DOT/FAA/AM-96/15

Office of Aviation Medicine
Washington, D.C. 20591

# Use of Off-The-Shelf PC-Based Flight Simulators for Aviation Human Factors Research

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April 1996



Final Report



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U.S. Department of Transportation
**Federal Aviation Administration**

# NOTICE

**Technical Report Documentation Page**

| | | |
|---|---|---|
| 1. Report No. DOT/FAA/AM-96/15 | 2. Government Accession No. | 3. Recipient's Catalog No. |
| 4. Title and Subtitle<br>Use of off-the-shelf PC-based flight simulators for aviation human factors research | | 5. Report Date<br>April 1996 |
| | | 6. Performing Organization Code |
| 7. Author(s)<br>Dennis B. Beringer, Ph.D. | | 8. Performing Organization Report No. |
| 9. Performing Organization Name and Address<br>FAA Civil Aeromedical Institute<br>P.O. Box 25082<br>Oklahoma City, OK 73125 | | 10. Work Unit No. (TRAIS) |
| | | 11. Contract or Grant No. |
| 12. Sponsoring Agency name and Address<br>FAA Office of Aviation Medicine<br>Federal Aviation Administration<br>800 Independence Avenue, SW.<br>Washington, DC 20591 | | 13. Type of Report and Period Covered |
| | | 14. Sponsoring Agency Code |
| 15. Supplemental Notes | | |

16. Abstract

Flight simulation has historically been an expensive proposition, particularly if out-the-window views were desired. Advances in computer technology have allowed a modular, off-the-shelf flight simulation (based on 80486 processors or Pentiums) to be assembled that has been adapted, with minimal modification, for conducting general aviation research. This simulation includes variable flight instrumentation, forward, 45 and 90 degree left external world views, and a map display. Control inputs are provided by high-fidelity analog controls (e.g., damped and self-centering yoke, high-performance throttle quadrant, gear, flap, and trim controls; and navigation radio frequency select). The simulation is based upon two commercially available flight simulation software packages, one originally designed as an instrument flight trainer and the other as a "game"-type flight simulation. The provisions of these packages are discussed highlighting their particular research capabilities. as well as their limitations. The comparatively low cost and ease of assembly/integration allow multiple "standardized" systems to be distributed for cooperative inter-laboratory studies. The approach appears to have utility for both research and training.

| 17. Key Words | 18. Distribution Statement |
|---|---|
| Personal Computer-Based Aviation Flight Simulation, Simulator Research, Instrument Flight Psychology, Applied Psychology | Document is available to the public through the National Technical Information Service, Springfield, Virginia 22161 |

| 19. Security Classif. (of this report) | 20. Security Classif. (of this page) | 21. No. of Pages | 22. Price |
|---|---|---|---|
| Unclassified | Unclassified | 17 | |

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

## FOREWORD

This is the first study of a series planned to be conducted as a part of the CAMI general aviation (GA) human factors research program. The following mission statement guides the overall effort:

> Conduct applied human factors research in the laboratory and in the field on carefully selected GA problems, to obtain objective, scientifically derived data which will aid in identifying affordable options for reducing the risk exposure, and number of incidents and accidents in the general aviation community, and which will serve to enhance GA pilot performance under non-routine flying conditions.

The CAMI general aviation human factors research program is consistent with the FAA policy statement on general aviation, promulgated by the FAA Administrator in 1993, and the goals of the Flight Standards General Aviation Action Plan, distributed in 1992. Development of the program was coordinated with AFS-800, AFS-200, AIR-2, ACE-100 and with guidance by the General Aviation Coalition, accident prevention and pilot training working groups. FAA human factors program management support was provided by AAR-100.

The CAMI GA human factors research program incorporates both near-term and far-term objectives. The primary near-term focus of the program, stressed by the General Aviation Coalition, is to develop approaches to current general aviation problems so that payoffs in reduced risk exposure, accidents and incidents can be realized relatively soon. The long-term focus of the program is directed toward future problem solutions utilizing advanced technologies that require longer development times and more substantial funding commitments. These two program approaches are non-redundant, mutually supportive, and provide for timely human factors research on general aviation safety and pilot performance issues with payoffs distributed over time.

This report resulted from a FY'94-95 effort to consider GA cockpit innovations that were affordable and would promise a more-or-less immediate enhancement of GA pilot performance. Mr. Thomas C. Accardi, Director, Flight Standards Service, AFS-1, sponsored the study. Mr. Robert A. Wright, Manager, General Aviation & Commercial Division, AFS-800 and Mr. Michael, L. Henry, AFS-801, provided project oversight. Dr. Thomas McCloy and Mr. Ronald Simmons, Human Factors Division (AAR-100) of the Office of Aviation Research, provided human factors program management.

The CAMI General Aviation Research Simulation Facility, Human Factors Research Laboratory (HFRL), was used in conducting the study. Dr. Robert E. Blanchard is HFRL manager. Dr. Dennis Beringer was principal investigator, assisted by Mr. Robert Touchstone and Mr. Howard Harris.

# Use of Off-The-Shelf PC-Based Flight Simulators for Aviation Human Factors Research

## INTRODUCTION

Flight simulation for training has been available in one form or another for over 75 years (Edwin Link's trainer in 1929; a simulation in France in 1917). Some of the early simulators were really more on the order of "trainers," representing a class of devices and not any specific aircraft. This was certainly true of Link's first device, which was relatively simple and was assembled from readily available components from a number of non-aviation applications. This simple device ultimately gave way to more complicated and far more expensive devices as the training community sought to approximate more closely the flight dynamics and mission environments for specific aircraft (Valverde, 1968; Eichler, 1974).

The development of the digital computer greatly accelerated advances in this field, and these digital machines now offer the opportunity for a greater dissemination of flight simulation than ever before realized. Recent developments in processor speed, video memory/bandwidth, and memory speed/density as well as small hard-disk drives with previously unheard of capacity mean that flight simulations can now be run on personal computers at reasonable update rates and with out-the-window views that provide a moderate level of scenic detail. The potential for applications in both research and training is substantial given the represented reduction in acquisition and maintenance costs and ease of use. The comparatively low cost of such systems may justify reexamination of many of the previously held beliefs concerning what the necessary criteria are for useful flight simulation.

Given the compromises that one must accept when conducting flight simulation on a personal computer, it is of definite interest to the simulation community to determine empirically how some of the specific tradeoffs engendered in the PC-based devices may affect both the efficacy of training and the applicability of research results to the real world. It is, in a very real sense, a continuation of the discussions about fidelity and its effect on both simulator task performance and learning. In these continuing discussions, answers are still sought for:

1) how much fidelity is needed for effective transfer of skills or for research data to generalize to the operational environment,
2) how much of the task can be effectively represented in simulation, and
3) how much we should pay for that box (Hopkins, 1975).

Although these are not new questions, the economics of simulation have changed such that we can now get more simulation for less capital investment. This requires us to ask the question, "If we can get more simulation for the same investment, what is the 'more' that we should ask for?" Simply getting "more" does not mean a better or more effective simulation. In most instances, however, the question of what more to ask for is not being asked because the low software costs and the proliferation of personal computers make flight simulation much more affordable and available. There is no perceived need to weigh the features against the associated costs at this level of simulation. The result is that low-fidelity flight simulation is being used by more people in more places than ever before. The economic balance point has shifted because of the positive cost curve acceleration (Figure 1) being reduced (cost: time 2), as compared with previous simulation costs (cost: time 1), which theoretically increases the expected transfer per dollar for the lower-fidelity systems. This constitutes the difference between historic discussions of flight simulation and the current weighing of the issues, where cost is now a facilitating, rather than a prohibiting, factor. Some simulation programs cost less than one-hour's rental of a single-engined aircraft. The degree of positive transfer available for such simulations needs to be assessed to determine if the actual cost of transferring a given unit of knowledge is less in these simulations than in previously available ones. Transfer in the training environment can be seen, to some degree, as similar to generalizability in the research environment. Taylor (1995) reported substantive positive transfer from such devices to the aircraft for a number of maneuvers. Other recent studies indicate that these simulations have utility for research as well (Thornton, Braun, Bowers and Morgan, 1992; Beringer, Allen, Kozak and Young, 1993; Hennessy, Wise, Koonce, Smolensky and Garland, 1995).

## SPECIFIC APPLICATION: A RESEARCH SIMULATOR

Over the past 30 years, much has been published about flight simulation for training. Although much less has been generated dealing specifically with research simulation, the balance of publications has recently shifted in that direction. Eichler (1974) made reference to the use of flight simulators for training and for engineering research and development, but virtually no mention of behavioral research as an application area. It was interesting that in their Appendix, "Examples of Simulators," Jones and Hennessy (1985) devoted five pages to engineering simulators, seven to training simulators, but only three and a half to research simulators. A quick look at the state of things in 1993 presents a picture of considerable use of simulation for behavioral research. In the Proceedings of the Human Factors and Ergonomics society annual meeting of that year, 27 presentations referenced flight simulation. Of these, 90% used it as a behavioral research tool and 10% used it for performing behaviorally oriented research on simulation.

There are a number of reasons for one to simulate flight rather than engage in the actual activity. Jones' (1967) listing of many of those justifications bears repetition here:

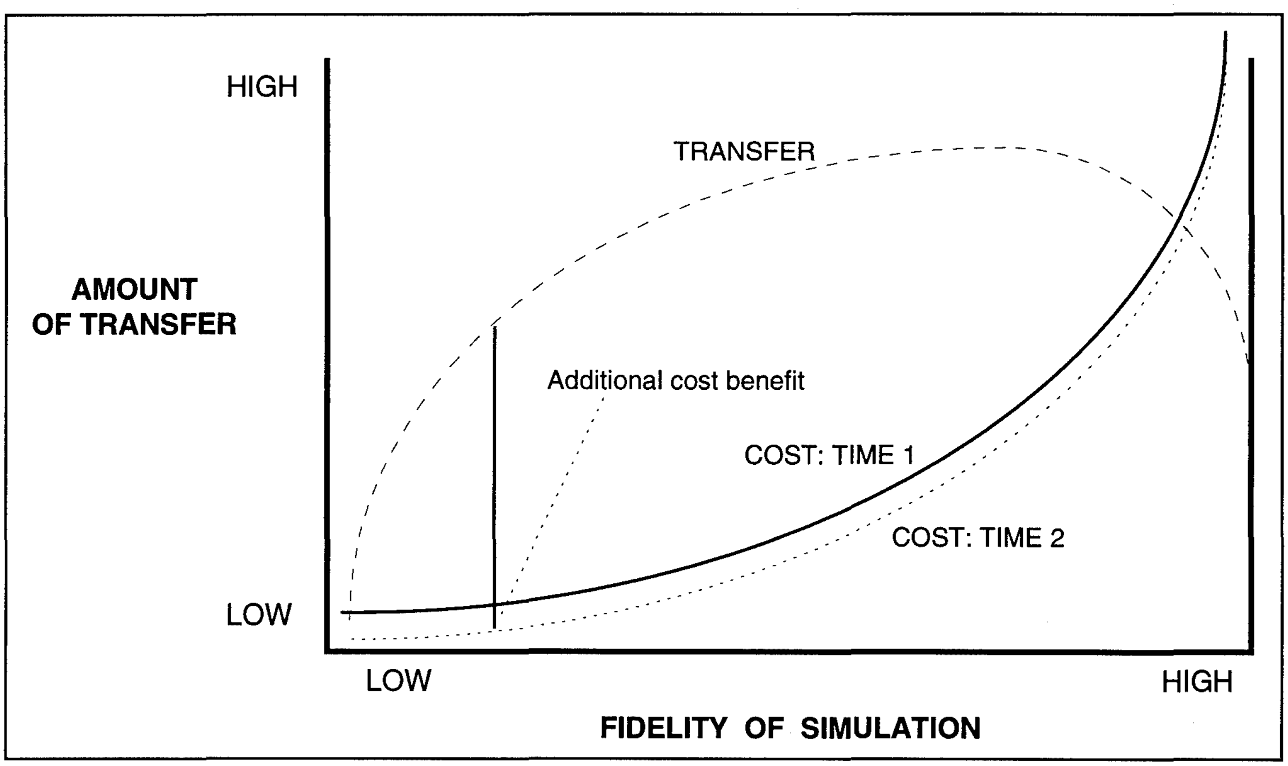


**Figure 1.** The hypothetical relationship between system fidelity and system cost (from Roscoe, 1980; Figure 17.1)

1) **Consequences of inadequate performance.** *This can be reflected in economic loss or physical injury.*
2) **Cost of using actual system for training.** *In the case of commercial airlines use of an aircraft incurs revenue plus salaries.*
3) **Hazard of using actual system for training.** *Avoids possible undesirable effects on society. Can simulate system failures (aircraft crashes, nuclear power plant fails).*
4) **Availability of actual system for training.** *Use where system is not available for training (spacecraft) or where first performance in new system must be accurate (single-place aircraft).*
5) **Capability of actual system to provide emergency training.** *Conditions constituting an emergency cannot be reproduced in system without great expense or damage to system.*
6) **Requirement to integrate complex team activity.** *Integration of activities of large number of people (complex information assembled and reacted on quickly).*
7) **Susceptibility of task to stress.** *Tasks performed under stressful conditions (space flight) must be learned to high proficiency level, usually difficult on actual system due to impractical nature of repeating critical segments.*
8) **Capability to centralize training location.** *Reduced number of training locations using simulator may reduce cost and achieve standardization.*
9) **Face validity of training.** *"Realism" of simulator may be necessary to assure trainee participation.*
10) **National need.** *Need for specialized skills may be important enough to prompt federal funding for simulation equipment to speed training process.*

Although this listing primarily addresses training issues, some are applicable to research. Both ***cost*** and ***hazard*** are issues that clearly favor the use of simulation for flight research. The ***face validity*** issue may also be a factor in the attainment of generalizable research results, inasmuch as failure of the participant to ego invest in the simulated process is likely to negatively bias the results; responses may not be valid if the participant does not have to "live" with the consequences of actions and/or decisions. A high motivation to "succeed" among pilots, even when flying simulators, may have the positive effect of reducing the likelihood of unmotivated performance, particularly when most such simulations appear to be intrinsically motivating. Thus, this motivational factor may compensate, in some degree, for shortcomings in face validity if task validity is high.

Jones and Henry (1985) point out that:

> Simulators for research differ from simulators for engineering design and development principally in that the former use has the objective of gaining generalizable knowledge (i.e., discovering fundamental principles that are broadly applicable), while the latter use is to obtain specific data for the design of particular items of equipment, systems, or procedures ... Research simulators generally must allow for greater latitude in manipulating conditions, events, and fundamental functional characteristics than engineering simulators.

This is particularly evident when one contrasts, for example, the simulation platform needed to develop, evaluate, and support a specific airframe product (Boeing 767, for example)with that designed for evaluating different types of manual controls and control systems or for examining pilot response to different cockpit instrumentation and display formats. The differences between these two types of application platform appear, however, to be fading in many cases.

One of the major concerns in research simulations is the extent of ***control*** available, particularly over ambient conditions not controllable in the real world. It should be recalled that most behavioral research is *reductionist* in nature, rather than *holistic* (Egon Brunswik): attempting to control all variables with the exception of those being studied. It can be argued that reductionist experiments may not require a high degree and fidelity of flight simulation to examine many of the paradigms of concern given that much of the experimental space is represented in a steady state. That degree, the extent to which the full range of operational modes are represented, can be curtailed is clear, specifically when only a particular aspect of operation (e.g., landing) is under examination. The case of fidelity (the accuracy with which the system reproduces operational behavior) may not be as straightforward. The goal is to generalize from observed behavior; the extent to which that is possible is a function of the extent to which the operator behaves, in simulation, similarly to what can be observed in the operational environment. Evidence suggests that task *procedural* fidelity is very important for facilitating the desired behaviors. Events should occur in the expected sequence with the expected consequences.

In contrast with procedural aspects of the task, some of the psychomotor aspects may be compromises and still allow adequate performance by the pilot. Force characteristics and gain in manual controls, for example, might be of a lesser fidelity (given the flexibility of the human operator) so long as they provided adequate input to the system for achieving the specified tasks. Common sense can generally dictate many fidelity decisions with some notable exceptions. It should be clear that the study of navigation computer interfacing with the pilot, involving graphical interface and menu hierarchy design, will not likely require the fidelity of manual flight control input/output that one would need to execute manual control theory studies. This selective use of high fidelity has been the historical exception rather than the rule, with many simulation efforts striving to achieve high fidelity across the board. Such an approach generally increases both the acquisition and maintenance costs of a system.

Previous barriers to the general use of flight simulations in behavioral research largely involved these costs of acquisition and maintenance and system availability because many of the simulators had been developed for training or as engineering simulators within a full-mission context. The research community now stands to benefit from the development of lower-cost simulations that can reasonably represent selected flight tasks of interest. Such simulations have the promise of allowing research to be conducted, for a greatly reduced investment (*cost factor*), that will still generalize to the operational environment. The opportunity then is also present to use the lower-cost lower-fidelity devices to perform screening experiments, reducing the resources required from higher-fidelity simulations (*availability factor*) and freeing them for more focused investigative efforts. It should also be noted that simpler systems tend to have higher reliabilities as well as lower maintenance costs.

**Hardware & Software Components**

Specific constraints imposed on the present system development were that it (1) had to be operational within 6 months of project initiation, (2) had to reasonably represent a familiar (popular) single-engine general-aviation aircraft and its environment (instrumentation, controls, and external visual cues), and (3) needed to meet the criteria of a "research" simulator, to the extent that it allowed manipulation of experimental dependent variables of present interest and the extraction of relevant performance data. It was with these goals in mind that the moderate-fidelity general aviation flight simulation at CAMI, referred to as the Basic General Aviation Research Simulator (BGARS) (Beringer, 1994), was developed using widely available 80486-based personal computers (50 & 66 MHz) to generate a comparatively rich simulated flight environment. The criteria of low cost and short development time argued in favor of using commercial off-the-shelf products as much as possible. Thus, all hardware and software selected were available as commercial products. Minor modifications were performed in cases where components needed to communicate but did not already embody the necessary features.

The system includes variable flight instrumentation, forward, 45- and 90-degree left external-world views, and a map display. Left-side external views were included to facilitate VFR flight and the execution of visually referenced left-hand traffic patterns. A simplified block functional diagram of the system appears in Figure 2. High-fidelity analog control inputs are provided (e.g., damped/self-centering yoke, high-performance throttle quadrant, gear, flap, and trim controls; radio controls). The simulation is based on commercially available flight simulation programs, one (FS-100) an instrument flight trainer and the other (ATP), a "game"-type flight simulation. The modified FS-100 package provides the cockpit displays, control input processing, continuous collection of 16 performance variables, choice of either a Beech Bonanza (A-36) or Beech Sundowner aero model, and concurrently feeds six-degree-of-freedom data to the second program, producing the out-the-window view. This latter program is used to produce all outside views, one per processor/display combination. Thus, the three outside views (Figure 2) require three separate processors, each running a copy of the same program but selected to depict the appropriate viewing vector. The forward view is projected to obtain accommodation distances exceeding 3 meters and a 55-degree field of view. All interprocessor communications are serial, obviating any need for network hardware or software. Although the initial configuration used *five* processors, at an overall cost of approximately $25,000 (hardware/software), an acceptable simulation (i.e., forward view and instruments) can be produced using *only two* computers; each added function/view requires another processor (Figure 2). A more detailed system diagram depicting the revised system using Pentium 100 MHz processors can be found in the Appendix. Included in the diagram is a sixth processor used to deliver ATC and pseudo pilot verbal messages from digitized sources.

**Software Considerations for Integration**

The simultaneous use of two previously self-contained simulation programs, each with its own internal representation of the real world, required that a number of issues be addressed before an acceptable system could be fielded. These included issues related to the geographic database, communications between programs, and the specific requirements of the research application.

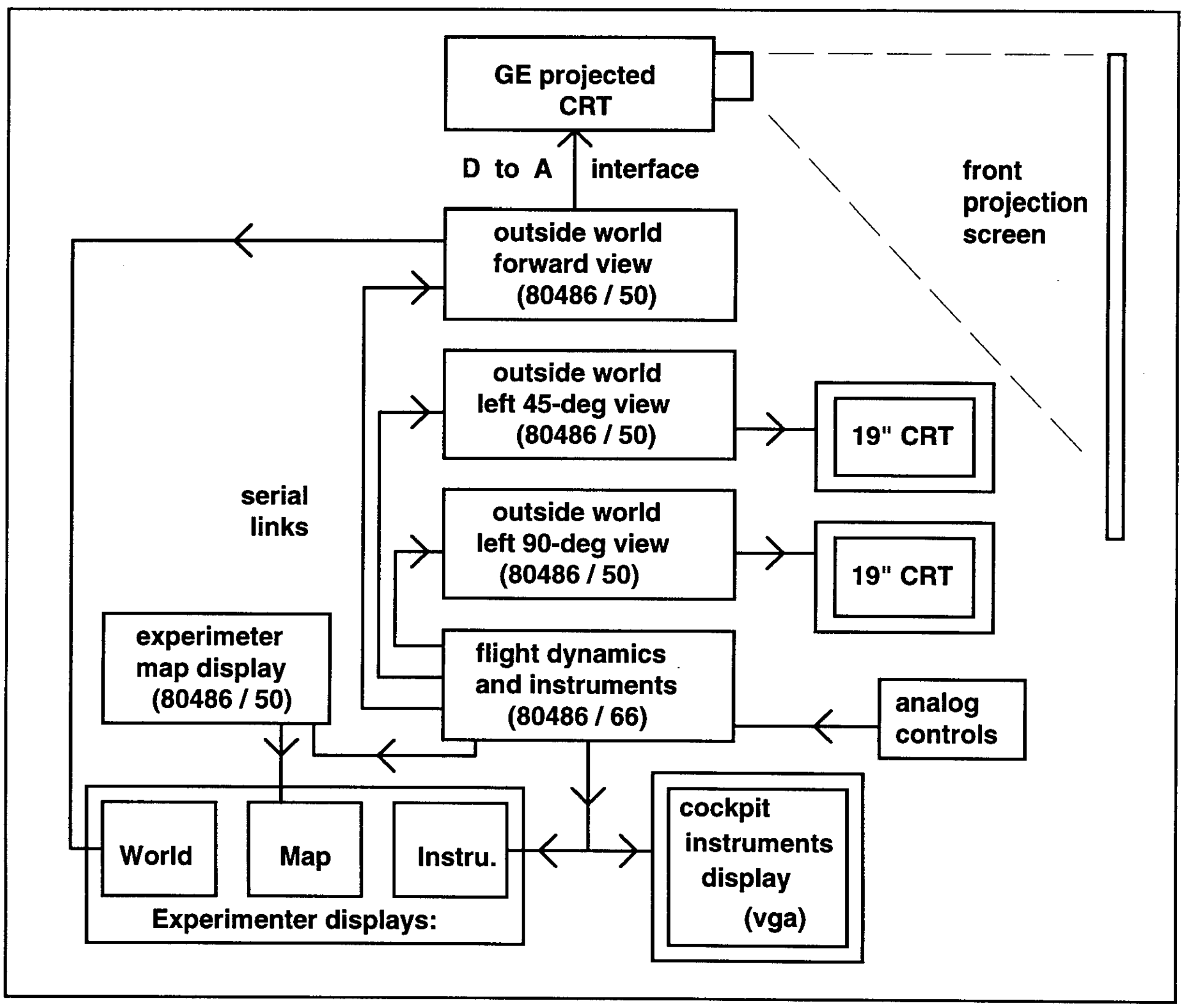


**Figure 2.** Simplified schematic of the BGARS, version 1.

*Geographic location of airports.* Although the system intercommunications considerations were relatively straightforward and elegant in their simplicity, the architecture requires that each processor/software package in the system contains a geographic database identical with those in the other systems. One needs to be aware that not all databases are equal and most low-end flight simulations distributed for the mass market use the National Oceanic & Atmospheric Administration (NOAA) database; it is readily available for minimal cost and does not require licensing for use. Some of the more expensive instrument training packages use the Jeppeson-Sanderson (J-S) database. This commercial product is expensive and requires licensing, but its data are updated very frequently. The two databases are not congruent; indeed we have found displacements orthogonal to runway centerlines ranging from 50 to 200 feet. This can be most unnerving when one flies a "perfect" Instrument-Landing-System (ILS) approach and finds, on short final, that the aircraft is *not* aligned with the runway. We have obtained editing functions for the package (ATP) using the NOAA database, allowing us to move the airports into alignment with the J-S database. In most cases, the adjustment required is small.

A related concern is the fidelity with which airport facilities are represented. We regularly found discrepancies between the representation of an airport in the instrument-package database (and thus moving map display) and the depiction in the out-the-window scene. Secondary runways were missing from the out-the-window view in a number of instances. This appeared to be more likely at "secondary" airports as primary airports generally had accurate runway and taxi way depictions. It is not clear to what extent these discrepancies represent changes in the facilities requiring updating of the database and to what extent they are simply omissions. Thus, it is recommended that one not choose airports as primary or secondary destinations (or even emergency fields) without fully assessing the agreement between the two databases.

*Altitude.* Differences in field elevation, however, are a more difficult problem. Each software package represents altitude in a different fashion. FS-100 assumes terrain elevation to be that of the nearest airport. ATP uses an interpolative approach to determining altitudes at locations falling between major reference points to approximate intermediate terrain elevations. Add to this small differences (50-100 feet) between the two source databases and the result is some interesting anomalies. We found an initial difference between databases of 50 feet at Will Rogers World Airport (OKC, runway 35 right), which occasioned a rather high and sudden contact with the ground on our first simulated approach (it was *literally* a highway in the sky), the field elevation in the visual scene database being lower than the field elevation in the instrument package database. Although ATP can make an initial adjustment on start-up to the current field elevation, differences at the destination of a flight can still produce the aforementioned effect. This problem was resolved by transmitting altitude above ground level (AGL) to the scene-generating packages. Flying over mountains represented in the visual database does not produce unusual effects, because FS-100 is not aware of the mountains if no airport is located there, and ATP uses the base of the slope as terrain elevation.

*Heading.* One other concern is the method by which heading, also represented as the forward viewing vector, is communicated between packages. Recall that heading has both true and magnetic representations and that both simulation packages must agree on the method for handling and communicating those data. An early experience during development was, again, a distressing one on approach to San Francisco (SFO) when all attempts to fly straight down the runway produced extreme drift to the right. Mismatches regarding true and magnetic headings and a difference in the internal representations of data between the two software packages contributed to this effect. Processing of transmitted heading was modified to correct this mismatch.

*Collision with ground or objects.* The enabling of collision detection has two levels. The first, already mentioned, requires that both packages operate from the same basic data. Compatibility is critical for a multimachine one-way communication environment because no handshaking or flow control is being executed; one machine is the transmitting "host" while the others are passive listeners (peripherals). The second level, object collisions, can be achieved by having the forward-view-generating processor determine, as the software is capable of doing, if an object in the visual scene has been struck and then send a signal back to the host. This would require only two processors to have full duplex operation, with the other machines remaining passive monitors of one side of the communications flow.

*Visual display considerations regarding color, brightness, and aliasing.* Not all software packages present visual data in the same manner. The temptation exists to opt for the highest-resolution out-the-window imaging available in order to reduce aliasing along the horizon line and on any other features with linear boundaries. FS5 (in VGA graphics mode), with its textured terrain depiction, does exhibit less aliasing than does ATP (in EGA graphics mode) as a function of the display resolution being used. However, FS5 tends to have a much darker overall affect with its textures than does ATP with its uniform area-fill color (primarily light green or brown with occasional yellow or orange blocks). While this may not be of much concern when displayed on a large direct-view CRT, the brightness issue becomes critical when a projection system is used. The image produced by the GE projection CRT was of an acceptable level of brightness when the backgrounds were area filled and primarily light green or light gray (urban), but the brightness was not acceptable in the initial adaptation of FS5 and terrain features and runways were difficult to detect. A subsequent modification was made to brighten all of the colors, but the effect was to wash out much of the contrast and lose some of the definition. Some additional tuning of brightness and contrast may resolve this problem. Detection of runways and runway centerlines was also more difficult at a distance with the textured-terrain display provided by FS5 than with the simpler area-fill graphics of ATP. This may or may not be desired, depending upon the tasks to be performed.

*Required modifications for research.* Two modifications were required to make the system suitable for research. These were to provide (1) the ability to manipulate the independent variables of interest and (2) the ability to record dependent variables of interest. The first two studies required selectable instrumentation, as we were interested in piloting performance with both conventional navigation displays, as represented by the very-high-frequency omni range (VOR) indicator and directional gyro (DG), and integrated displays, as represented by the horizontal situation indicator (HSI). Additionally, we were interested in the effects of simple memory aids/instrument bugs. The HSI was already available in the software; the modification allowed selection/deletion of bugs on the DG and altimeter. Thus, requirements of (1) were satisfied. Meeting the requirements of (2) was facilitated by the fact that most of the dependent variables of interest were already being recorded in the replay memory. This required only the addition of a header record to identify the data file, a sample number for each data slice, an event marker that could be inserted by the experimenter in real time from the keyboard, and lateral error, in feet, from the VOR/localizer course (for a total of 16 variables). An additional switch was added to allow data collection to be paused during a run while the aircraft continued to fly. A package was also provided that allows data files to be accessed and rewritten in ASCII format for subsequent use by data reduction and analysis packages.

*Flight task difficulty/aero models.* The original aero model provided was a Beech Bonanza A-36. This was used in the initial evaluation with instructor pilots and was found to be too sensitive to control inputs and somewhat unstable longitudinally. It did, however, provide a significant challenge to the participating pilots, and thus, a good task loading that was likely to exercise the pilot and system in such a way as to expose effects due to the experimental manipulations being used. A simplex (single-engine, fixed-pitch prop, fixed gear) model was desired for use with the private pilot samples to be examined and a Beech Sundowner model was added. Its flying characteristics were quite similar to the actual aircraft, and pilots without complex aircraft experience found it comparatively easy to fly.

*Update rates and throughput.* The initial installation of the system used 80486 processors for the flight instruments/aero model package (66 MHz) and out-the-window views (33 MHz). Different update rates were obtained for the instrument package and the external views. The instrument panel updates were generally on the order of 12 to 16 Hz. The out-the-window views involved much more in the way of graphics and generally did not operate much faster than 6 to 10 Hz. This update rate was not objectionable for most operations and only became noticeable in steep-banked turns. The upgrading of the system to 100 MHz Pentium processors with the PCI bus for all computers excepting the map display (486 66MHz) after conclusion of this study significantly increased throughput. Instrument and all out-the-window view update rates appear to be at or above 16 Hz. Some occasional stepping (discrete observable movements) can be observed in instrument indications, particularly in the CDI needle, but this appears to be a function of calculational and display-resolution artifacts and not system throughput.

### Advantages

The advantages of this approach are (1) low cost of hardware, often already available on site, (2) comparatively low cost of software, as modifications were minor, as compared with development of a completely customized system, (3) modularity of both hardware and software, allowing upgrade of any of the components or easy expansion of simulation by adding components, and (4) simplicity of the communications protocol. The low cost and ease of assembly/integration allow multiple "standardized" systems to be distributed for cooperative inter-laboratory studies. This approach appears to have great utility for both research and training.

### Disadvantages

One should expect that the advantages noted do not come without cost. The use of commercial off-the-shelf software without access to the source code poses a potential problem for investigators who wish to manipulate variables not directly accessible through the program. Although we have had reasonable success in working with the developers of the software to obtain modifications necessary to make the simulation useful for research, there are yet some areas where desired modifications are not immediately obtainable. This is due either to scheduling conflicts in securing development time or to changes that have major impact on the structure of the software. One solution to the problem that we have pursued is the addition of processors on the serial distribution to provide additional features (i.e., ATC and pseudo pilot digitized and automated voice inputs). The researcher then maintains control of the auxiliary functions and can modify and develop the code as needed. This approach can also be used to develop auxiliary instrument displays, given that the requisite data are available on some communication line coming from the host processor. Additional modifications are being made to the software that will provide access to more data variables in real time as well as to some discrete failure modes, multiplying the options available to the experimenter.

## EMPIRICAL VALIDATION

Having now fielded a functioning system, it was necessary to validate the utility of this system for research. A problem area was selected during development, as previously mentioned, that would allow experimental outcomes to be compared with outcomes of other aircraft- and simulator-based research for at least a preliminary empirical validation of the BGARS as a research tool.

### Problem

The selected comparisons were (1) between alternate ways of presenting course deviation information for very-high-frequency omni range (VOR) navigation and (2) between instrument formats both with and without short-term memory aids. The Horizontal Situation Indicator (HSI) has seen considerable use and combines the functions of the very-high-frequency omni range (VOR) and directional gyro (DG) indicators within a single instrument (a design suggested by Walter Grether; Williams, 1949, as reprinted in Roscoe, 1971). There has been little doubt that the HSI simplifies the pilot's task of integrating the various pieces of data, with some attendant gains in the performance of tracking and orientation tasks. Short-term memory aids or "bugs" are available to relieve the pilot of the tasks of recalling target altitudes and headings. It was anticipated that the aided (HSI and bugs) conditions would produce performance superior to that obtained in the unaided (VOR/DG and no bugs) conditions.

The question at hand was one of cost effectiveness: Did performance enhancements associated with the HSI and bugs justify the expense of acquiring and installing such devices in comparatively inexpensive general aviation aircraft? The questions relative to the simulation were several, involving (1) sufficient task fidelity to motivate generalizable behavior, (2) ability of the system to collect adequate continuous, real-time performance data, and (3) stimulation of the same types of procedural errors as those seen in the operational environment through appropriate task and workload representation. The reliability/availability of such a system was also of interest as compared with other such devices. A brief summary will be presented to address these questions.

**Task Fidelity and Generalizability**

More than 36 pilots flew the simulation over the course of three phases of the initial study. Of these individuals, 12 were experienced pilots (with more than 500 hours, of which at least 30 hours were logged in the last 6 months), most of whom were instructors, with the remainder being private pilots (with less than 200 hours of flight time and less than 20 hours in the last 6 months). Each participant flew the simulator for two 2-hour sessions, the first session for familiarization and training and the second for data collection. Training included traffic patterns, constant-altitude standard-rate turns, VOR radial interception and tracking, and a simple positive-control scenario that incorporated all previous components. The subsequent data collection consisted of more challenging VOR navigation courses and compliance with ATC-issued vectors and altitude changes as well as an ILS approach.

Pilot subjective reports were collected using posttest questionnaires. Comments and ratings concerning handling qualities and workload consistently indicated that pilots judged the A-36 simulation to be more sensitive to control inputs and more difficult to fly than the aircraft. These assessments, however, appeared to correlate with piloting style (i.e., interventionist versus noninterventionist). Ratings on the flying qualities of the Sundowner were also to the "sensitive" side, but not to the degree found for the Bonanza.

Pilots generally reported that the experimental scenarios were more challenging than their usual flying and thus, presented a significant workload. This, of course, was a positive bit of news, as the intent was to load the pilots sufficiently to detect performance decrements. Obtained ratings also indicated that participants felt the simulation reasonably represented flight tasks in the ATC environment. Ratings were all high on the "task realism" scale. A number of individuals expressed the desire to spend additional time in the simulator and several instructors indicated their interest in using such a system for training. Behaviors observed during the flights also indicated that the participants were ego involved in the process and were responding to the simulated flight much as one would expect them to respond during an actual flight. This was true of continuous aircraft control, radio navigation, and communications with ATC.

**Continuous Real-time Performance Data**

Flight data were sampled and stored at 0.5 Hz. Variables recorded included latitude, longitude, magnetic variation, altitude, airspeed, heading, cross-track error, DME indication, and a number of status variables (event mark, gear, flaps, marker beacons, etc.). Examination of the data suggests that performance variables that can be sampled at lower frequencies (2 Hz or less) and that represent outcome states (i.e., location of the aircraft in three dimensions relative to desired altitude and ground track) can be effectively monitored with the system and provide adequate measures of aircraft system performance for navigation and altitude maintenance tasks. Examples are shown in Figures 3A & B where the plan views are shown for one pilot to compare the HSI course tracking with the VOR/DG course tracking. It is evident that better acquisition and tracking performance was obtained using the HSI, consistent with the procedural data previously mentioned and with previous studies of integrated navigational displays.

Higher sampling frequencies up to at least 16 Hz are possible with the system, but storage becomes a problem as variables are held in memory until the end of a flight. The present system could be suitable for control-theory studies of manual flight control where the expected frequency of control reversal activity is

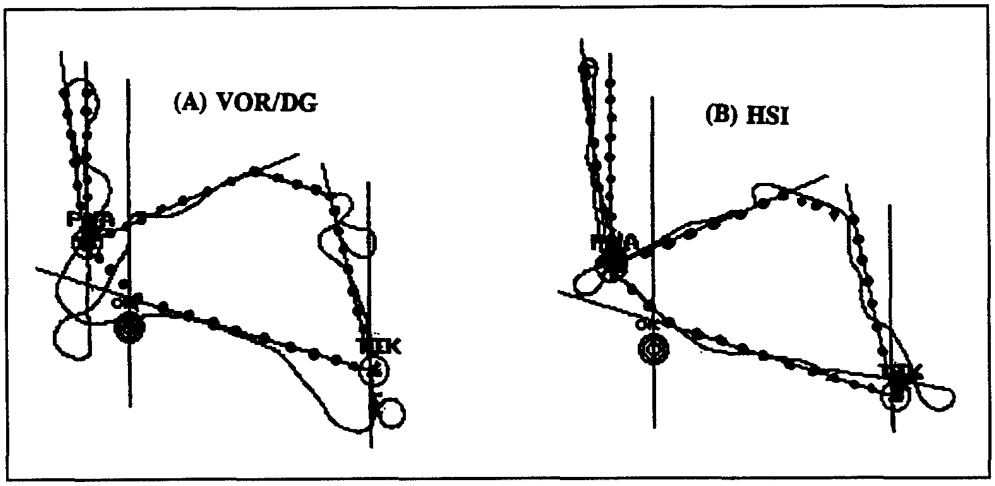


**Figure 3.** Example flight paths for one subject for (A) VOR/DG and (B) HSI instrumentation. Dotted lines indicate desired tracks.

not likely to exceed the measurement capabilities of the system during most normal realms of flight. The limitation, as suggested, is more one of available data storage space, limiting the duration of high-frequency data collection. Flight attitude data are presently being transmitted from the program at 16 Hz, so evaluation of maneuvers based upon sampling of aircraft attitude can apparently be accommodated, although such were not evaluated in the present study. A revision of the software is presently under way that would allow flight data to be transmitted to another computer system, thereby alleviating the storage space restriction and increasing the recordable flight durations even at high sampling rates.

### Observed Procedural Errors

Two categories of procedural/discrete errors were expected to be observed related either to the navigation/orientation problem or those related to memory of heading and altitudes or elements of the verbally issued clearance amendments. Navigation/orientation errors included inappropriate setting of the omni bearing selector (OBS), flying through radials without any corrective action, and turning in the wrong direction for an intercept. Memory errors included callbacks for heading, altitude, or radial, and failure to recall present assigned altitude. Errors observed for the experienced pilot sample are summarized in Table 1.

These findings were largely as anticipated, demonstrating more errors with the VOR/DG combination and without bugs than with the HSI and bugs. The direction and frequency are largely consistent with other research in the display aiding/predigestion literature. This suggests that the simulation system can be useful for examining problems of this nature where procedural compliance and navigational decision-making are involved and information is being derived from a dynamic instrument representation.

### Reliability and Ease of Use

The system, as of this writing, had been operated for over 880 hours (over the course of 18 months). During this time, only two failures occurred that required the halting of data collection. Both of these were microprocessor-system related, one being a disk controller failure. One transient failure of the GE projection system was observed, but it did not interfere with data collection. No failures of the custom hardware were observed. The audio system amplifier experienced one failure but was immediately replaced by on-site available equipment, as was the case with other components. Maintenance of the system can generally be performed on site by individuals with a knowledge of personal computer systems. The system is very easy to use, as all programs are run automatically following initial system boot using batch files

**Table 1.** Procedural errors, 11 subjects.

| | VOR/DG | | HSI | |
|---|---|---|---|---|
| Error | No Bugs | Bugs | No Bugs | Bugs |
| VOR/Nav | 17 | 12 | 6 | 8 |
| Memory | 5 | 4 | 5 | 1 |
| Total | 22 | 16 | 11 | 9 |

and all operator-software interfaces are straightforward and easy to understand. A cold start of the system (from power off to full operational status) requires approximately one minute.

## CONCLUSIONS

The data obtained to this point indicate that the simulation described herein has sufficient task fidelity to motivate generalizable behavior, producing outcomes that are comparable to those obtained in other simulation devices and, in fact, aircraft. The ability of the system to collect adequate continuous, real-time performance data has been demonstrated with reference to tasks limited to maintaining aircraft altitude and track. Control theoretic studies are likely to require some modifications of the software to provide sampling rates of sufficiently high frequency. It was also evident that the task environment simulated was sufficient to the degree that behaviors/errors likely to be observed in the real world were also observable in the simulation, allowing for the examination of procedural error, as well as continuous performance. The simulation has been comparatively inexpensive to integrate and maintain, and has had a very high level of availability.

The preliminary indications are that this modular microprocessor-based flight simulation system can be a useful and economical tool for examining experimental questions involving general aviation pilotage. No data are as yet available for the use of this tool in investigating tasks that are primarily VFR in nature. Software (textured visual databases) and hardware (100 MHz and faster processors and faster bus architectures) developments are becoming available that will further enhance the possibilities for research on visually guided behaviors beyond geographical orientation, pattern flying, and visually guided approaches.

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# APPENDIX A

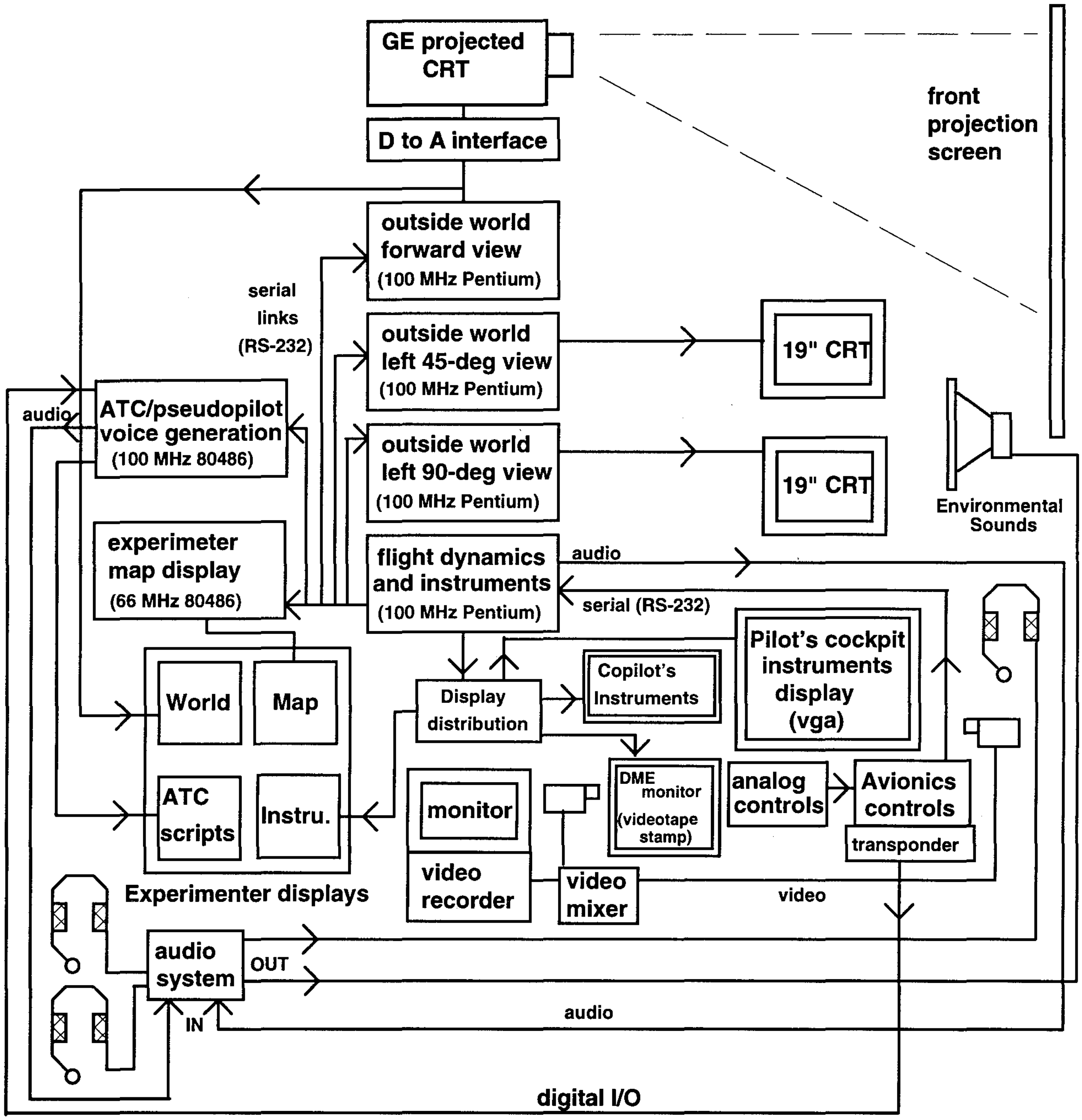


**Figure 1A.** CAMI BGARS schematic diagram, 6-processor configuration.

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