data Console. However, the capability is there and it is presumed that shortly after its introduction, use of the system will be expanded to include such communications. Grayson (unpublished data) reviewed the NASA Aviation Safety Reporting System files in order to catalog the kinds of problems DABS might serve to improve. Table 5 presents his assessment of the impact of DABS on present communications problems. The improvement through use of DABS should be considerable.

Table 5

Impact of DABS Data Link on Communications Problems

Problem Code	No. of Reports	Eliminate	Mitigate	Exacerbate	No Impact
Phonetic Similarity	71	X			
Transposition	85		X		
Other Inaccuracies	792		X		
Incomplete	296		X		
Ambiguous	529	X			
Untimely	710		X		
Garbled	171		X		
Absent	1991		X		
Equipment Failure	153		?		?
Not Monitoring	553		X		

From Grayson, R.L. Unpublished report by Battele Columbus Laboratories.

The results of the present project can be applied directly to the DABS program. If DABS is to be as successful as the FAA believes and as Grayson implies, serious attention must be given to the human factors problems associated with the introduction of such a system into the general aviation flight scene.

SUMMARY AND CONCLUSIONS

General aviation is the largest and fastest growing segment in American aviation, having many more aircraft and flying many more hours than the commercial airlines. Since 1975, it has been the largest single user of the instrument flight system. Carrying roughly one-third of the people who travel intercity by air, general aviation has become an integral part of our national transportation system.

The emerging role for general aviation in air transportation is accompanied, unfortunately, by an accident rate considerably higher than that found in commercial operations. During instrument approaches, general aviation was found to have, over a two-year period, an accident rate 17 times as high as that of the carriers. A closer review of these accidents shows that almost 90 percent are attributed wholely or in part to pilot error. Of these pilot error accidents, the preponderance occur during single-pilot IFR flight.

The conditions of single-pilot instrument flight, particularly without an autopilot, show heavy workload conditions. Much of this workload is a function of critical requirements for data management and information processing of ATC data items. The reduced number of accidents when a copilot is aboard is believed to result from the sharing of the data management tasks.

In this project, a Flight Data Console (FDC) was developed to allow simulation of a digital communications link to replace the current voice communications system. The voice system requires manipulation of radio equipment, read-back of clearances, and mental storage of critical information items, all contributing to high workload. This study was a human factors evaluation of a digital communications system, as represented by the Flight Data Console, to determine how such a system might reduce cockpit workload, improve flight proficiency, and be accepted by general aviation pilots.

The Flight Data Console was evaluated inflight, using general aviation pilots, in order to encompass realistic conditions of cockpit workload and reasonable inflight stress. Instrument approaches were flown into Washington Metropolitan Area airports. In one flight condition, the Flight Data Console allowed a full instrument approach to be completed with no voice communications between the pilot and ATC. The performance of subject pilots, as well as problems encountered by them, was recorded by a safety pilot. Extensive interviews were conducted with subject pilots at the completion of the flights.

The results of this project support the following conclusions and recommendations.

Inflight Data Management

1. There are no formalized rules for the management of inflight data in general aviation except as imposed by the nature of the tasks. This results in considerable variability in the manner in which information processing is done. Some pilots jot data on knee-pads; others rely entirely on memory; still others manipulate panel instruments as an aid. Results of this study indicate more elaborate electronic devices, serving only as memory aids, are of little value.

2. General aviation pilots tend either not to use the services of a qualified copilot or to use him poorly. The most frequent use, presumably to reduce workload, is with radio communications. In one use with obvious importance for flight safety, that of providing altitude callouts during instrument approaches, the services of the copilot are rarely employed.

Use of a Digital Display (Flight Data Console)

3. Instrument flight, including approach and landing, can be accomplished by general aviation pilots receiving all Air Traffic Control communications through a digital data link system like the Flight Data Console.

4. The cockpit workload during an instrument approach with ATC providing information through the Flight Data Console was judged by subject pilots to be less than that found when flying alone and using the normal voice communications link. This is possibly the most significant finding of the study. Use of the FDC, in its ATC interactive mode, reduced workload to the point where it matched that found when a qualified copilot was present.

5. Flight performance using the FDC was comparable to that achieved in single-pilot IFR flight. However, the considerably greater workload when flying alone, using normal voice channels, would imply that the maintenance of flight proficiency is at some cost to the pilot's reserve work capacity.

6. A digital data link communications system is entirely feasible for general aviation flight operations. There are, however, a number of human factors issues which must be addressed if such a system is to achieve its potential. Great care must be taken in placing the sytem in the cockpit. Message content must be matched to pilot needs, instrument scan must be

considered, and display complexity should not be great. In addition, a voice channel allowing instant communication with the controller, if necessary, should be included as a backup system.

Future Air Traffic Control Environment

7. The direction of efforts supported by the FAA, NASA, and industry is toward presentation of cockpit information through electronic systems. Results of this study indicate that ATC command information, including maneuvering instructions, can be provided to general aviation pilots through a digital data-link display rather than through a voice link. System efficiency (including capacity) should increase through the elimination of a read-back requirement and a reduction in errors of interpretation. The present study supports movement toward use of digital communications and electronic displays.

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APPENDICES

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APPENDIX A

PREFLIGHT QUESTIONNAIRE DATA

Flight Experience of Subject Pilots

(Time in hours)

Pilots	Total Flight Time	Instrument Flight Time	Instrument Time Last 6 Mos.	Time in Aztec/Apache
1	1550	130	22	7
2	935	75	1.5	14
3	350	20	10	13
4	450	50	0	0
5	1700	225	25	20
6	1000	170	20	0
7	7000	1000	5	0
8	500	50	25	0
Average	1685.6	215.0	13.6	6.8

APPENDIX B

PREFLIGHT QUESTIONNAIRE DATA

IFR Responses

When flying with a qualified instrument pilot as copilot, how do you use his services?

Activity	Number
Radio Work (communications)	7
Navigation/Charts	3
Flap/Gear Operation	2
Check List	1
Flight Procedures	1

Does having a copilot on an IFR flight:

	Number	
	Yes	No
Make the flight easier?	7	1
Reduce the workload?	6	2
Make the flight safer?	7	1

What is the most difficult aspect of single-pilot IFR flight?

	Number
Missed Approach	2
Approach Planning/Procedures	2
Traffic Observation	1
High Density Area Operations	1
Workload	1
Take-Off & Climb Procedures	1
Chart Handling	1

APPENDIX C

WORKLOAD RATINGS BY SUBJECT PILOTS AT COMPLETION OF EACH FLIGHT

10 = very heavy workload
5 = moderate workload
0 = light workload

(Values shown are averages of ratings for the ILS, VOR, NDB and ASR approaches comprising each flight.)

	Flights			
Pilots	Copilot A	FDC used as memory aid B	Single-pilot C	FDC/ATC interactive D
1	5.25	5.0	4.0	3.12
2	4.75	6.75	6.5	2.0
3	3.67	5.0	4.75	4.5
4	6.0	4.25	4.75	5.5
5	5.5	5.0	5.0	5.0
6	5.3	5.0	4.0	5.0
7	6.87	5.67	6.0	5.75
8	4.0	4.75	1.0	1.0
Average Rating	5.17	5.18	4.5	3.98

APPENDIX D

WORKLOAD RANKINGS BY SUBJECT PILOTS AT COMPLETION OF ALL FLIGHTS

4 = lightest workload

1 = heaviest workload

	Flights			
Pilots	Copilot A	FDC used as memory aid B	Single-pilot C	FDC/ATC interactive D
1	4	1	2	3
2	2	3	1	4
3	4	2	1	3
4	4	2	1	3
5	3	2	4	2
6	2	3	4	4
7	4	2	1	3
8	3	1	2	4
Average Ranking	3.25	2.0	2.0	3.25

Friedman's non-parametric test: T=7.8; df=3; p=.05.

The null hypothesis is rejected (p=.05).

There is a significant difference among the flights in the workload judged to be imposed. Flight A (use of copilot) and Flight D (use of Flight Data Console interactive with Air Traffic Control) are considered to have a reduced workload as compared to Flights B and C.

APPENDIX E

SAFETY RANKINGS BY SUBJECT PILOTS AT COMPLETION OF ALL FLIGHTS

4 = most safe

1 = least safe

	Flights			
Pilots	Copilot A	FDC used as memory aid B	Single-pilot C	FDC/ATC interactive D
1	4	1	3	3
2	3	1	2	4
3	4	2	1	3
4	4	3	2	1
5	4	4	4	3
6	4	1	2	3
7	4	3	1	2
8	4	1	3	2
Average Ranking	3.87	2.0	2.25	2.62

Friedman's non-parametric test: $T=10.65$; $df=3$; $p=0.02$.

The null hypothesis is rejected ($p<.05$). There is a significant difference among the flights in their judged safeness. Obviously, Flight A (use of copilot) is considered to be safer than the other three.

APPENDIX F

ACCEPTANCE RANKINGS BY SUBJECT PILOTS AT COMPLETION OF ALL FLIGHTS

4 = most preferred

1 = least preferred

	Flights			
Pilots	Copilot A	FDC used as memory aid B	Single-pilot C	FDC/ATC interactive D
1	4	1	3	2
2	2	1	3	4
3	4	2	1	3
4	4	3	2	1
5	4	2	3	1
6	2	1	4	3
7	4	2	1	3
8	2	1	3	4
Average Ranking	3.25	1.6	2.5	2.6

Friedman's non-parametric test: T=6.45; df=3; p=.09.

The null hypothesis is accepted ($p < .05$). There is no statistical difference among the flights in terms of pilot acceptance. An inspection of the totals, however, shows a tendency for Flight B (use of Flight Data Console as a memory aid) to be somewhat less preferred than the remaining three flights.

LIST OF ABBREVIATIONS

ASR	Airport Surveillance Radar
ASRS	Aviation Safety Reporting System
ATC	Air Traffic Control
ATIS	Automatic Terminal Information Service
DAAS	Demonstration Advanced Avionics System
DABS	Discrete Address Beacon System
DH	Decision Height
FDC	Flight Data Console
IFR	Instrument Flight Rules
ILS	Instrument Landing System
MDA	Minimum Descent Altitude
NDB	Non-Directional Radio Beacon
VFR	Visual Flight Rules
VHF	Very High Frequency
VOR	Very High Frequency Omnidirectional Range

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16. Abstract

A Flight Data Console (FDC) was developed to allow simulation of a digital communications link to replace the current voice communication system used in Air Traffic Control. The voice system requires manipulation of radio equipment, read-back of clearances, and mental storage of critical information items, all contributing to high workload, particularly during single-pilot operations. This was an inflight study to determine how a digital communications system might reduce cockpit workload, improve flight proficiency, and be accepted by general aviation pilots.

Results show that instrument flight, including approach and landing, can be accomplished quite effectively using a digital data link system for ATC communications. Workload for single-pilot flight, using the FDC, matched that found when a qualified copilot was present. Comments by subject pilots identified a number of human factors issues (placement, size, message format, etc.) which influence the acceptance of a digital system.

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