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March 1978

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SYSTEMS TECHNOLOGY, INC.

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CONCEPTS AND OVERVIEW

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National Aeronautics and Space Administration
Ames Research Center
Moffett Field, CA 94035

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16 Abstract

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FOREWORD

This report was prepared under Contract NAS2-9024 to the NASA Ames Research Center. The effort was monitored by Mr. William B. Cleveland of the Simulation Sciences Division.

The author acknowledges the patience and criticisms of Mr. Cleveland and is grateful for the review comments and suggestions of Messrs. David C. Nagel and D. Francis Crane of NASA Ames Research Center and Mr. Warren F. Clement of Systems Technology, Inc.

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1.1 HISTORICAL PERSPECTIVES SURVEY

1.1.1 Definitions

Flight simulation is the art of mimicking flight. Although practiced in an engineering sense, it is not far from pure art in that it uses the mechanisms of illusion and deception to achieve a purpose. While strictly speaking, the term "flight simulator" refers to any device that imitates flight such as a wind tunnel, it is commonly used to mean a piloted flight simulator. This class of devices is used for both research and training in the integration of man and flight vehicle. The emphasis may vary from man to machine but always with the interaction of both.

The modern flight simulator consists, in varying degrees, of a cockpit, computer, visual system, and motion system. The cockpit, which may be supported on a moving platform, contains seats, instruments, controls, visual displays, and aural and tactile devices. All of these elements are controlled by the pilot through a central computer which solves equations representing the simulated aircraft.

The simulator is designed to create as many of the sensations of flight as are experienced by the pilot. Figure 1-1 shows an example; the flight simulators used by the British Aircraft Corporation.

1.1.2 Advances in Flight Simulation Technology

The chronological development of flight simulators is described in the following paragraphs and in Table 1-1. There, the advances in contributing technologies are shown together with milestones in simulator development.

Flight simulation began with flight itself. The flight pioneers built special devices such as wind tunnels that helped them to develop

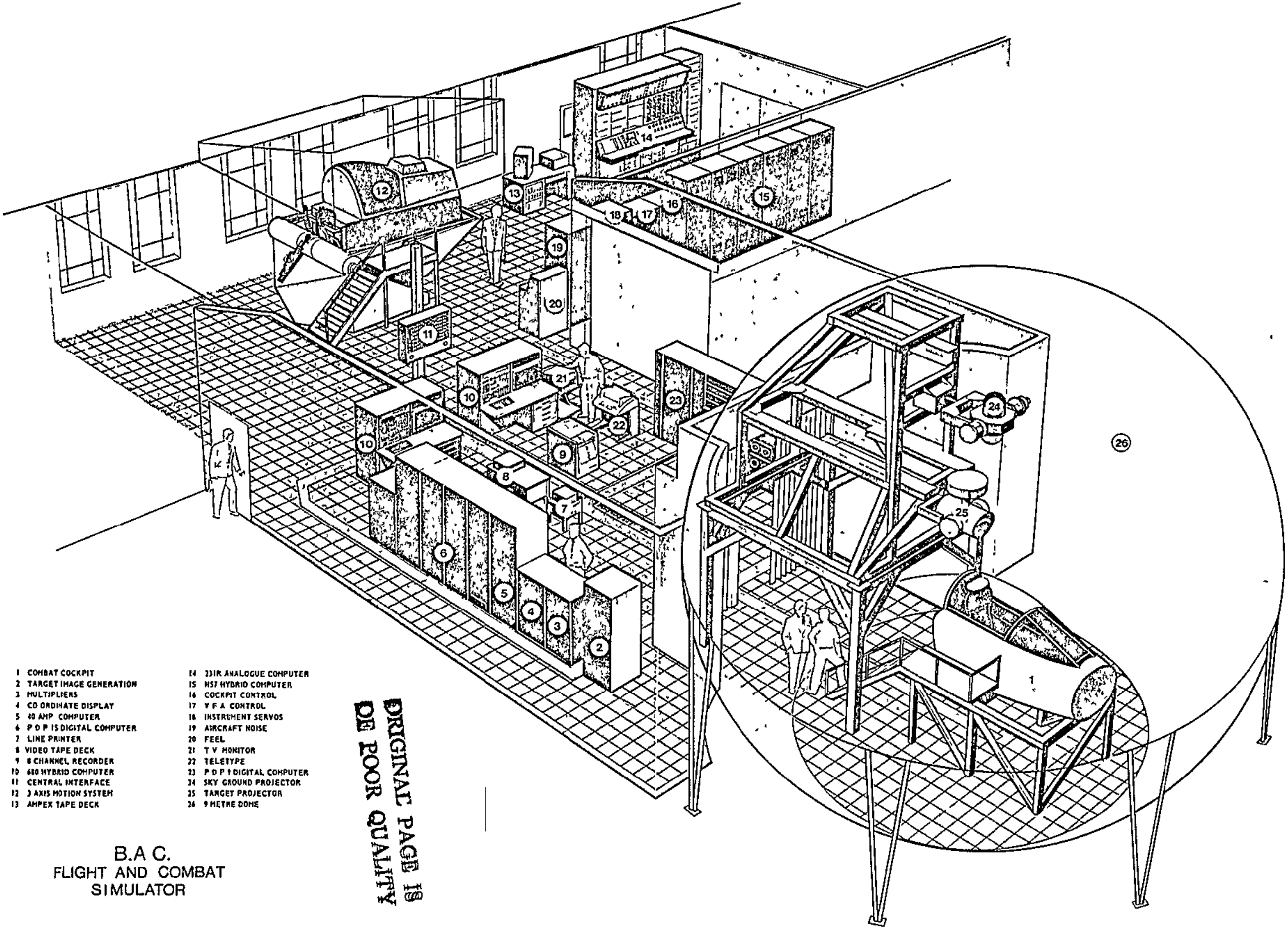

Figure 1-1. The British Aircraft Corporation Flight and Combat Simulator

TABLE 1-1

CHRONOLOGY OF FLIGHT SIMULATION TECHNOLOGY

	1900	1910	1920	1930	1940	1950	1960	1970–1980
FLIGHT SIMULATORS	Sander's Teacher, Eardley-Billing Oscillator			1st Link Trainer	Link Instrument Trainers	Laboratory Analog Simulations	Transport Trainers; Apollo; ASUPT → ASPT; SAAC; ISAA, DMS, LAMARS; 747; DC-10	Full Mission Multi-Crew; Aircraft Industry Facilities
AIRCRAFT CONTROL	Gyroscopic Stabilizer for Torpedo Control	Sperry's Autopilot	Siemens Autopilot		Frequency Response Methods; Advanced Autopilots		Fly-by-Wire, Airborne Computer Control	Shuttle Optimal Guidance and Control
SERVO-MECHANISMS, DYNAMIC ANALYSIS		Gates Studies Continuous Control		Nyquist Criterion; Bode's Logarithmic Plots	Wartime Developments, Evans' Root Locus, Fire Control Systems		Fast Fourier Analysis, Computer Implementation,	Optimal control
ELECTRO-OPTICS		Photography		Cinema	Television; Virtual Image Optics, VAMP; Computer Generated Display			Laser Display; Solid State Display
COMPUTERS	Mechanical Counters	Great Brass Brain; Mechanical Analog and Digital Computers →		Automatic Sequence Controlled Calculator	MIT Mechanical Analog Computer, Ragazzini Operational Amplifier	Electronic Analog Computer, U of Pennsylvania Digital Computer Study → UDOFT		Minicomputer; Microcomputer Advances; Advanced Architecture

ASUPT = Advanced Simulator for Undergraduate Pilot Training
ASPT = Advanced Simulator for Pilot Training (later name for the same device)
SAAC = Simulator for Air-to-Air Combat
DMS = Differential Maneuvering Simulator
LAMARS = Large Amplitude Multi-Mode Aerospace Research Simulator
VAMP = Variable Anamorphic Motion Picture
UDOFT = Universal Digital Operational Flight Trainer

their machines. They also developed additional pilot training aids. According to Valverde (Ref. 1) two devices appeared in England together with early powered airplanes. They were advertised as the "Sanders Teacher" and the "Eardley-Billings Oscillator." They were parts of aircraft that could be moved on pivots to simulate the attitude movements expected in flight. Most early aircraft were single-place machines and one learned to fly them by trial-and-error, at best a risky prospect.

For thirty years following the advent of the powered airplane, the simple flight simulators that evolved were used mostly for pilot training. During the same period, advances in aeronautics, control, computing, and cinema continued. Simulators, however, appear to have developed on their own, i.e., with little influence from related technologies. By the time of the start of World War II, however, the picture began to change. The related technologies of aircraft control, servomechanisms and dynamic analysis, electro-optics, and computers began influencing training simulator designers. The first Link trainer introduced in 1929 grew into a relatively sophisticated and widely used wartime instrument trainer. Aircraft control and autopilots became reasonably well understood and the wartime need for accurate fire control systems spurred the development of servomechanisms and analog computers. Although the Greeks appear to have built an analog for computing celestial body motions as early as the first century B.C., the modern mechanical analog computer appeared about 1910 (the Great Brass Brain used by the Coast and Geodetic Survey to calculate tide tables) and refined versions were developed at MIT about 1940 by Bush. About the same time, the communications industry developed the operational amplifier, the essential element of electronic analog computers.

The mechanical digital "computers" prior to World War II were not suitable for the real-time calculations required of trainers. This was due to their use of relays. The application of vacuum tubes to digital computers at the University of Pennsylvania during the war resulted in computational speeds high enough for real-time applications. The University's design was converted into a prototype by 1960 that resulted in the Universal Digital Operational Flight Training (UDOFT).

After the war the influence of the related technologies grew. The analog computer began to be used for laboratory simulations of flight dynamics and in the 1950 decade, television became popular. By the 1960 decade, the digital computer had firmly found its way into training devices and the television camera/model technique was first explored for takeoff and landing training. Further motivation was provided by the Apollo lunar exploration, as the high concern for safety in that program resulted in training and engineering development devices that incorporated the sophisticated virtual image displays and powerful digital computers that are essential to today's simulators.

The related technologies such as aircraft flight dynamics analysis, airborne computers, and the computer-generated display were developed to the point that refined aircraft models were possible together with simple but potentially complex displays. By the late sixties and early seventies, the airlines had successfully attempted transition training using only simulators.

A variety of devices were used by the airlines for training pilots for the 707, 727, 747, and DC-10 aircraft. They incorporated large motion platforms, television and cinematic visual systems, and digital computers.

The military services followed later with extensions of the Apollo virtual image displays for their full mission simulators requiring wide fields of view (SAAC, ASPT).

While the airline use continues to be driven by profit constraints, the military use of sophisticated trainers is motivated primarily by a peacetime atmosphere emphasizing cost effectiveness and the beginnings of the energy shortage.

The simulation industry today is characterized by rapid advances in visual system technology and is heavily influenced by computer hardware. The current ability to define complex aircraft models capable of representing the full flight envelope drives the computer requirements. New concepts in computer systems and architecture are emerging that, together with the advanced displays, will press the visual simulation technology to new and dramatic highs. Today, the military use is the main stimulus for full mission simulation development. Military sponsored work on laser displays and computer-generated imagery shows promise of achieving full field coverage and high brightness levels with a resolution approaching that of the eye. The television camera/model technique will probably fall into disuse by 1985. The television industry, however, is already developing the solid state picture tube, a device that could revolutionize visual simulation of all kinds by 1990. The full mission simulators such as the Simulator for Air-to-Air Combat (SAAC) and the Advanced Simulator for Pilot Training (ASPT) (formerly the ASUPT; Advanced Simulator for Undergraduate Pilot Training) represent the advanced military simulators and hold the vision of what's to come.

While a look at the simulator technology certainly reveals a strong emphasis on training uses, the research community to which this report is addressed has been busy putting together pieces of this technology for its own use in developing aircraft. It is not clear exactly when the first engineering development simulator was assembled. It probably took place in a computer laboratory during the early fifties in response to an engineer's desire to understand a simple flight control problem. The extension of a simple laboratory setup to a more sophisticated simulation is almost the natural result of engineering growth and awareness. When components are common (servomechanisms, etc.), it is easy to justify an engineering development simulator on the basis of total development cost effectiveness.

The motivation for engineering development simulators, of course, had to be different from that for training. The early stimulus probably was curiosity, later, it was necessity. Two notable examples from the past and one from the present are cited in this respect. In the 1950's, the century-series of fighters encountered roll-coupling problems that were subsequently solved with the aid of sophisticated computer simulations. The unstable dynamics of the Vertical Takeoff and Landing (VTOL) aircraft of the 1960's prompted the use of simulators to ascertain their suitability for piloting without electronic assistance. Recently, high-performance fighters show departure (spin entry) properties at high angles of attack. This has spurred the use of development simulators in both alleviating the condition and training for its prevention.

1.1.3 Kinds of Simulation

The overall purpose of a training simulator is to develop people's skills, whereas that of an engineering development simulator is to develop aircraft. Within the two broad classifications of training and engineering development simulators, several distinct types can be identified. For training simulators, the types vary with the training scope. With engineering development simulations, the important factor is the amount of flight hardware included or represented. The important features of several types within each class are further amplified in Table 1-2.

1.1.4 Results of Simulation

The result of all simulation is learning although it assumes many forms. The learning associated with pilot training is obvious. It results in what is termed "transferability" to the actual aircraft. This simply means that skills learned in the simulator will allow the pilot to fly the actual aircraft with the same performance. Measures of simulator training effectiveness include training trials (time) required to perform according to a criterion (performance) compared to that for the actual aircraft. While it is a relatively easy matter to measure this "transferability," it is more difficult to determine what elements of the simulation contribute to it, e.g., cockpit, visual system, motion platform, instructional method, etc.

The result of engineering development simulations is knowledge about hardware or design concepts. This takes the form of pilot opinion, maneuver time histories, hardware performance in a simulated environment, or engineering judgments following observation of the simulated aircraft as it is "flown" through various maneuvers. The physical result of the training device is intangible, whereas that from the development simulator is usually quite visible and sizable. The training simulator's computer is a "hard-wired" device that cannot be re-programmed or accessed easily while the computer of the engineering simulator is a general-purpose device that permits re-programming and access to a large number of its computations, a feature that is necessary in the laboratory. This aspect is the main distinguishing

TABLE 1-2

CLASSES AND TYPES OF SIMULATION

CLASS	TYPE	DESCRIPTION	USES	END PRODUCT
TRAINING	Procedural	Simple, non-functional cockpit	Teaching normal and emergency procedures	Procedural Skills
	Part-Task	Simple, but limited function cockpit computer, displays, motion platform, etc.	Teaching required skills for limited tasks	Flying skills for a few tasks
	Full Mission	Complex, full capability visual, motion cockpit multi-crew multi-aircraft, etc.	Teaching required skills for all phases of a given aircraft's mission	Full spectrum of flying skills for a given aircraft
ENGINEERING DEVELOPMENT	Computer Simulation	Simple or complex computer with some hand manipulator inputs and graphic outputs	To study dynamic problems, proof-of-concepts, preliminary design, etc.	Dynamic problem solution, design verification
	Rudimentary Cockpit Simulation	Simple or complex computer with simple cockpit and crude displays	To conduct preliminary assessment of handling and ride qualities	Preliminary handling and ride qualities
	System Simulation	Sophisticated computer simulation with complex displays and motion, extensive data analysis	Engineering design verification and refinements. Detailed performance estimates. First flight procedures	Confidence in design concept
	Hardware Simulation	Sophisticated computer, motion, visual systems integrated with actual flight hardware	Hardware verification, failure analysis; life cycle estimates and environmental effects	Confidence in hardware

feature between training and engineering development simulations. The Advanced Simulator for Pilot Training (ASPT) is an exception since it is used for training research. It uses a general-purpose computer and is operated in a laboratory environment.

1.2 SURVEY OF SIMULATION ADVANTAGES AND LIMITATIONS

1.2.1 Savings Through Simulation

By far, the largest savings associated with simulation is the operating cost per hour compared with that of the machines represented. This is the case for both training and engineering simulations but is especially clear for trainers. This is because accountability associated with a training program is simpler than that for an engineering laboratory where hardware is shared with other programs. Engineering development simulators, on the other hand, cannot be easily described in the same terms because direct comparisons of costs associated with development without simulation are seldom available.

Some examples of direct operating cost, however, are available and they are described here to illustrate the point. In the early 1970's, American Airlines set out to achieve 747 transition training using only simulators. The cost drivers cited were that the 747 direct operating cost for training was $2900/hour (loss of passenger revenue is not included) while the simulator cost was about $300/hour, a cost advantage of ten to one. This demonstrated example is an airline industry milestone and since that time, the acceptance of simulation for nearly all training among the airlines has been high.

The acceptance in the military services has been slower, primarily because of the difficulty in designing simulation equipment to meet the more demanding military needs. Recently, the rate of acceptance is increasing because hardware (particularly visual) is rapidly improving, and because of the pressures to reduce fuel usage and extend the life of aircraft.

The example cited for engineering development is one where an airborne control computer was verified using a ground based simulation. The actual computer was integrated with an engineering simulation of a helicopter, and its control laws were verified by "flying the simulation" to the design limits. Approximately 100 hours of simulator testing were required to "debug" the computer which was subsequently flown without incident. It was estimated that the reduction in flight test costs (approximately $4000/hour) more than offset the cost of the simulation and resulted in a savings of at least $100,000.

1.2.2 Flight Hardware Evaluation

Although the methods for analysis of piloted aircraft are highly developed, these methods are still not comprehensive or able to handle complex interactions. The large variety of flight conditions possible also makes analysis cumbersome.

In the early days of aircraft development, the only way to assess the "flyability" of an aircraft was to fly it. The pilot's observations and judgments were the only "flight data" available. While today's engineering development simulations are largely justified and evaluated on more technical and abstract terms, the "try it out" philosophy still provides a great stimulus to simulation work. The "first flights" in an engineering simulation of a new aircraft are quite revealing. The complete flight envelope can usually be explored in an hour and potential problems quickly assessed. The controlled laboratory environment allows for safety while simplifying data acquisition.

What is really attractive about an engineering development simulation is that actual hardware elements may be inserted into it for evaluation. When a new aircraft is built, a "hardware test stand" is built to verify the flight control concept. This consists of an "iron bird" that mounts the actual flight control hardware. It usually contains a partially instrumented cockpit and sometimes a platform-mounted sensor unit. It is a relatively simple matter to include more visual display equipment and build an engineering simulator out of the stand. On the other side, a simulation that includes only mathematical representations could be tied to the hardware test stand. In essence this is nothing more than replacing computer models by real hardware. The important interaction here is the gradual replacement of simulated elements by real elements. This is the basic mechanism that gives the designer a means for evaluating his knowledge and establishing confidence in his designs in a safe, controlled operational environment.

Some of the more important uses of an engineering development simulator are summarized below:

- Evaluation of Flight Control Hardware. The kinds of hardware commonly evaluated by this method are: control surfaces, actuators, linkages, force feel systems, sensor packages, airborne control and air data computers, and central and side manipulators.

- Evaluation of Displays. Fire control, target acquisition, reconnaissance, systems monitoring, navigation, and landing displays are among those evaluated by the simulation method. Low-light-level television displays, infra-red scanning devices, and other similar equipment is generally not evaluated in the simulator but used as an element in an experiment. This is because these devices are not usually compatible with the outside scene generator of the simulator.

- Evaluation of Human Factors Equipment. It is especially useful to test equipment designed to maintain human effectiveness. Lighting, panels, seat arrangement, auxiliary controls, and communication equipment can be effectively evaluated. Devices such as "g" suits which compress parts of a pilot to prevent blackout under high acceleration obviously cannot be evaluated in a device that can only produce small accelerations. Centrifuges are normally used for this level of work. These are of course a special-purpose simulator.

The reader will see that the above uses center about the human and how he is integrated with the machine. Human outputs and inputs are generally areas where fruitful work can be accomplished in simulators. Devices that more effectively accomplish human integration can easily be evaluated by the simulation method.

1.2.3 Effects of Fidelity on Results

Fidelity is a word commonly used to indicate the degree of quality of a simulation. It is inferred that quality is synonomous with closeness to the real world but this is not necessarily true. For example, a particular visual display may provide enhanced cues so, in some respects, its quality may exceed that of the real world. To aid the discussion, fidelity will be defined in two ways. Engineering fidelity will mean the measured physical closeness to the real world. Perceptual fidelity will mean the perceived closeness. Engineering fidelity will be used to describe the mathematical model quality, for example. Perceptual fidelity will be used to describe the quality in terms of subjective pilot response and could be used to describe the quality of a visual landing display, for example.

It is natural to expect that the fidelity of simulation will affect simulation results. A clear example of this is the fidelity effect of the mathematical model*. All simulations include a body of computations that describe the motions of the aircraft being simulated. Pilot control commands form the inputs to these computations. They then produce the aircraft's attitude and position in space and higher derivatives of these quantities. The "modeling art" is highly developed, and the "modeler's bag of tricks" is extensive. With the use of sophisticated tools such as wind tunnels, flight test instrumentation, and good theoretical methods, a model of an aircraft can produce responses that can closely approach those of the real aircraft.

When these models become large enough that their computer implementation becomes difficult, compromises are sought that generally reduce engineering fidelity. This is almost always the case and the desired model has to be simplified in order to "fit" on the computer.

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* The term "model" means the mathematical function has a theoretical basis as opposed to a representation which could be a fitted function of measured wind tunnel data.

If such a compromise is made, the resulting simulated aircraft responses will differ from those of the real aircraft and the observed handling qualities, for example, may also differ.

The simulation user must, therefore, determine the level of engineering fidelity required for his experiment. Some of the factors that affect this judgment are:

- The kind of results sought; handling qualities estimates generally do not require the high fidelity that performance measurements do
- The accuracy of the environmental aerodynamics, propulsion data, etc., that are the basis of the model
- The degree to which the simulation can show to the pilot the effects under study. If, for example, the visual or motion system cannot show the differences between several configurations due to system limitations, there is no justification to examining these configurations. In other words, the engineering fidelity desired should depend in part on the perceptual fidelity available.

Perceptual fidelity is the term that is usually used to describe the pilot interfaces, i.e., the visual, motion, force feel, tactile, and aural subsystems. This index relates to the quality of information to and from the pilot. It can be measured subjectively using pilot opinion and, in some cases, objectively through the identification of pilot model parameters. Often, a low value is the root cause of simulator-related problems.

In assessing perceptual fidelity, the most important factors appear to be:

- <u>Hardware performance relative to human performance</u>. By this it is meant that hardware performance should be judged relative to human performance. For example, the ability of a visual display to show fine detail should not be greater than that of the eye. The ability of a motion platform to show a force change should be judged relative to the human's ability to sense it.

- Pilot bias or prejudice. A pilot familiar with helicopters would probably be less sensitive to fine changes in perceptual fidelity associated with a transport because he has had to learn so many compensating control techniques not required for flying the transport.

- Pilot skill level. There is some evidence suggesting that neophyte pilots are insensitive to motion platform engineering fidelity, whereas experienced pilots are more sensitive. This suggests that skill level is commensurate with information processing capability. The inference is that training simulation may not require the fidelity that an engineering simulation does.

- Pilot workload. Recent research results (Ref. 2) indicate that motion perception threshold levels vary with workload. The varying threshold implies a varying perceptual fidelity.

- Task. This is considered to be one of the more important factors in establishing validity. Whether the task be height judgment using a visual system or tight control of attitude during an attack using visual and motion systems, the task will affect perceptual fidelity because the sensory mechanisms of the human are structured for excellence in some tasks but not others.

The effects on the fidelity measures described almost always result in degraded total (pilot/aircraft) performance. There are cases, however, when no degradation is apparent because the pilot adapts a new strategy in flying the simulator. For example, the current television visual systems do not allow real-world landing performance (e.g., touchdown sink rate) probably because of their optical and mechanical properties. Pilots, however, can, by practicing, achieve real-world landing performance using them (Ref. 3). Their workload is higher than that in the real world and their eye scanning behavior is different. It is generally agreed that for perceptual fidelity to be high, pilot workload, pilot behavior, and aircraft performance should be close to that of the real world.

Before leaving this introduction to fidelity, which is covered more in later sections, it is stressed that engineering fidelity is a relatively straightforward measure. It is readily estimated by a variety of mathematical methods and is applied to the hardware elements of the simulation that include the mathematical model and those that affect the hardware performance. The perceptual fidelity, on the other hand, is used to describe the effectiveness of the pilot interfaces such as the force feel, visual, aural, tactile, and motion systems. It is a more difficult measure to take and requires clever experimental procedures and special equipment.

1.3 SURVEY OF CURRENT SIMULATORS

1.3.1 Overview of Visual and Motion Simulators in Use Today

The following paragraphs contain an overview of five simulators in use today within the U.S. and Canadian Governments. Both engineering development and training devices are represented. They are described in terms of their major subsystem elements and uses, namely:

- Cockpit
- Computer and control station
- Visual system
- Motion system
- General uses.

Four of the five examples illustrated are of the ground-based type. The fifth is an airborne simulator. All show the variations possible such as provisions for single or multi-crew members, single or multi-aircraft, visual or motion emphasis, and engineering or training emphasis.

The in-flight simulator will obviously appear different because it is a modified helicopter as opposed to the laboratory environment of the ground-based facilities.

One ground-based simulator described (ASPT) is devoted totally to training research. A comparison of this device with the others will reveal the basic differences between training and engineering simulations. This is, in essence, a difference in the structure of the computer control station. In general, the training device computer is a special-purpose machine whose program is relatively fixed. The control station (used by the instructor) contains an extensive array of controls and displays. These allow the instructor to vary quickly the flight condition and monitor <u>student</u> performance. The ASPT computer system, however, is general-purpose in keeping with the research uses of the device.

The engineering simulator is usually supported by a complex of general-purpose computers and peripherals. The control station in this case is the computer terminal and may include graphic displays, plotters, and strip chart recorders. These permit the monitoring of the <u>aircraft</u> being simulated.

The concepts employed in today's simulations are summarized below by element.

a) <u>Cockpit</u>

This is usually a metal structure similar to the cockpit portion of a typical airplane or helicopter. It contains seats, manipulators, instruments, displays, and aural devices. The engineering cockpits embody quick-change principles so that the instrument, control, and seat arrangements can be varied. Some cockpits may be completely lifted off their mounts for changeover to another. The interior of the cockpit of the P-3C Weapon System Trainer is shown in Fig. 1-2.

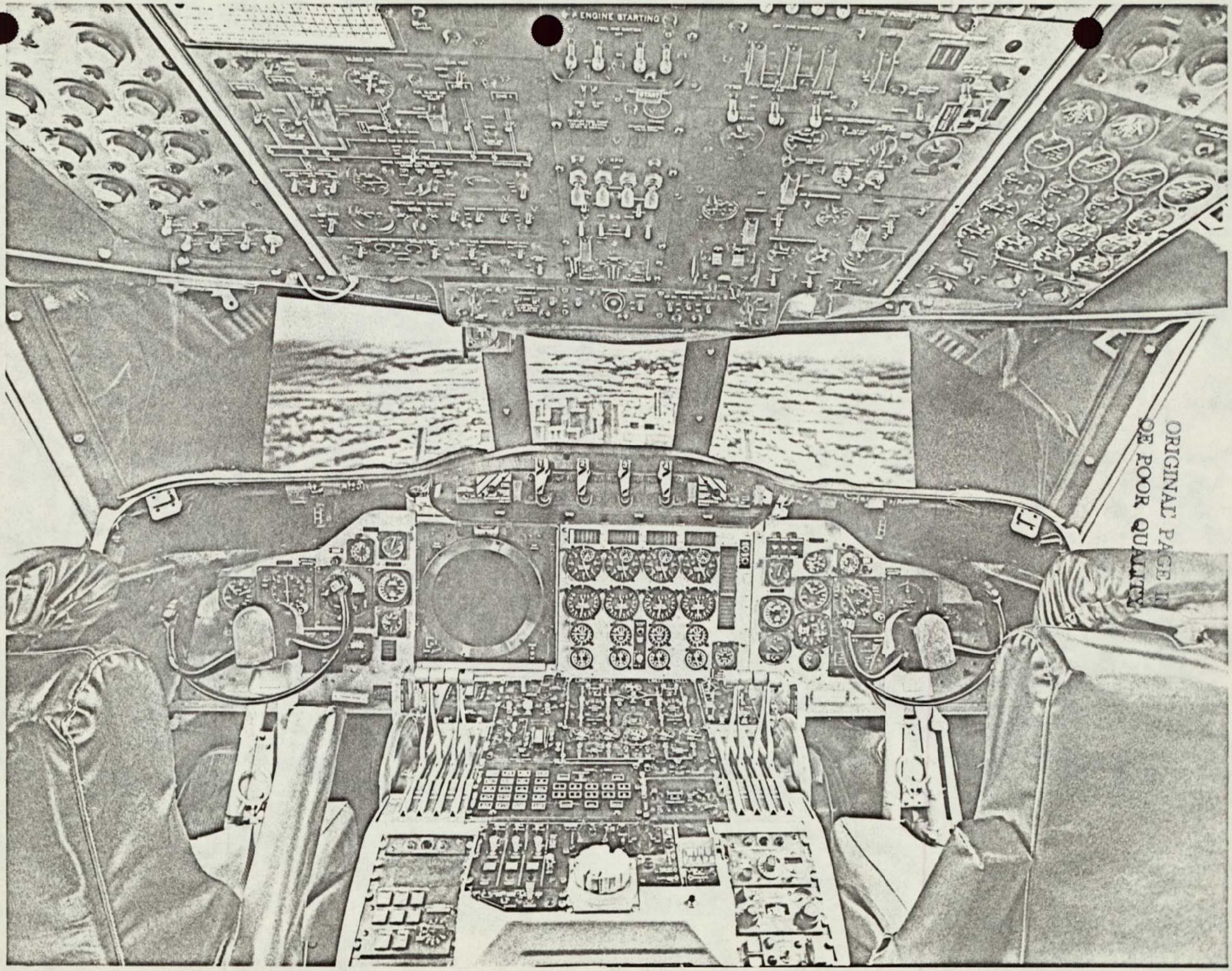

Figure 1-2. Cockpit of the P-3C Weapons Systems Trainer

b) Computer and Control Station

This is the intelligent heart of the simulation. From here, all functions are monitored and controlled. The computer may be of the digital, analog, or hybrid type. Commonly employed peripherals such as printers, teletypewriters, etc., can be attached or a sophisticated control station may be included for the instructor's use. All the computations required by the simulation are performed by the computer complex. Figure 1-3 shows this complex for the Air Force Flight Dynamics Laboratory Flight Simulation Facility.

c) Visual System

This element produces the outside scene as would be seen by the crew members. Three concepts are commonly used today, television, computer-generated imagery (CGI), and point light projection. The television concept employs a camera driven past a vertical model of the simulated world. This is accomplished by a computer-controlled motorized gantry structure. The camera is fitted with an optical device called a probe. This varies the "look angles" of the camera and serves to fix the "viewing point" relative to the model board. The small size of the probe head also allows a close approach to the model board to simulate low altitudes. A view of a model runway with a penny on it is shown in Fig. 1-4 as photographed through a probe. The gantry and model board of the Flight Simulator for Advanced Aircraft are shown in Fig. 1-5.

The computer-generated scene is employed in much the same way. The cockpit display elements are similar; the method of creating the scene being different. Within a digital computer are stored the coordinates of and numbers representing the light values of the simulated

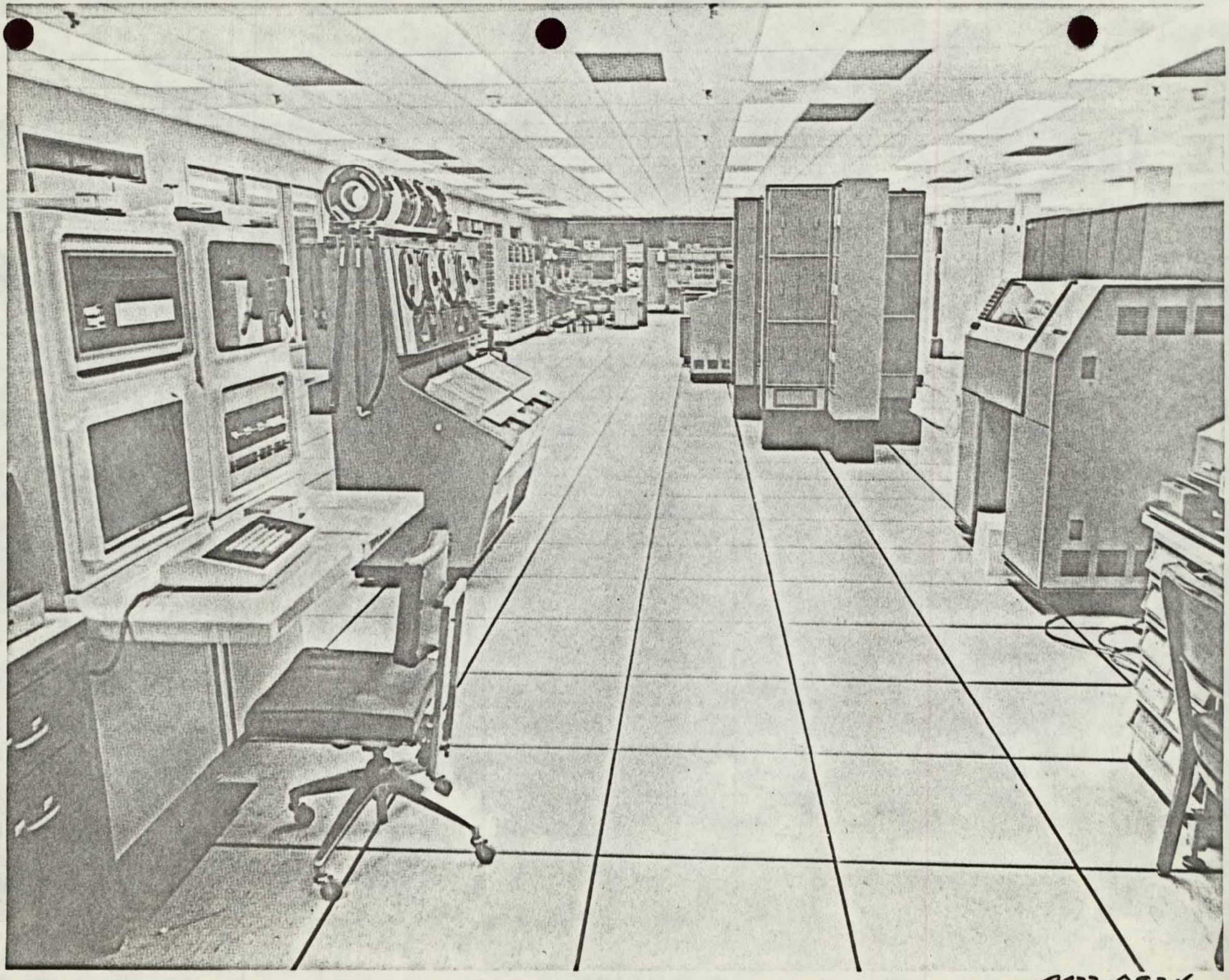

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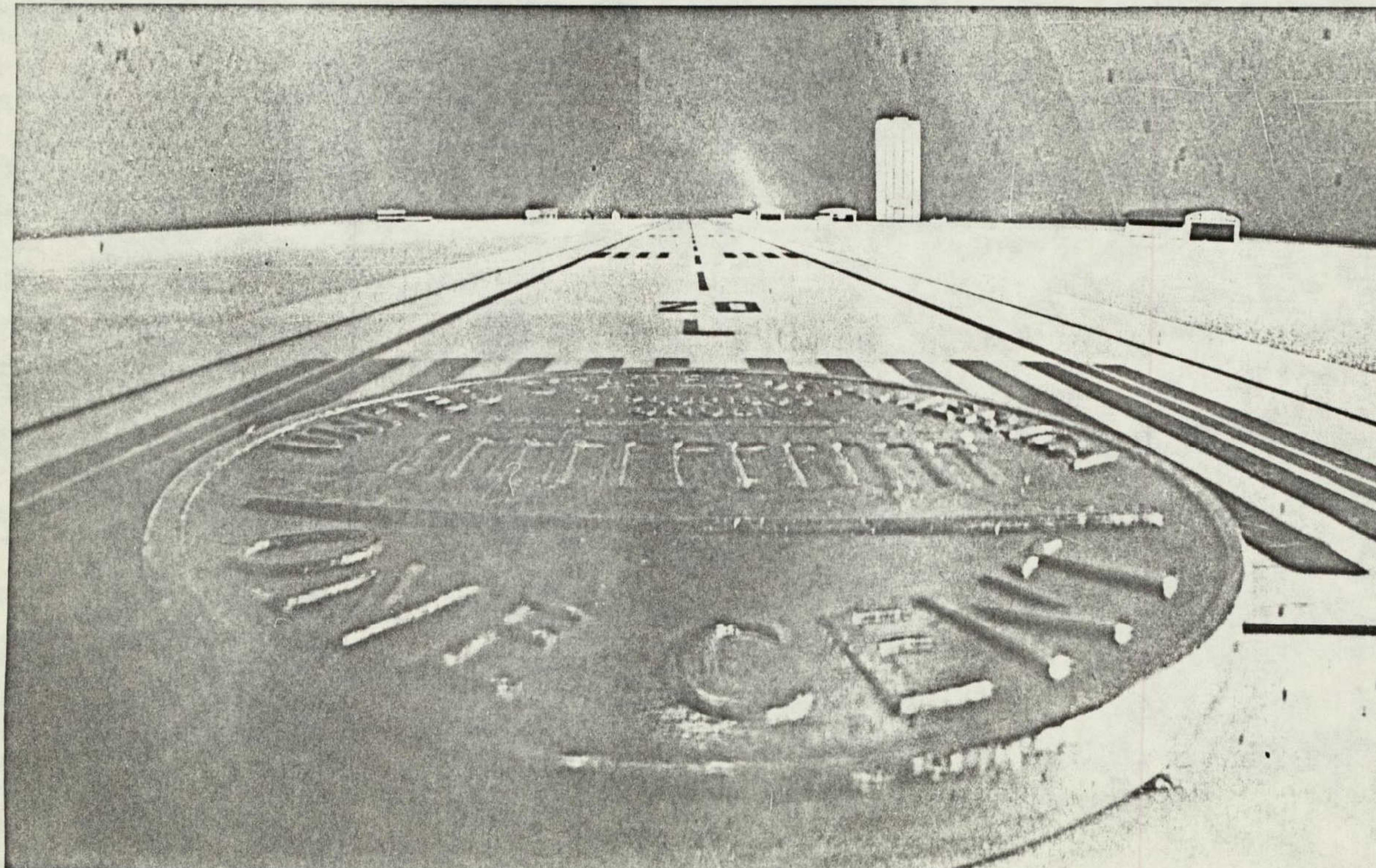
Figure 1-3. Computer Laboratory of the Air Force Flight Control Development Laboratory (Flight Dynamics Laboratory)



Photograph Represents a Horizontal 97 degree Real Field of View and was Taken at 0.2 inches (8 foot long Model 1400:1 Scale) at F/7.0. <u>Tilt Focus Correction Applied</u> (Focussed on the Runway).

Figure 1-4. Pilot's Eye View of a Scale Model Runway

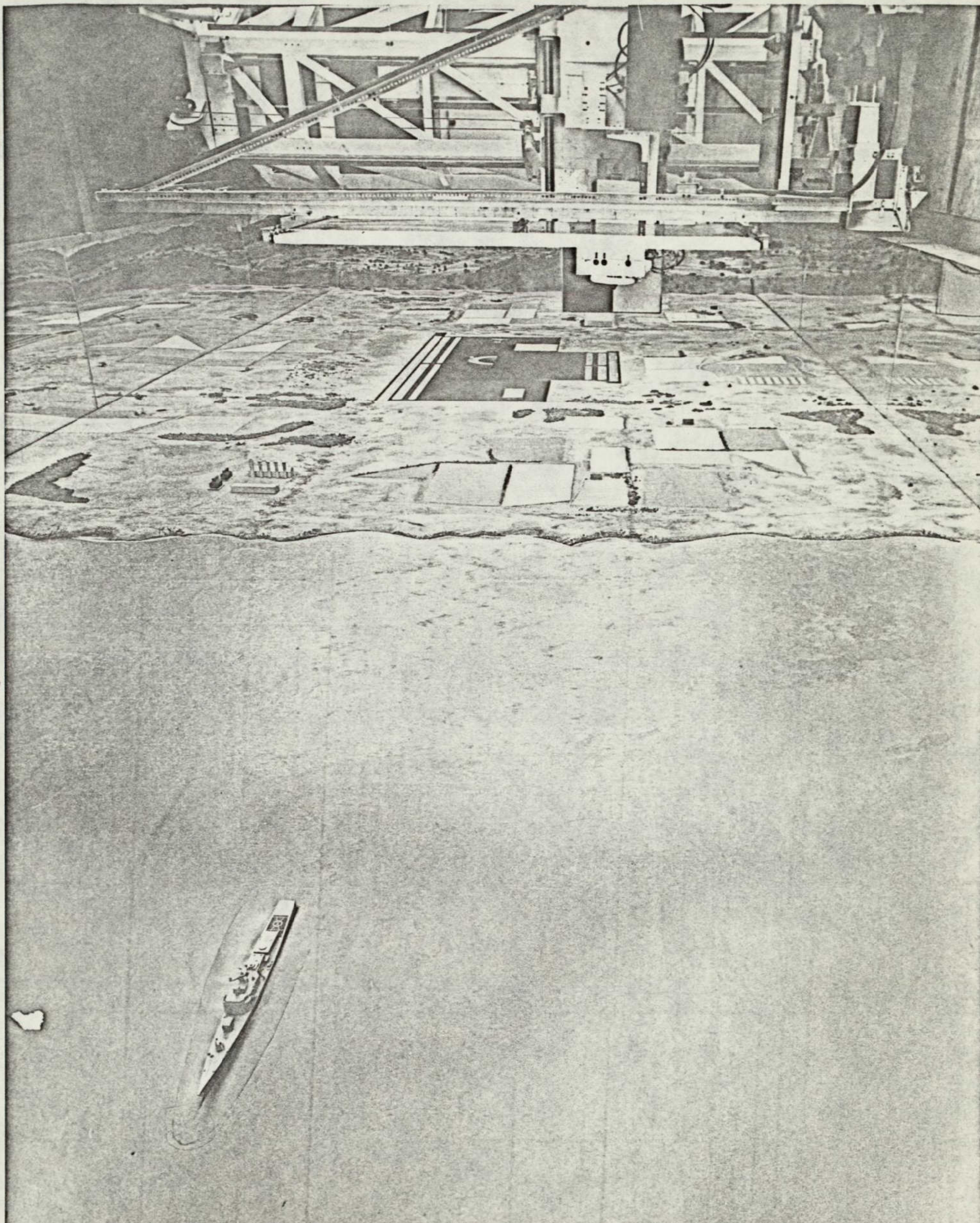


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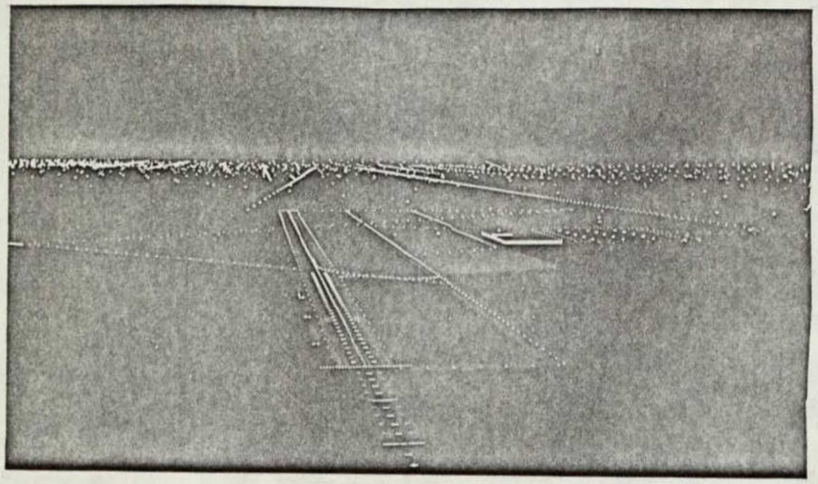
Figure 1-5. Gantry and Model Board of the Flight Simulator for Advanced Aircraft world. These are then retrieved for any viewing point in this world and the data used to reconstruct the scene as would be viewed from this point. The scene details are then "drawn" on a cathode ray tube device in the cockpit. Smoothing and shading techniques are used to create imagery that is convincingly realistic. Several computer-generated scenes are shown in Fig. 1-6.

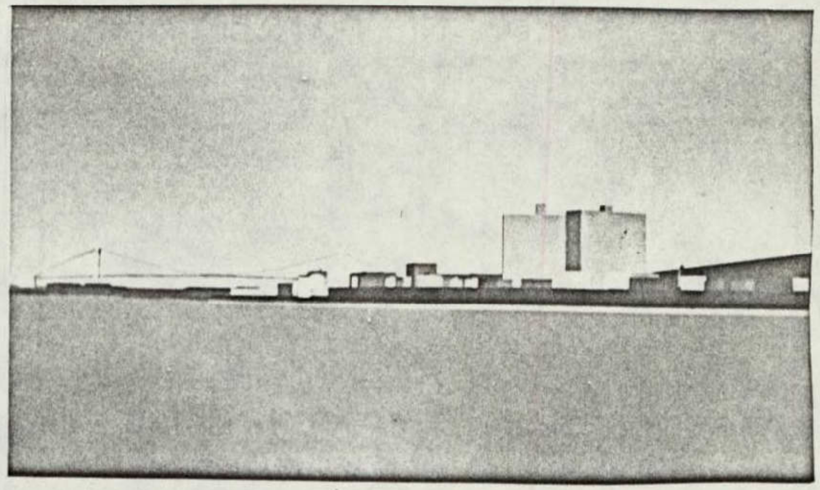
Point light source projectors are also used when wide fields of view are required without fine detail. A transparency containing models is driven past a point source near the center of a spherical screen. The transparency's shadows projected onto the screen will form a dynamic image of the models that is useful for wide-angle visual flight reference. Figure 1-7 shows a photograph of a scene created by a De Florez point light source projector.

When the cockpit device is a cathode ray tube (CRT) a series of lenses or mirrors and beamsplitters is used to create the impression of distance. These optical devices collimate the light emanating from the CRT so that the scene appears to be far away. When large lenses are placed before TV monitors, they act as magnifiers; enlarging the apparent view of the TV picture while collimating it or focusing it far away.

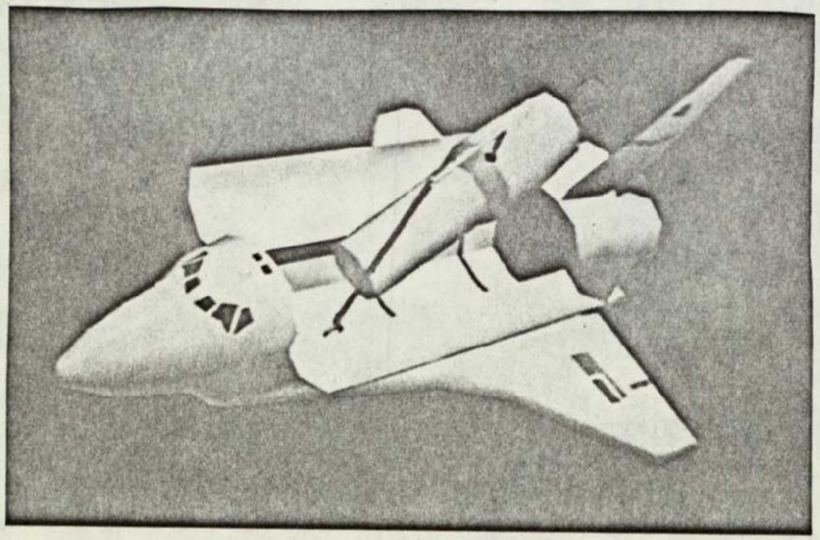
Collimation can also be created by a spherical mirror except that the TV monitor must be coincident with the viewer's eye. To overcome this, the viewer's eye and the TV monitor display device are offset. This is the principle of DUOVIEW. A 45 deg beamsplitter may be used to separate monitor and eye. The "pancake windows" of the Advanced Simulator for Pilot Training fold the light path through the use of polarizing



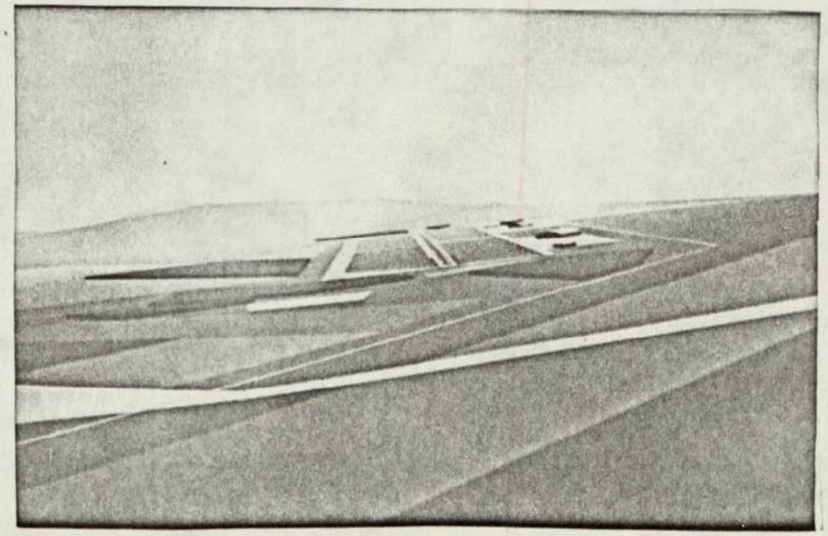
NOVOVIEW



Visual Scene for Ship Operations



NASA Space Shuttle Orbiter



Airport Scene for the Lufthansa Trainer

Figure 1-6. Computer-Generated Scenes (Courtesy of Evans and Sutherland)

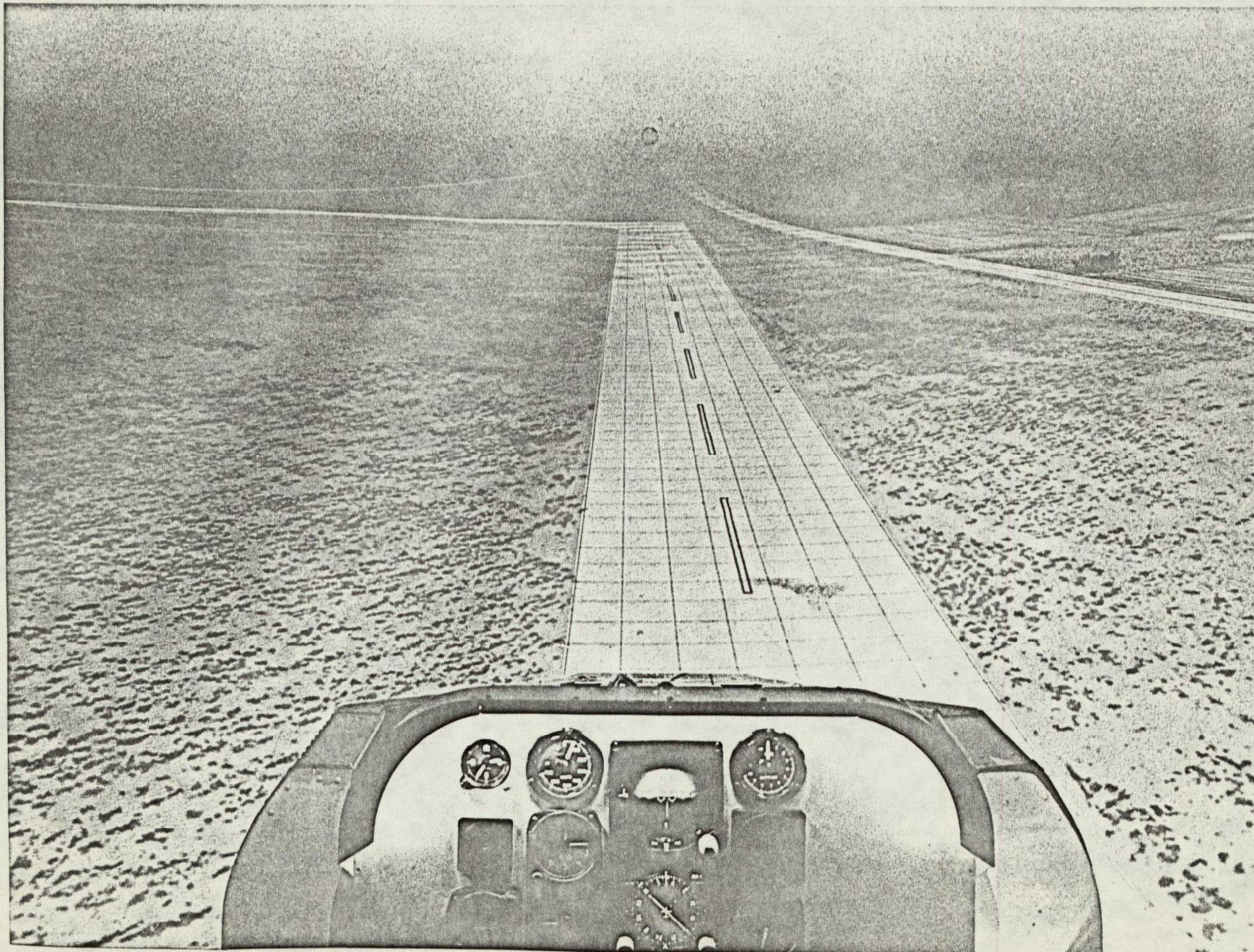


Figure 1-7. Airport Scene Created by a De Florez Point Light Projector

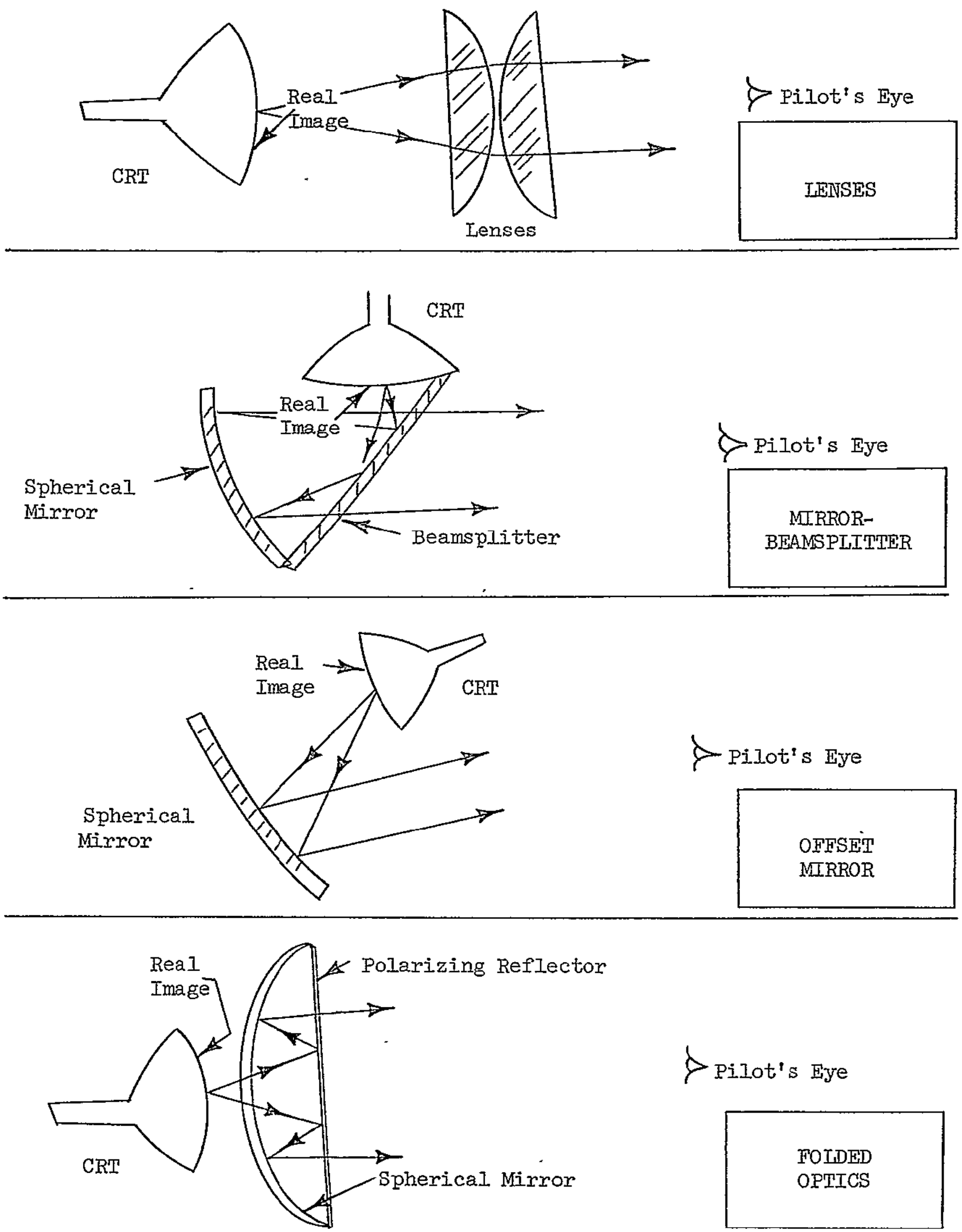


Figure 1-8. Four Methods of Collimating a CRT Display

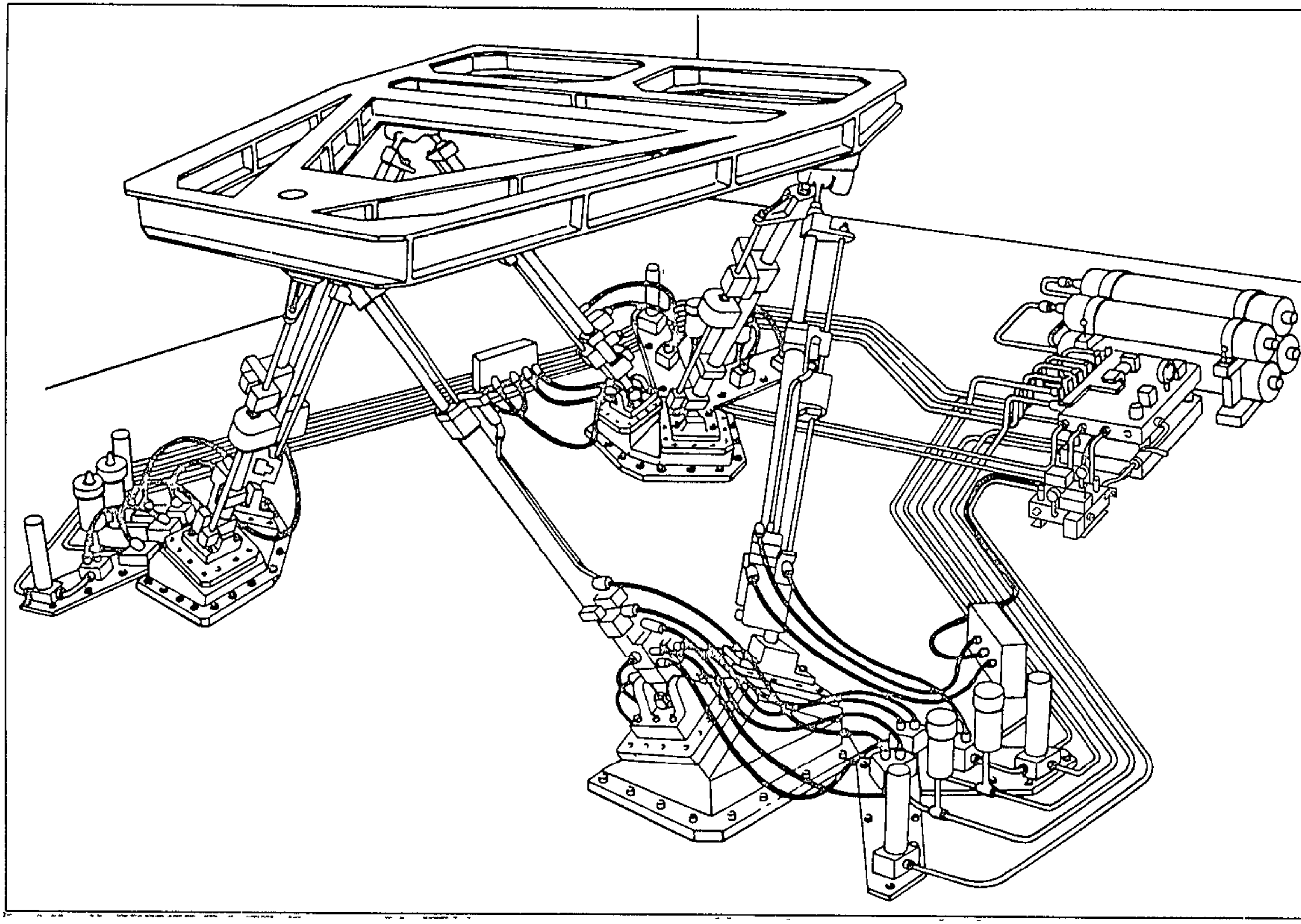


Figure 1-9. Six-Degree-of-Freedom Motion System

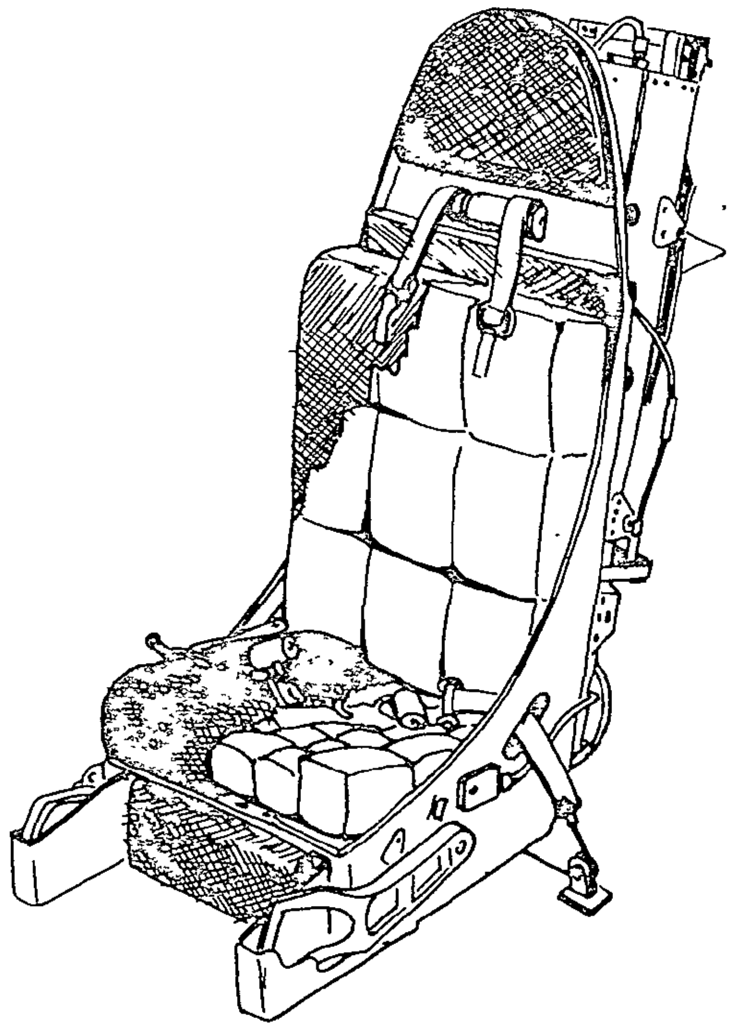


Figure 1-10. "G" Seat of the Advanced Simulator for Pilot Training

1.3.2 The Flight Simulator for Advanced Aircraft (FSAA)

The NASA-Ames Flight Simulator for Advanced Aircraft	
CLASS	General purpose, engineering research and development. Ground-based.
USES	Research and development of aeronautical vehicles and systems
Elements	
COCKPIT	Transport-type; side-by-side seating with jump seat. Center overhead and side consoles. Three-axis control loaders with stick or wheel and pedals. Standard instruments. Dual speakers for aural cues. Collimated television monitors for both pilot and copilot for outside scene. Communications and computer controls are provided.
COMPUTERS	Xerox Sigma 8 and Sigma 7, two EAI 8400 digital computers. PDP-11 graphics digital computer. EAI 8800 and numerous 231-R analog computers. Comcor 175 analog computers. Disk units, printers, CRT terminals, and conversion units.
VISUAL SYSTEM	Two color television camera/model systems. Scales of 400/1 and 600/1. Field-of-view 36° vertically by 48° horizontally. Resolution about 480 TV lines in both directions. Roll and yaw continuous, pitch ± 25 deg. Approximate fly-over space, 13 km x 3 km x 700 m. Closest approach to the model is about 2 mm. Closest focus is about 25 mm. Generates scene from a single aircraft.
MOTION SYSTEM	Six-degree-of-freedom gantry and gimbal assembly supporting the cockpit. Driven by electric motors through gears, chains, toothed wheels on rubber faced tracks. Large amplitude; approximately ± 30° rotations, ± 12 m sway, ± 1.3 m heave, ± 1.0 m surge. Bandwidth 2 - 4 Hz. Variable linear drive logic with limiting functions.
Photograph of this device in Fig. 1-11.	

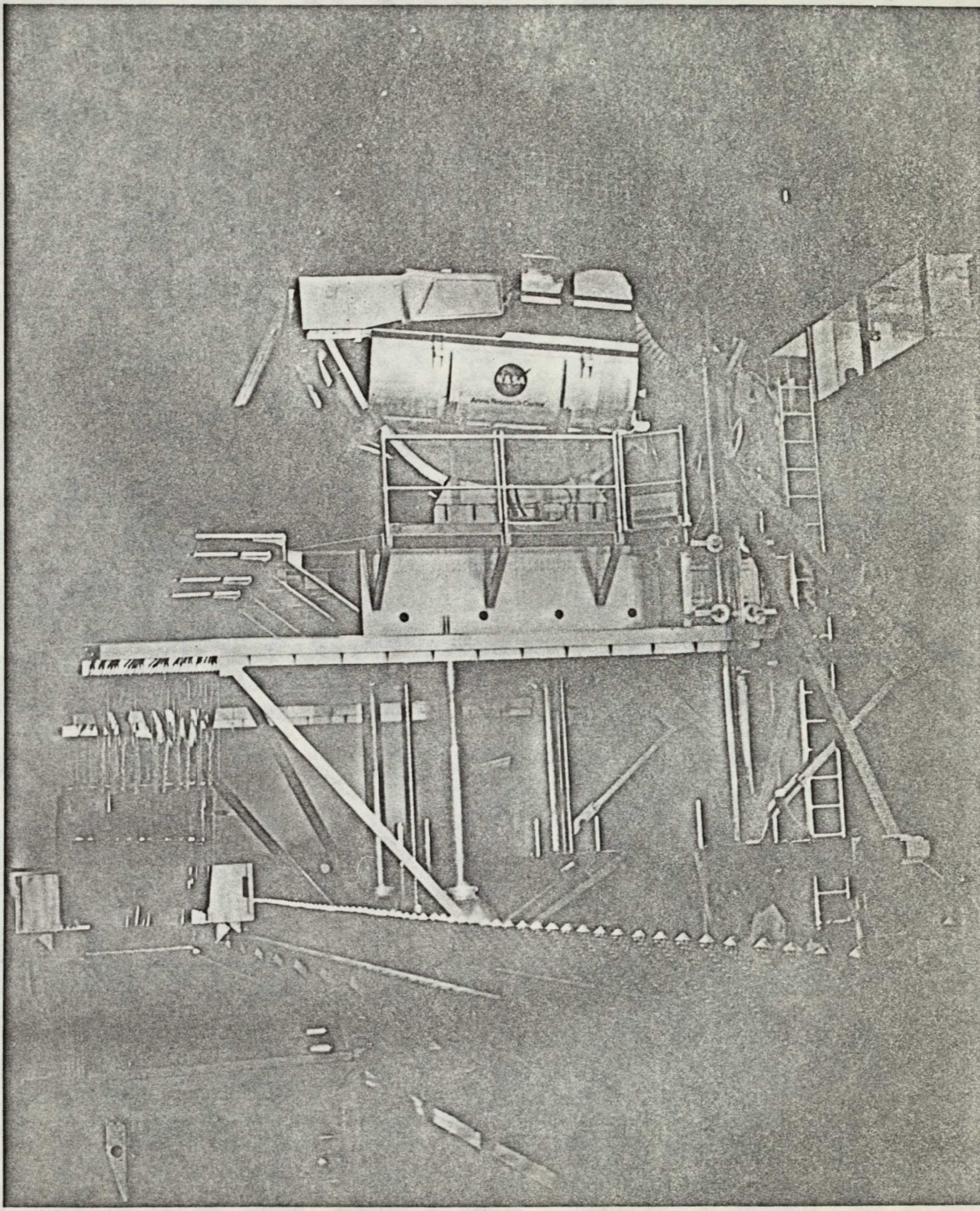


Figure 1-11. The NASA Ames Flight Simulator for Advanced Aircraft (FSAA)

1.3.3 The Advanced Simulator for Pilot Training (ASPT)

Advanced Simulator for Pilot Training (ASPT)	
CLASS	General-purpose training research simulator; ground based
USES	Research and development of training methods and related simulation equipment
Elements	
COCKPIT	Two T-37B cockpits, two-place side-by-side; standard instrument group. Additional displays and controls for simulator operation, monitoring, and control. Control loaders for both student and instructor for stick, pedals, and throttle. Aural simulation of engine, airflow, landing gear, rain, hail, thunder, etc. Closed circuit television for monitoring pilots.
COMPUTER/CONTROL STATION	Single SYSTEMS 86 central processor unit with 93K word core memory. Peripherals include: teletypewriter, line printer, card reader, disc, two magnetic tape units, and digital plotter. Linkage and real-time monitor system. Foreground/background computational capability allows computer use without simulator down time. Two conventional and one advanced instructor/operator station. The conventional station is a standard instructor/operator station with repeater instruments and traditional input/output. Advanced station uses four cathode ray tubes, switches, and a keyboard for control of many varied simulator and training functions.
VISUAL SYSTEM	Wide-angle ($\pm$ 150° horizontally, +110°, -40° vertically) high-resolution (7 arc-minutes) display formed by seven pentagonal display units. Units are 30 inch diagonal high-brightness CRT's with pancake windows for collimation. Units are mosaicked together and held by a common frame. Monochromatic images are generated by a computer-generated imagery scheme producing 2000 edges in the scene. Scenes generated include Williams AFB, all T-37 contact practice areas, auxiliary airport, a formation flight image of another T-37, and a 50 nautical wide perimeter around the flight areas. All attitude capability.
MOTION SYSTEM	Six-post synergistic six-degree-of-freedom electrohydraulic motion platform with redundant legs. G seats in both cockpits. Stick shakers and buffet simulation. Flexible drive algorithms for research.
Photograph in Fig. 1-12.	

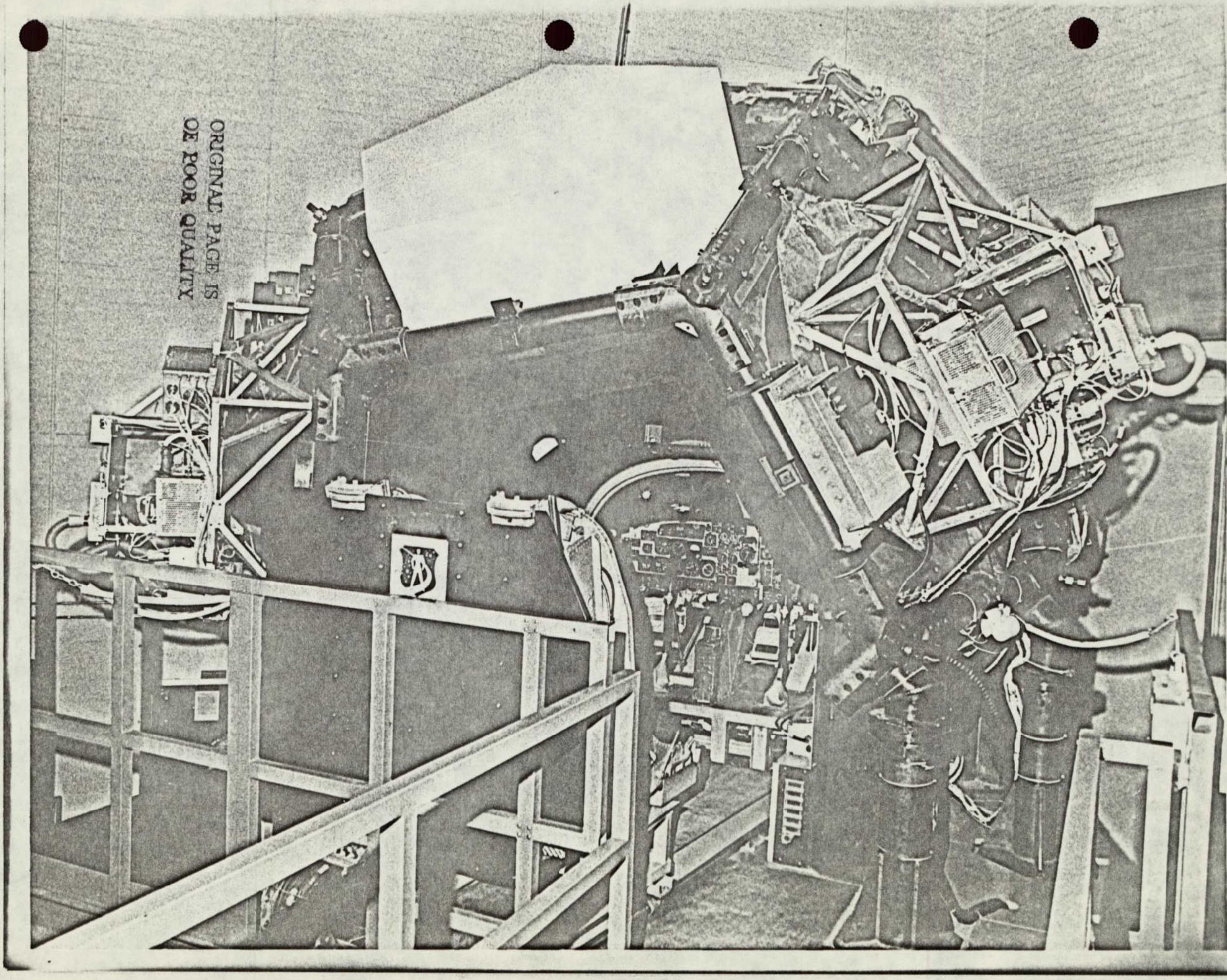


Figure 1-12. Advanced Simulator for Pilot Training (ASPT)

1.3.4 The Differential Maneuvering Simulator (DMS)

The NASA-Langley Differential Maneuvering Simulator	
CLASS	General-purpose engineering research and development. Ground-based.
USES	Research and development of air combat vehicles and tactics.
Elements	
COCKPIT	Two cockpits, single-place, century series fighter configuration. Standard instrument group with head up and head down graphics displays. Three-axis control loaders with conventional stick and pedals. Aural cue generator. Buffet actuator on heave. Communication and computer controls. "G" suit. Interchangeable front and side consoles. Bubble canopies.
COMPUTER	Eight digital computers operate in multi-program, multiprocessor environment. These include three Control Data Series 6000 machines, two Cyber 175's, two Cyber 173's, and a Star-100 Vector Processing Computer. Multiple access switches provide access to standard peripherals, bulk storage, and special real-time interfaces. A real-time simulation subsystem synchronizes and accesses programs for the Differential Maneuvering Simulator. Three fully-expanded EAI 231-R and two GPS 10,000 repetitive-operation analog computers are available.
VISUAL SYSTEM	Two fixed-base spherical screens surround the cockpits. On each is displayed a sky-earth scene produced by a four-gimbal point light source projector. The sky-earth projector shows only rotational movement, not translations. A television projector is combined with gimballed mirrors and a zoom lens to produce an image of a fighter aircraft anywhere within the spherical screens. The fighter image is generated by a camera viewing gimballed models. Continuous rotation is possible without lock or occlusion. System bandwidth is 4 Hz. High performance servosystem makes the simulator capable of following spins, departures, etc.
Photograph in Fig. 1-13.	

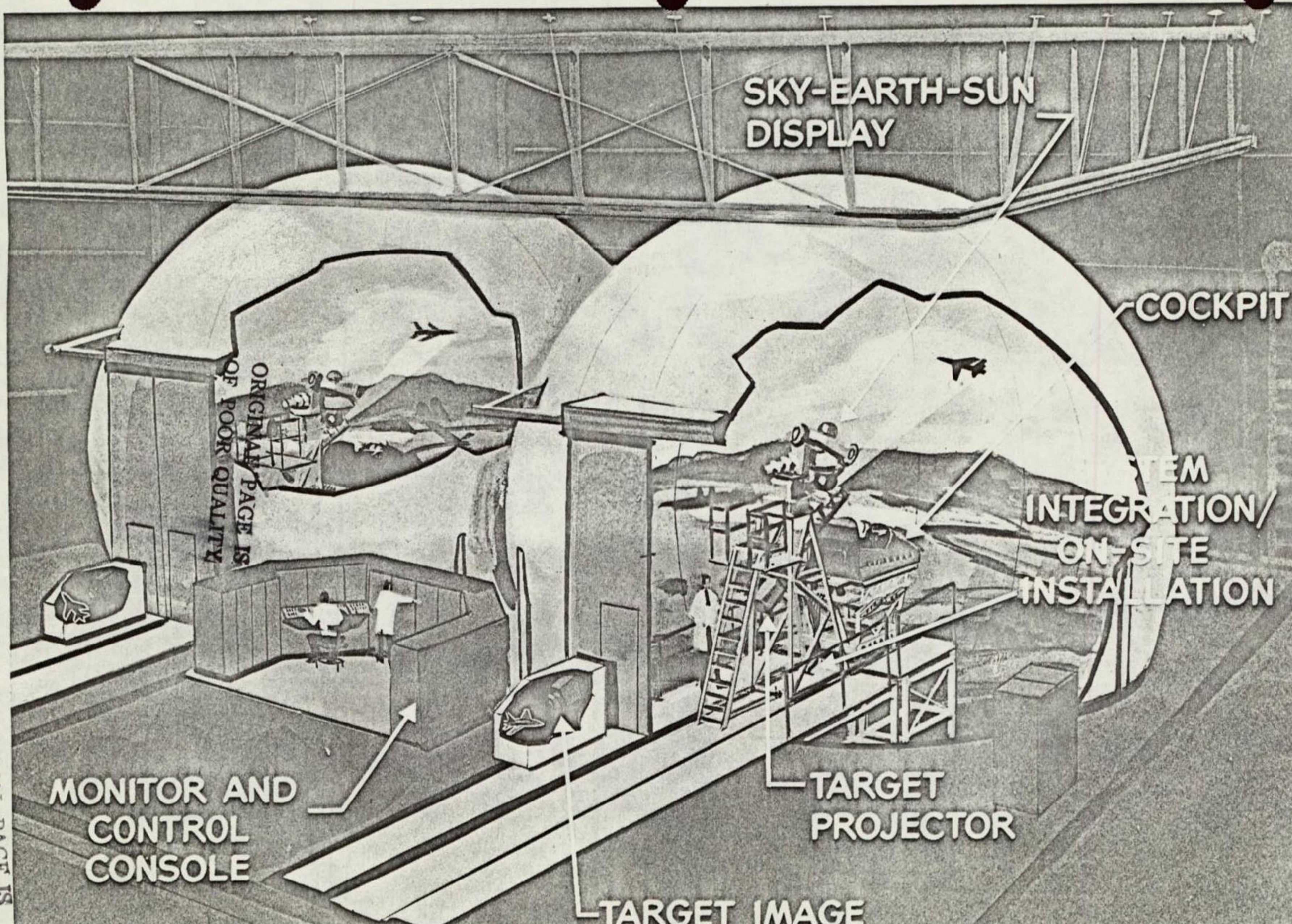


Figure 1-13. The NASA-Langley Differential Maneuvering Simulator (DMS)

1.3.5 The Large Amplitude Multi-Mode Aerospace Research Simulator (LAMARS)

The Air Force Large Amplitude Multi-Mode Aerospace Research Simulator	
CLASS	General-purpose engineering research and development. Ground-based.
USES	Research and development of aeronautical vehicles and systems.
Elements	
COCKPIT	Fighter-type. Typical of century-series aircraft with a single seat. Center and side consoles. Three-axis control loaders with stick and pedals. Standard instrument group with head up and head down displays for fire control. Communication and computer controls.
COMPUTERS	Several EAI 8400 and PACER digital computers linked to many EAI 8800 and 231-R analog computers and peripheral equipment. Basically a hybrid facility with high flexibility in architecture.
VISUAL SYSTEM	Television projection and point light type. Cockpit is surrounded by a spherical screen on which are projected a sky-earth scene from a point light sky-earth projector. A gimballed television projector produces a fighter aircraft image or a ground scene generated by a camera model system. Field-of-view is 266° horizontally by 108° vertically.
MOTION SYSTEM	Five degree-of-freedom, beam type motion base. Driven by electrohydraulic servomechanisms. Vertical actuator is integrated with a pneumatic equilibrator to hold the beam up and provide safety margin. Heave and sway travels ± 3.3 m. Pitch, roll, and yaw ± 25 deg. Bandwidth is 4 Hz. High performance velocity and acceleration.
Photograph of this device in Fig. 1-14	

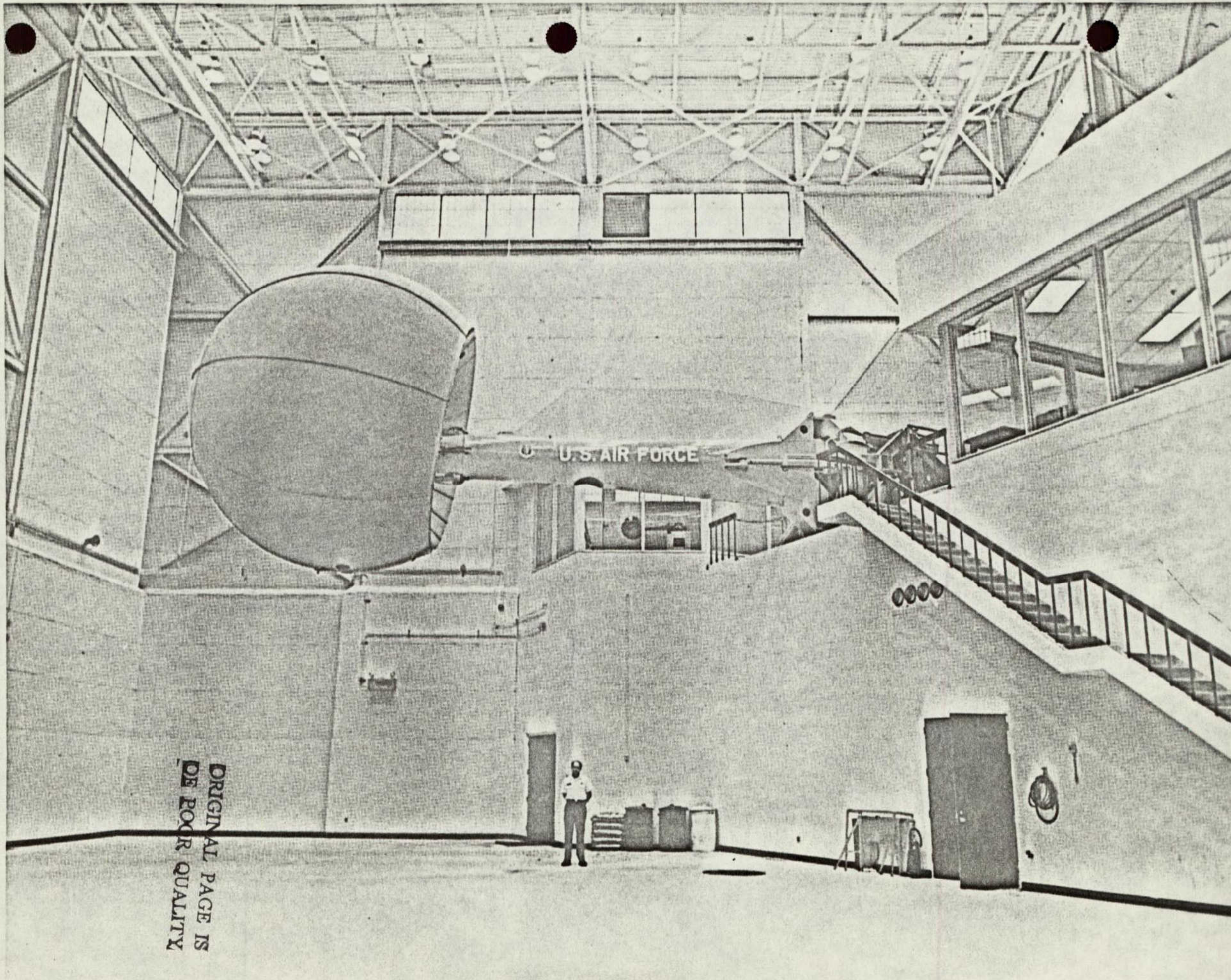


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Figure 1-14. The U.S. Air Force Large Amplitude Multi-Mode Aerospace Research Simulator (LAMARS)

1.3.6 The National Aeronautical Establishment (NAE, Canada) Airborne V/STOL Simulator

The NAE (Canada) Airborne V/STOL Simulator	
CLASS	Special-purpose, engineering research and development, airborne.
USES	Research and development of V/STOL aircraft and helicopters
Elements	
COCKPIT	Actual cockpit of the Bell 205-A1 helicopter with right hand controls modified for electrical outputs only. Active electrohydraulic feel system. Center console modified to incorporate computers and computer control panels.
COMPUTER	Interdata Model 5 minicomputer with 24K byte memory. Digital Equipment Corp. PDP 11/03 digital microprocessor. Dedicated analog computer for controlling the feel system.
VISUAL SYSTEM	The actual out-the-window scene.
MOTION SYSTEM	The helicopter itself. This implies the full six-degree-of-freedom capability of the helicopter but can be controlled through its normal controls only. These are normal force and pitch, roll, and yawing moments. Choice of model-following or response feedback techniques for varying flight characteristics. Performance limited to that of the basic helicopter. Preliminary designs for adding fore- and aft- and side thrusters for six-degree-of-freedom control.
Photographs in Figs. 1-15 and 1-16	

Figure 1-15. NAE Airborne V/STOL Simulator

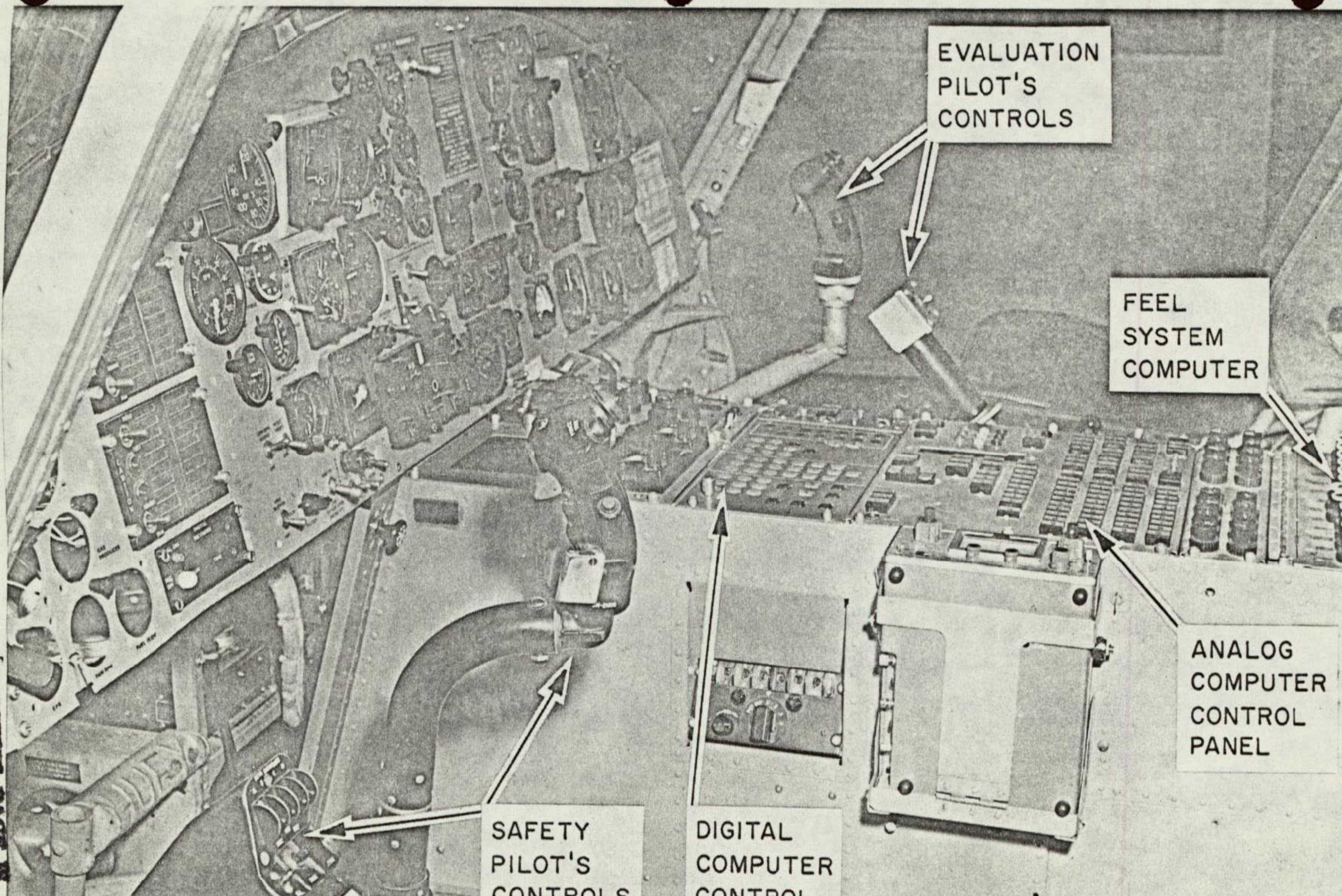

Figure 1-16. Simulator Cockpit

NAE Airborne V/STOL Simulator

1.4 SIMULATION APPLICATION

1.4.1 Example of a Research and Development Simulation at NASA Ames Research Center

In the following paragraphs, an example of a research and development simulation is described. This particular effort demonstrates the effectiveness of a rudimentary cockpit simulation. Not only did the participants learn from the experience, but valuable insights were formed regarding the required handling qualities for a helicopter operating close to the ground.

An Army requirement for terrain flight operations of helicopters in all possible lighting and weather conditions is currently motivating some research into the required handling qualities and related configurations. An accurate description of the terrain flight missions in engineering terms does not exist, and the simulator hardware employed in the study was suspected of not having sufficient fidelity to allow low-level simulation. In spite of these factors, a useful simulation was performed because the authors of the effort know about the deficiencies and tailored their experimental investigations to fit with the overall research program.

The research objective was:

> "To investigate the effects of large variations in several rotor system design parameters on the handling characteristics of single-rotor helicopters without stability augmentation in nap-of-the-earth (NOE) flight."

The simulation was part of a larger coordinated effort to research the problem. Since gross trends were desired, the level of mathematical modeling was kept modest and special display features were designed that allowed control of task and partly offset the visual system deficiencies. A simplified generic main-rotor system mathematical model was developed for real-time pilot-in-the-loop simulation. With this model, the effects of rotor-system parameters of interest on the stability and control characteristics was assessed to help develop the test plan.

The authors, Talbot and Chen, described their work in Ref. 4. Excerpts from this paper are presented below.

"Description of Simulation

For this study, a fixed-base simulator was used in conjunction with a Redifon closed-circuit television camera/model system. The simulator cockpit consisted of a Bell UH-1A cabin section facing a shrouded screen and TV projector. The UH-1A control system was used with working hydraulics, bungee cords, and magnetic brake, i.e., with force-displacement characteristics and a force-release feature similar to an operational helicopter. The instruments were all functional except the torque pressure and percent gas generator rpm. Little reference was made to instruments in this task; most cues were provided by the projected television scene. A 1:400-scale terrain model was used in the simulation (Fig. 1-17). The model is based on a section of Hunter-Liggett Military Reservation in central California.

Three artificial courses were placed on the model. The longitudinal course (or hurdles) consisted of 50-foot-high barriers placed at irregular intervals at least 700 feet apart. The lateral-directional course (or slalom) consisted of trees about 75 feet high spaced similarly to the barriers in a straight line. The combination course consisted of barriers combined with trees placed down the centerline of the barriers. The spacing distribution of trees and barriers for the combination course was the same, but the sequence was different so that the difficulty levels were not matched in coordinating lateral and longitudinal controls down the entire course.

The three obstacle courses were designed to give the pilots a specific and repeatable precision flying task. The longitudinal and lateral-directional tasks were included to allow the pilots to concentrate on one set of aircraft axes at a time. The combination task was included so that the vehicle characteristics as a whole could be evaluated in a

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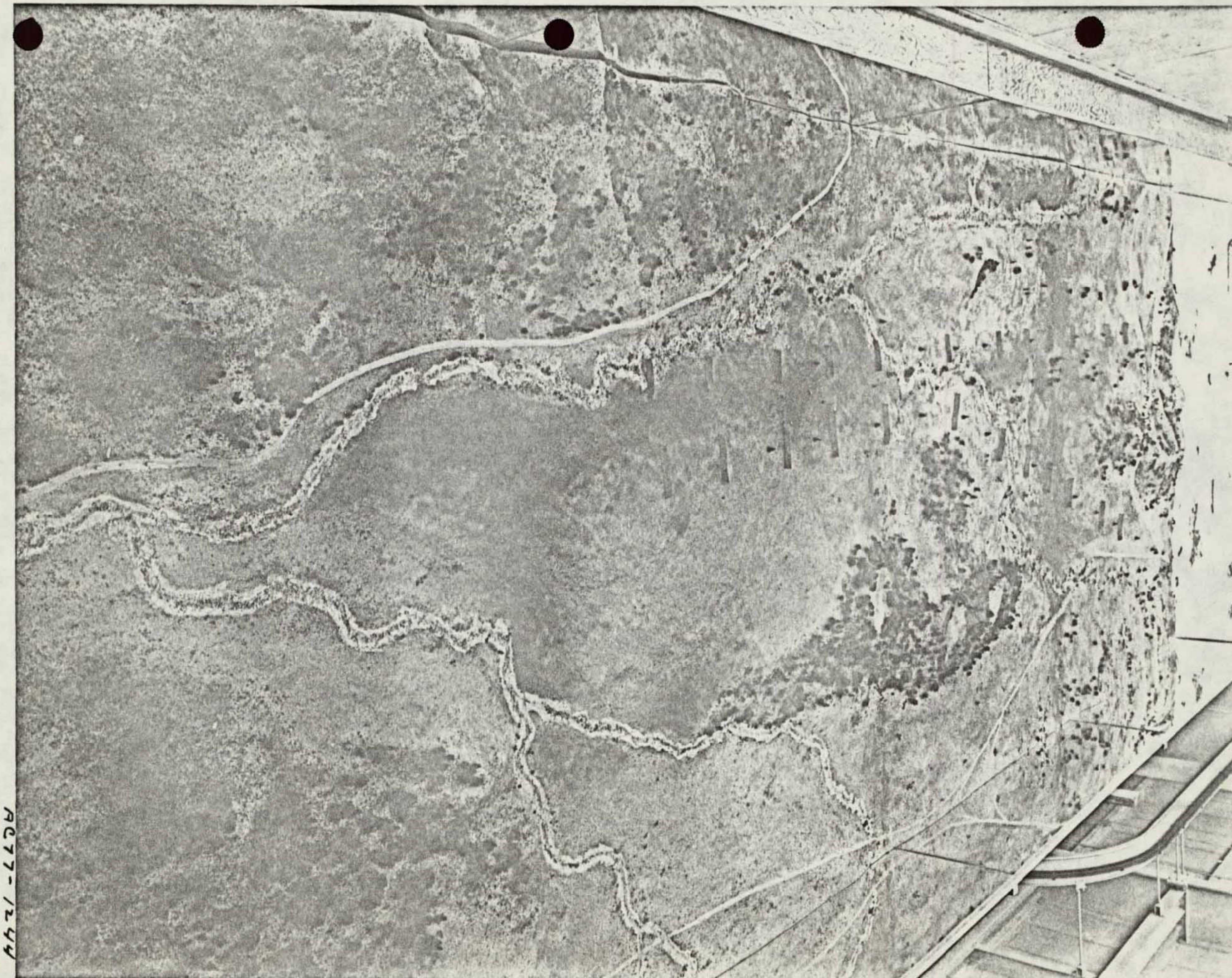


Figure 1-17. 1:400 Scale Model Terrain Board of a Portion of the U.S. Army Hunter-Liggett Reservation

> control tendency, cross-coupling, or low stability. A rating of 8 or more reflected a controllability problem or a near collision; ratings from 5 to 7 indicated high workload; ratings from 2 to 3, a good gun platform. The pilot felt extremes of ratings were most significant. Pilot B looked for agility and precise control while flying at maximum speeds and lowest tolerable altitudes. His perception of exaggerated pitch coupling due to collective pitch consistently biased his pilot ratings by 1 to 2 points toward unacceptable. For most configurations, any longitudinal inputs made for speed changes were overshadowed by cyclic pitch corrections needed to counter collective-to-pitch coupling. At no time was loss of control imminent. If pilot compensation was extreme, slowing down and increasing clearances helped."

Note that considerable effort was made to define tasks that exercised the properties under investigation. Also, pilot performance measures were taken (time-altitude data) to support the findings. Task definition is extremely critical and the authors openly acknowledged that the courses flown may not represent combat-type terrain flight. Nevertheless they considered their findings valid because they were supported by some analytical basis.

For these tests, the visual display field of view was 48 degrees horizontally by 36 degrees vertically (standard 525 line TV format). The pilots would occasionally comment about the restrictive field of view and lack of clarity and detail especially when making large pitch and roll attitude changes.

At the time of writing, portions of the experiment had just been repeated using the moving base FSAA. The interest here was to assess the effects of motion on the results and to advance the research. Some early comparisons of results from both simulations show the familiar effect of motion, which is to cause poor configurations to appear a little better.

1.4.2 Usefulness of Training Simulations

It is difficult at best to define the usefulness of training simulations. Effectiveness measures vary, and tests to determine effectiveness in terms of transferability require large, carefully-controlled experiments; something not compatible with the training environment.

It is generally accepted that the usefulness of a training device not only depends on its inherent fidelity, but also on the way it is utilized in training. With the proper instructional method, a low-fidelity trainer can be very effective and vice-versa.

The special features of a simulation can be advantageously used in training. For example, training for instrument approaches and landing under adverse weather conditions can be more effectively accomplished by simulation rather than in flight because the simulation may be re-started at the initial approach point and ended at touchdown thereby saving time. The experimental laboratory-type environment of the simulation allows close control over visibility and runway conditions, factors difficult to control in the real world.

From another viewpoint, the measurement of training effectiveness can be more easily made in the simulator because a host of variables may be examined. Freeze and playback functions are also helpful unique features. In some instances, the aircraft characteristics can be changed to vary task difficulty and so on.

The point here is that training simulators are rarely used like their aircraft counterparts because of their unique features making them different from the aircraft they represent. With the advent of sophisticated full-mission simulation, instructional method development is sure to blossom.

Prior to World War II, simulators were used mostly as instrument or procedures trainers. The requirement to train many pilots during the war spurred investigations into synthetic trainers. The equipment of the day left much to be desired. Now, with the advanced visual systems emerging, full mission simulation is possible. Instructional methods are sure to improve and, with that, training simulation usage should expand. The energy constraints should surely serve to fuel this process.

The traditional role of simulators as part-task, procedures, and instrument trainers prevalent before and after the war will change. Already the airlines have demonstrated transition and continuation training using mostly simulators. The military services are attempting to train basic air combat on simulators and they already are developing full-mission trainers for air-to-ground weapons delivery tasks, part task trainers for aerial refueling, and full-mission devices for low-level helicopter warfare training.

On an optimistic note, there appear to be no limitations to the effective utilization of simulation in training if there are no constraints on the development of computer-supported instructional methods.

SECTION 2

SIMULATORS AND HUMAN PERCEPTION

2.1 HUMAN PERCEPTIONS IMPORTANT TO SIMULATION

2.1.1 Human Visual Perception

2.1.1.1 Field of View. The human eye is a wide field optical sensory organ. Its structure suggests a half hemispherical field of view ($\pm$ 90 degrees both horizontally and vertically) but the usable field is limited by the skull shape surrounding the eye. This limits the field of the right eye to typically 70 degrees left and 100 degrees right of the foveal point* and 50 degrees above and 80 degrees below it. The pattern is reversed horizontally for the left eye so that in combination, the net field is approximately $\pm$ 100 degrees horizontally, 50 degrees above, and 80 degrees below the fovea. The eye muscles are capable of rotating the eye about $\pm$ 60 degrees in azimuth and elevation. With eye movements, the average human is able to see $\pm$ 110 degrees horizontally and + 50 degrees and -80 degrees vertically. There is a counterroll reflex that is discussed in Section 2.1.4.

2.1.1.2 Resolution. Resolution is a term used to describe the ability of the eye to discern fine detail. It is not only dependent on the optical properties and nerve structure of the eye, but also on object contrast and background luminance. This is usually defined as the ratio of object luminance to background luminance. Obviously nothing can be seen at a constrast ratio of one. On the other hand, stars have a high contrast ratio and in spite of their small angular size are easily seen. The complex nerve interconnections and the diffraction produced by the eye's optical elements may account for the ability to detect fine wires and stars even though their subtended angle is less than the angle subtended by a single nerve cell.

* Point of highest acuity or where it appears that we are looking.

Figure 2-1 shows the measured visual acuity mean and range as a function of horizontal field angle for two background luminance levels (Ref. 5). Note that the minimum acuity is about one-half minute of arc for a background luminance roughly equivalent to that of the average sky on a cloudy day. For a background luminance level equivalent to that of light from the full moon on an average earth, the acuity is about 12 arc-minutes.

Vernier acuity is the ability to detect separate parallel segments of a line. It may be facilitated by diffraction effects, and is much lower or better, typically 0.03 arc-minutes. This is the acuity associated with detection of offset lines and telephone wires. The minimum perceptible acuity may also be determined by diffraction effects and may have no lower limits on the angle subtended by the intrinsic size of the object. This is the acuity associated with seeing stars and is a function of brightness, not angular size. For example, the giant red star Betelgeuse (magnitude +1) subtends an angle of 0.001 arc-minutes but can easily be seen due to atmospheric scintillation (twinkling effect) and the diffraction properties of the eye that cause the star's image on the retina to be about one arc-minute in diameter.

It is stressed that all of the above values of visual acuity are for a detection task. More complex tasks such as recognition require a pattern of barely-detectable shapes. This implies a larger subtended angle. For example, the 20/20 line of letters in the familiar Snellen eye chart subtend an angle of five arc-minutes at the correct test distance of twenty feet.

2.1.1.3 Contrast/Luminance Sensitivity. The details of a scene are visible because their various elements contrast with each other in luminance and/or color. Limiting visual performance is often useful for determining simulation visual equipment properties, and a variety of ways exist for establishing visual performance. Generally, the probability of accomplishing a visual task (such as detection or recognition) is given along with the contrast required. Contrast can be expressed in many ways. The usual definition is the difference in luminance (target minus background luminance) divided by background luminance. Other expressions can be found in the literature such as:

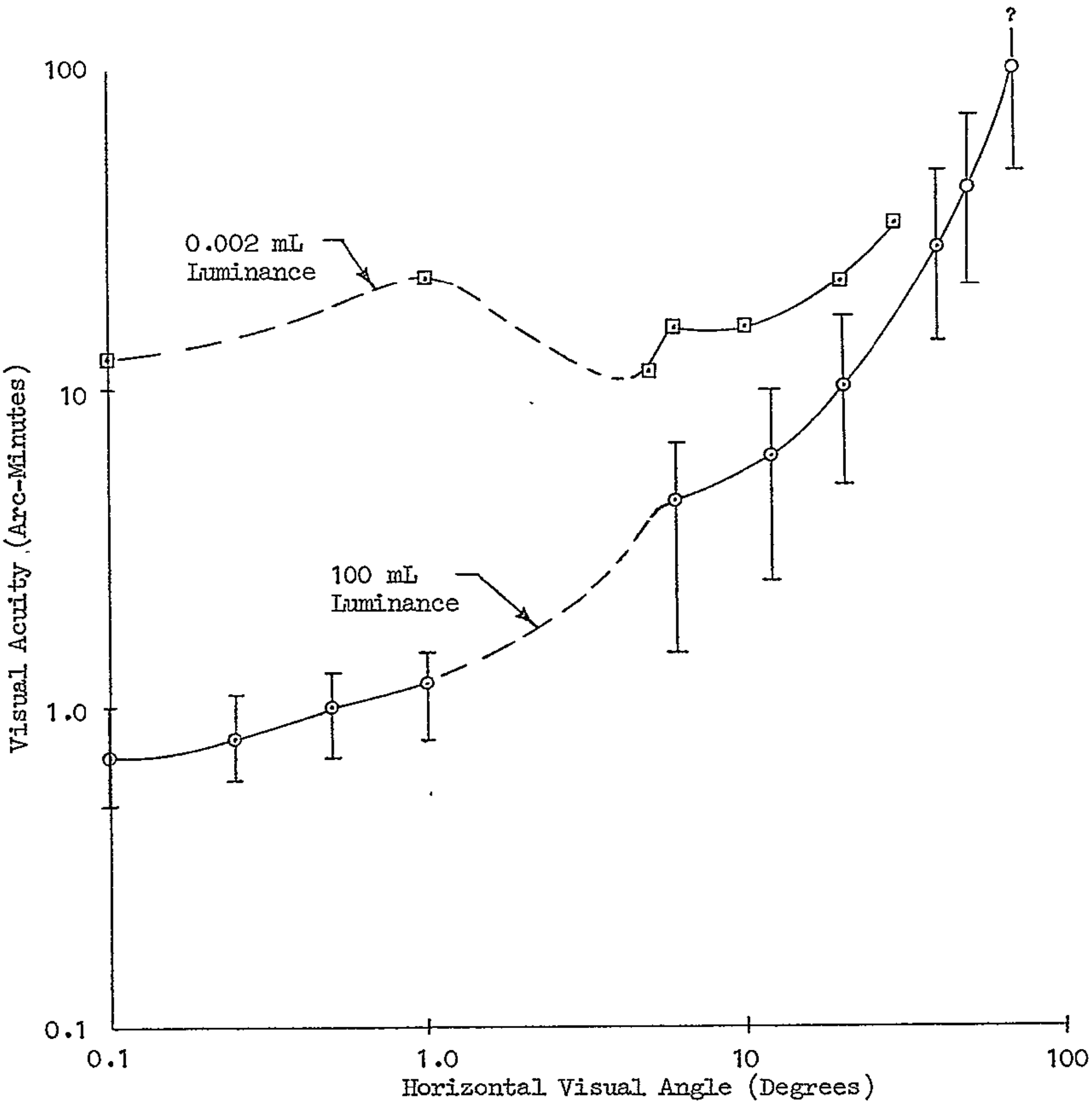


Figure 2-1. Visual Acuity Versus Horizontal Field Angle

$$\frac{\text{Target Luminance - Background Luminance}}{\text{Average Luminance}}$$

and

$$\frac{\text{Target Luminance}}{\text{Background Luminance}}$$

At low contrast levels, the last definition, the simple contrast ratio, is nearly unity and all the other expressions involving a difference approach zero. The values are sometimes multiplied by 100 to yield percent contrast.

Tests have shown that the contrast threshold is a function of at least three variables:

- Target size
- Target pattern
- Background luminance.

To illustrate this point, two sets of data will be described by sketches. The first is by Blackwell (Ref. 5) and shows the variation of the 50 percent probable contrast threshold with background luminance and target size (Fig. 2-2). In this case the target was a gray disk on a darker background. Note the transition from cone (photopic) to rod (scotopic) vision as shown by the break in the curves.

The second illustration is from the results of Campbell and Maffei (Ref. 6). The authors measured the 100 percent probability contrast threshold as a function of target pattern. This was a sinusoidally-varying luminance pattern that resembled alternating light and dark bands. The spacing between bands was varied and the number of light or dark bands per degree of angular dimension, termed the "spatial frequency," was therefore varied.

Figure 2-3 shows a sketch of these data for a human and, by measurements of evoked potential, a cat. Note that the lowest threshold for a human is 0.004 and occurs at a spatial frequency of 3 cycles per degree.

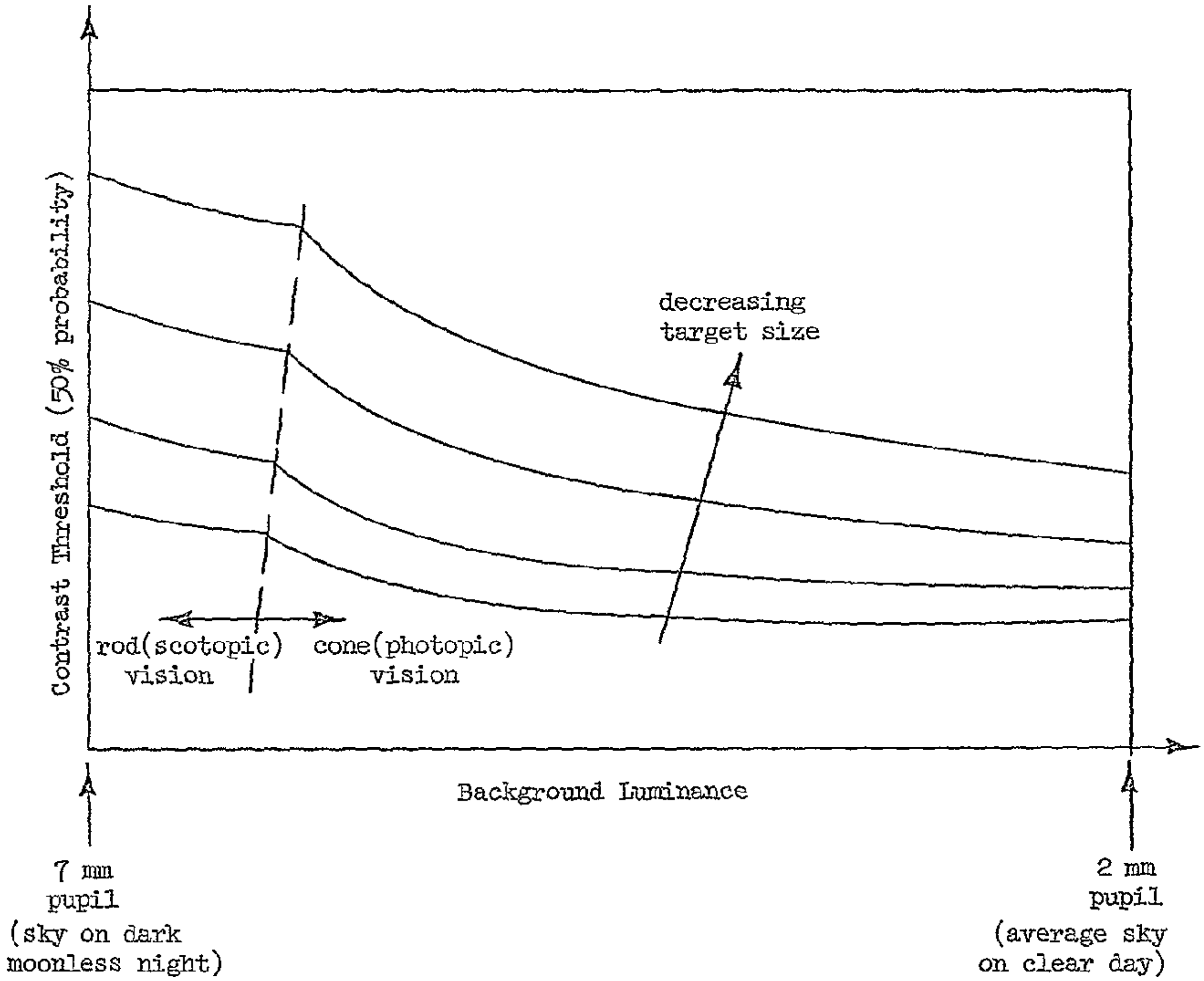


Figure 2-2. Contrast Threshold (50% probability)
as a Function of Target Size and Background Luminance

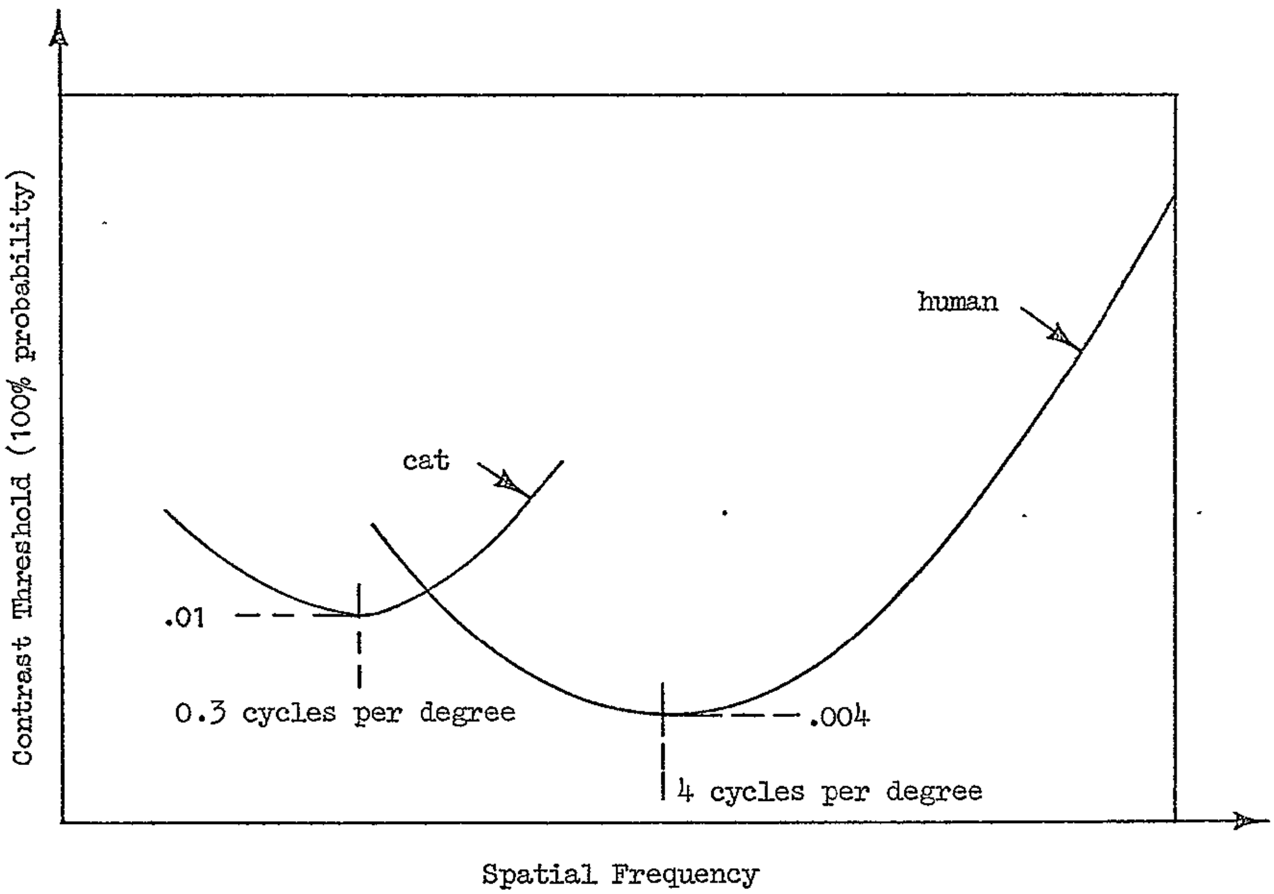
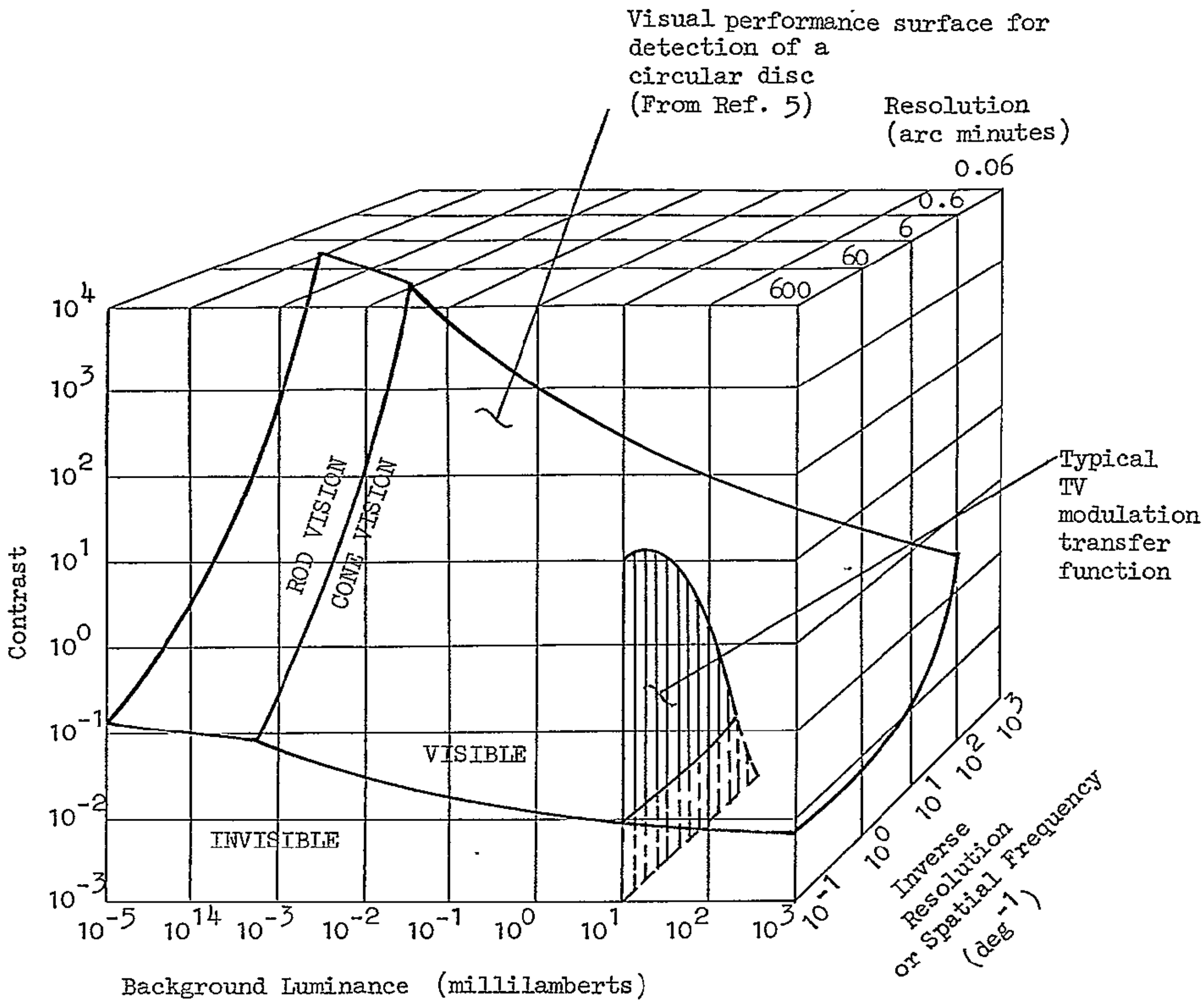


Figure 2-3. Contrast Threshold (100% probability) as a Function of Spatial Frequency (Sinusoidal)

For the cat, however, the lowest threshold is 0.01 at a spatial frequency of 0.3 cycles per degree. The suggestion is that vision may be naturally optimized for some function.

These concepts may be unified by the use of a three-dimensional plot. Such a plot is shown in Fig. 2-4. The abscissa relates the background luminance and the ordinate, the contrast. The third dimension (into the paper) contains the resolution metric, which, in this case, is the inverse of angular resolution or could describe the spatial frequency. The surface sketched represents typical results for a detection task where the space above the surface represents detection and that below, no detection. The data projected on the frontal plane is that of Fig. 2-2. The side plane projection could show the data of Fig. 2-3 (it does not because the data of Figs. 2-2 and 2-3 are for different types of targets). Such a plot would show the effect on contrast of an increasing spatial frequency if the target were an alternating luminance pattern. This is termed the modulation transfer function (MTF) and is useful in describing the visual performance of electro-optical visual systems. For example, a hypothetical television MTF is sketched showing how it could intersect the detection threshold. The MTF describes the ability of a visual system to show a periodic luminance function whose frequency is increasing. At some point, the system cannot "follow" any longer and the resultant contrast is zero. Generally the plot is normalized to "static conditions," i.e., the lowest spatial frequency but in the sketch the absolute contrast is implied. In another sense, the MTF is analogous to the frequency response function of a dynamical system.

2.1.1.4 Color Sensitivity. The spectral response associated with vision shows peaks depending on whether the rods or cones are being stimulated. Rod (scotopic) vision can occur at very low luminance levels (average illumination on a dark moonless night) and is colorless, having a single spectral peak at a wavelength of about 500 nanometers (green). This results, in part, from the visual pigment associated with the rods that contains photosensitive molecules that respond to a wide band of light waves with the spectral peak as identified above. It is interesting to note that the greatest density of rods occurs at a field angle of about 20 degrees. In this area, night vision is most sensitive.



NOTE: Contrast $= \dfrac{\text{Maximum Luminance - Minimum Luminance}}{\text{Minimum Luminance}}$

Figure 2-4. Unifying Plot of Typical Visual Performance

The cones, on the other hand, are adapted to high luminance (photopic) vision and are most dense at the fovea, the area of highest acuity. The cones are responsible for color vision and contain three visual pigments similar to that of the rods, but whose spectral peaks occur at about 440 nanometers (blue-violet), 540 nanometers (yellow-green), and 560 nanometers (yellow-orange).

In Ref. 7, Land presents an interesting theory of color vision which he calls the "retinex theory," the word being derived by him from the two words retina and cortex. Using experimental results, Land ascribes color vision to the action of both the retina and the visual cortex. He maintains that it is not the absolute illumination level on each pigment that results in color impressions, but rather the relative intensities on each of the pigments. It is as though the action of the cortex is to compare the various pigment stimulations in order to form a color impression. This is similar to stereoscopic vision where it is thought that the slightly disparate images of both eyes are processed together in the brain (perhaps the cortex) to form an impression of depth. Furthermore, Land maintains that stimulation of only two pigments is sufficient to form the impression of a wide range of colors. The implication of this is, of course, that color visual simulation systems may only need to include two basic colors.

2.1.1.5 Depth Perception. This is that property of vision that results in the world being perceived as three dimensional rather than as just a flat picture. There are many mechanisms by which this takes place but only a few can be effectively simulated. The mechanisms can be separated into two groups; those associated with binocular vision (use of both eyes simultaneously) and those associated with monocular vision (one eye only).

Binocular Effects

Physiologists have suggested that the images formed by each eye are fused in the visual cortex. Also, that visual pathways starting from nerves at corresponding points in each retina are associated in the cortex so that disparate images can be used to form the impression of depth. This is called binocular disparity. The principle of this mechanism is that each eye sees a different image because of their separation. The slight differences in these images can be interpreted by the brain as depth. In this regard, the impression created is of a three-dimensional version of the objects in the visual field as would be seen by a single "Cyclopean eye" located midway between the eyes. Other clues to range are produced through the use of both eyes. The slight "toeing in" of the eyes to a close object is called convergence and provides a clue at ranges up to about 20 meters (66 feet) (Ref. 5).

The slight change in accommodation (focus) for close objects is also a clue but is accurate only at ranges less than 1 meter (3.3 feet) (Ref. 5).

According to Ref. 5, the most accurate mechanism for perceiving depth using internally-generated cues is the stereopsis resulting from binocular disparity. Experimentally-determined values of stereoscopic acuity (smallest detectable angular disparity) are in the range from 10 to 2 arc-seconds. The reference states that an observer, for example, with a corresponding stereoscopic acuity of 5 arc-seconds can discriminate that an object at 2600 meters (8530 feet) is closer than one at infinity.

Monocular Effects

There are a number of other clues available to the single eye as to depth and range. Seven are mentioned below:

1) Motion parallax describes a change in relative position of objects due either to object or observer motion.

2) Apparent size of familiar objects is also a powerful clue.

3) Linear perspective or the geometrical aspect of a vanishing point, parallel or convergent lines, and related effects is important.

4) Interposition or the masking of objects by others that are closer.

5) Aerial perspective is the loss in contrast produced by atmospheric effects at increasing distance from the observer.

6) Shadows are an important clue to depth.

7) Apparent intensity of point light source objects can give a clue as to range and depth.

2.1.1.6 Movement Thresholds. The threshold of sensitivity to an abrupt change in angular velocity of a target moving across the visual field is approximately 1/10 of the angular velocity. At zero angular velocity the "rate threshold" or minimum step of angular velocity perceivable is between 1 and 2 arc-minutes per second. For movement toward or away from the observer, the time required to detect a movement, varies roughly inversely with the speed (Ref. 5). This suggests a minimum range difference that can be detected. Reference 5 describes data taken at initial ranges of 7.6 meters (25 feet) using a 90-millimeter (3.5 inch) wide target. This corresponds to a change in the target visual angle of about 1 arc-minute.

2.1.1.7 Effects of Motion. Two effects are known although subject differences are large. The first is the reduction in visual acuity for objects moving with an angular velocity and the second is the compensatory eye movements caused by head movements in space.

1) Dynamic acuity is the visual acuity threshold for objects moving with an angular velocity relative to the observer's eye. Data from Ref. 5 shows that the dynamic acuity is less than the static value and, like static acuity, varies with target and background luminance. If the static acuity is 1 arc-minute,

the dynamic acuity is 2 arc-minutes at an angular velocity of 80 degrees per second. At an angular velocity of 120 degrees per second, it is about 8 arc-minutes.

2) The effect of head movements

Head movements aid depth perception and range judgments. They also aid fixation under moving conditions. The vestibular organs of the inner ear are known to cause compensatory eye movements in a particular range of frequencies. These movements appear to aid fixation when the head is moved rapidly. The compensating movements are elicited by angular as well as rectilinear head motions. For example, rotating the head about the vertical axis causes fast as well as slow compensating eye movements. Translation up and down causes corresponding up and down eye movements. Side force either due to tilt in the gravitational field or acceleration causes a counterroll reflex in both eyes that is dependent on the normal force.

An object may be easily fixated even with head movements at frequencies of up to 2 Hertz. However, fixating a vibrating target with eye movements alone cannot be done beyond frequencies of 1 Hertz without increasing errors (Ref. 5).

2.1.1.8 Flicker. Critical fusion frequency is a term that describes the visual fusion of a flashing light. When a flashing light is presented to an observer, there exists a critical frequency of these flashes where the impression of light is continuous. The frequency at which this occurs is the Critical Fusion Frequency and increases with the luminance of the light source. For example, Ref. 5 shows that for commercial television sets with luminance levels of about 10 foot-lamberts, the Critical Fusion Frequency is about 52 Hertz. Commercial TV which provides a new picture

60 times a second is rarely perceived as flickering. However, the European power frequency of 50 Hertz sometimes causes a bright light to appear as flickering.

2.1.2 Human Motion Perception

2.1.2.1 <u>Angular Motion Perception</u>. The sensation of rotation is thought to come largely from the semicircular canals of the inner ear. While certainly other sense organs such as the surface pressure receptors and those in joints and tendons are sensitive to applied forces resulting from rotation, evidence from experiments in rotation sensing strongly suggest that the primary rotational sense organs are those of the vestibular system.

As early as 1931, it was proposed that the function of the semicircular canals could be represented analytically by that of a heavily damped torsional pendulum. Experimental evidence supports this view. Young (Ref. 8) has developed comprehensive models of this sensory process.

In summary, the properties of angular motion sensing are:

1) Angular motion perception is frequency and amplitude dependent. Large, rapid motions are sensed while small, slower ones are not.

2) Head movements while rotating can strongly influence the perception of rotation, and can cause disorientation.

3) Compensatory eye movements are synchronous with the perception of rotation.

For example, it is well-known that a human subjected to a step of angular acceleration accurately reports the buildup of angular velocity. As time passes, however, the impression of buildup ceases and the angular velocity appears to hold constant when in actuality it is still increasing. This is the consequence of the "washout" property of the semicircular canals that precludes our sensing slow movements.

The thresholds associated with the "torsional pendulum model" view lead to a prediction of latency time for the perception of angular acceleration. A longer time is needed to sense a smaller acceleration. Typical examples of such data are described by Young in Ref. 8. From the point of view of the dynamicist, the organs "pass" motions in the frequency band of approximately 0.1 to 10 radians per second and are structured as angular velocity transducers in that frequency range. The threshold velocity in this range is about 0.1 degree per second.

2.1.2.2 Force Perception. It is not clearly established that the vestibular organs account for all of the force perception observed. The view of the utricles (an accelerometer-like organ near the junction of the semicircular canals) as damped linear accelerometers leads to the notion of phase lags for the perception of force. The best data on this subject were obtained by Meiry (Ref. 9) using a linear acceleration device. The subjects were instructed to report velocity reversals while stimulated by sinusoids of acceleration. The reported perception of velocity reversals relative to the actual reversals shows a phase lag of 45 degrees at a frequency of 1.5 radians per second. These data are from tests where the subject is seated in a soft chair that offers no other kind of stimulation. Threshold data similar to those for rotational movement are reported in Ref. 9.

2.1.2.3 Tactile and Kinesthetic Perception. Tactile sensitivity or the "sense of touch" is part of the broader array of sensory processes that are the function of the proprioceptive system. The sensing elements that form this system include surface receptors that sense touch, temperature, pressure, and pressure gradients as well as those elements deeper in the body that sense muscle tension, skeletal deflection, and internal organ movements. The proprioceptive system also includes the vestibular organs. Some attempts have been made to determine models of the tactile and kinesthetic senses (Ref. 10) but they are far from described adequately to allow formal design of simulation equipment. Applied forces are the primary stimuli for these proprioceptive elements. Forces cause the pressure receptors to react and cause skeletal movements that are sensed by the muscle, joint, and tendon receptors. According to Gum (Ref. 10), a more rapid response is available from the head/muscle and body pressure sensing system than is available from the vestibular system under identical forcing functions. This is probably the reason why a buffet or vibration signature may be accurately identified. Also, the tactile elements' response appears to decay rapidly with repeated stimuli (habituation Ref. 10).

While the proprioceptive system elements may be viewed individually, it is customary to consider their stimulation and response as a unit. The tactile and kinesthetic system's primary function appears to be the creation of postural reflexes, control of limbs and torso, and protection from hostile intrusion such as piercing or burning.

For this reason, a variety of devices are under development that are designed to stimulate this system. They include the "g" seat, "g" suit, harness and limb loaders, and stick shakers. They are all designed to reproduce somewhat the surface pressure distributions and limb/head deflections experienced in flight. Limited successes with "g" seats are reported by Tiesler (Ref. 11). This reference also reports an extensive table of threshold levels determined by various researchers. As with other human senses, a large variability exists in such data owing to the probabilistic nature of sensory processes involving thresholds.

The method or device used for stimulation is highly important. For example, a seat arrangement where the human is securely strapped tends to reduce the pressure sensitivity on the parts of the body that are under high pressure. By proper design, however, the low pressure portions may be used to elicit responses to low levels of force change.

2.1.3 Aural Perception

The human auditory system is configured to respond to changes in air pressure at frequencies that range from about 30 to 15000 Hertz. The hearing response shows a peak that occurs at about 2000 Hertz. Reference 5 gives allowable signal-to-noise ratios for various speech levels and speech content. Habituation effects are present which result in reduced hearing following exposure to noise. These are also given in Ref. 5. The sense of hearing is an obvious method of detecting and using the various sounds associated with flying machines. Among these are aerodynamic "hiss" from the boundary layer; engine compressor and exhaust noise; runway rumble; the periodic noise from propellers, rotors, and fans; and the whine of transmissions. The rhythmic nature and beating associated with periodic sound makes it ideal for sensing important aircraft parameters. For example, rotor speed may be readily held within close tolerances using rotor noise alone.

Besides these simple examples, it is well known that the human is able to discriminate complex sounds, e.g., music. This implies the ability to analyze and identify these sound spectra, particularly to pick out tonal peaks associated with a particular aircraft effect. The fact that the hearing sense, like the vestibular and kinesthetic senses, is always "on" (as opposed to vision) makes this sense and the others especially valuable as an alerting mechanism for failure detection experiments.

2.1.4 Perceptual Integration

The selection of the order of presentation for the preceding material is intentional. This is done to emphasize the ascending order of frequency for the response of the various human sensing systems. Figure 2-5 shows a sketch of the inferred human sensory frequency response from speculation arising from the data reviewed for this work. The ordinate is an arbitrary scale normalized to the visual response, and represents "information acquisition rate." The abscissa is frequency in Hertz. The areas under each curve represent the relative "information acquisition capacity." The peaks for the semicircular canals, kinesthetic, and aural systems are shown. Note that the visual sense encompasses a large area signifying the large information capacity that sense is capable of acquiring.

The visual, utricular, and kinesthetic senses all have a static response. Note also the cutoff frequencies and peaks suggested in the response. Vision begins to cut off at about 1 Hertz. The semicircular canal's response peaks at 1/6 Hertz and extends slightly beyond the visual response. The kinesthetic system's response begins where the visual and

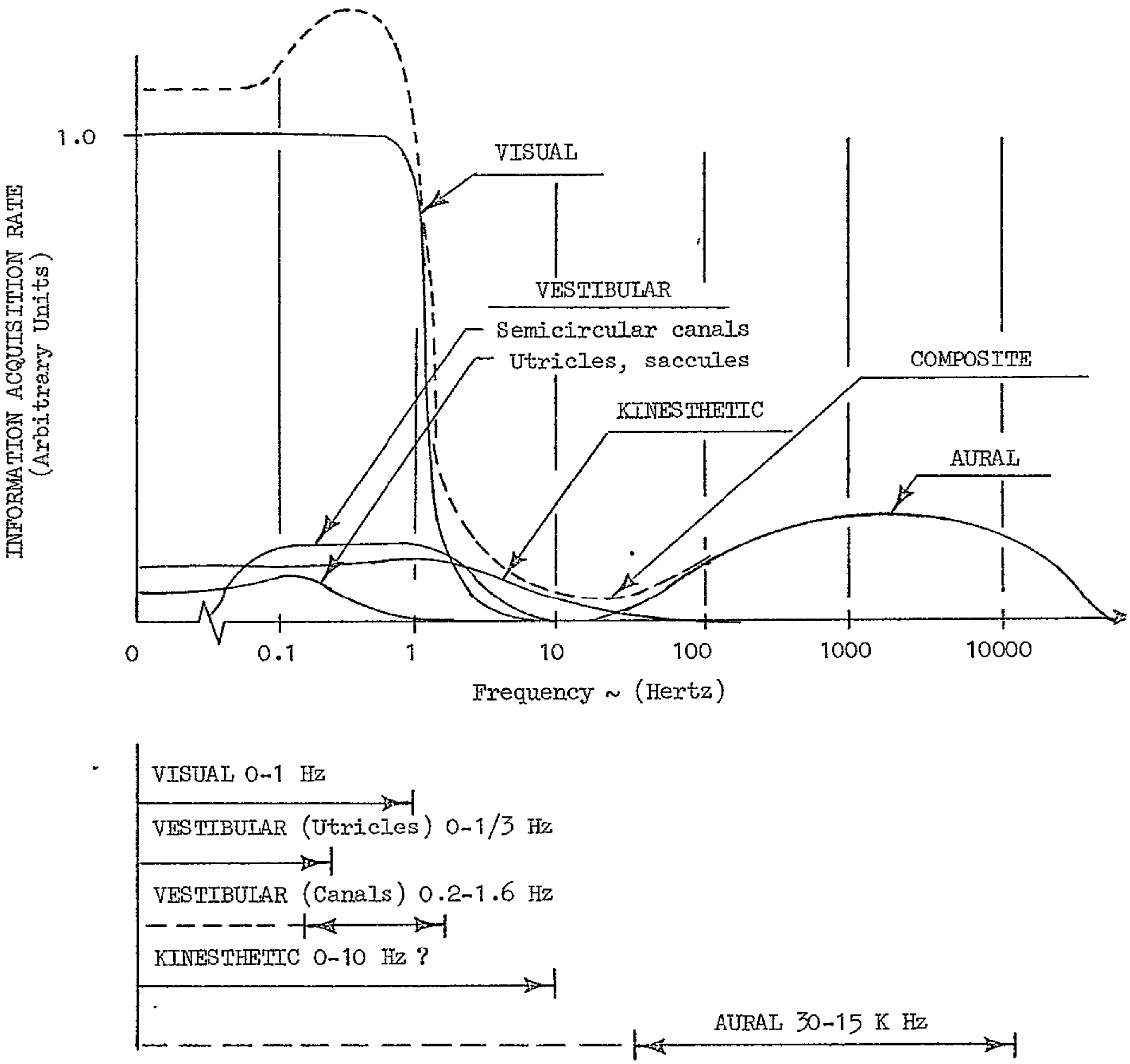


Figure 2-5. Sketch of Hypothetical Human Sensory Frequency Response

vestibular response fades, reaching a peak at about 3 Hertz. Thresholds of vibration detection begin rising at frequencies of 100 to 200 Hertz. At these frequencies, the auditory response begins, reaching its peak at about 2000 Hertz. Beyond 15000 Hertz, the body sensors do not seem to respond to anything. The sum of all the sketches is also shown in Fig. 2-5 and it is interesting to note how relatively wide band the human sensory processes are when considered this way. They seem to overlap very conveniently.

Figure 2-6 shows an attempt to describe the probable time delays associated with each process. It is known that visual time delays associated with detection or recognition tasks vary with the scene complexity (information). Typically, pilot time delays associated with high-performance motor tasks requiring the processing of a simple scene can be as low as 0.44 second (Ref. 12). When motion stimulation is introduced, the delay can be reduced to about 0.2 second. Could it be that the sensory processes sensitive to higher frequencies produce perceptions with smaller time delays? This possibility is sketched in Fig. 2-6 where a hypothetical perceptual time delay range is plotted for each sensory process.

Just how are all these sensory processes integrated into a total perception? Attempts to formulate a theory of perceptual integration is reported by Young, et al, in Ref. 13. The theory advanced includes the concept of "expected stimulation" from an internal model of the external world (aircraft, for example). An interpretation of Young's concept is shown in Fig. 2-7. The important feature here is the internal model that is developed through learning. This model structure is important to the explanation of:

1) Differences in disorientation effects between pilot and passenger
2) Differences in disorientation effects between student (neophyte) and instructor (experienced pilot)
3) Effects of head/limb movements
4) Various visual illusions
5) Training

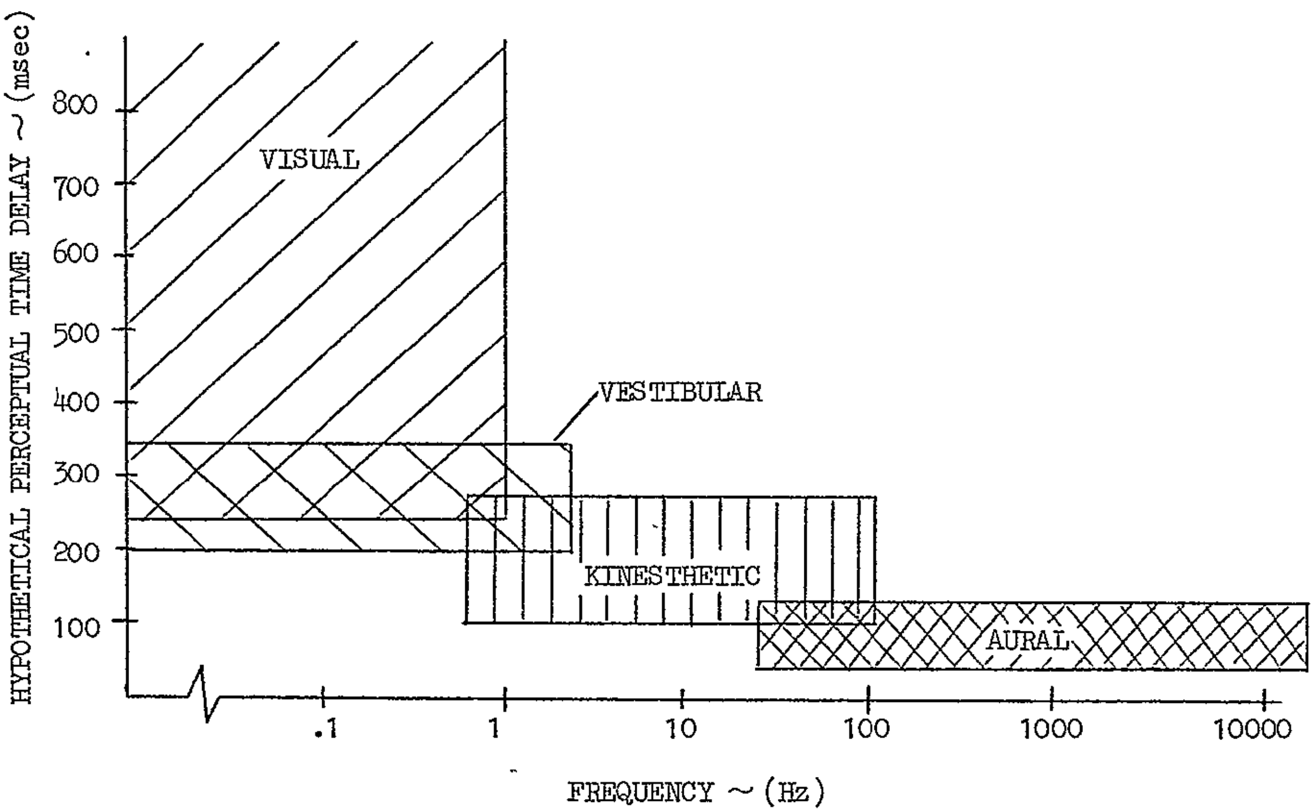


Figure 2-6. Hypothetical Perceptual Time Delay Ranges for the Various Sensory Processes.

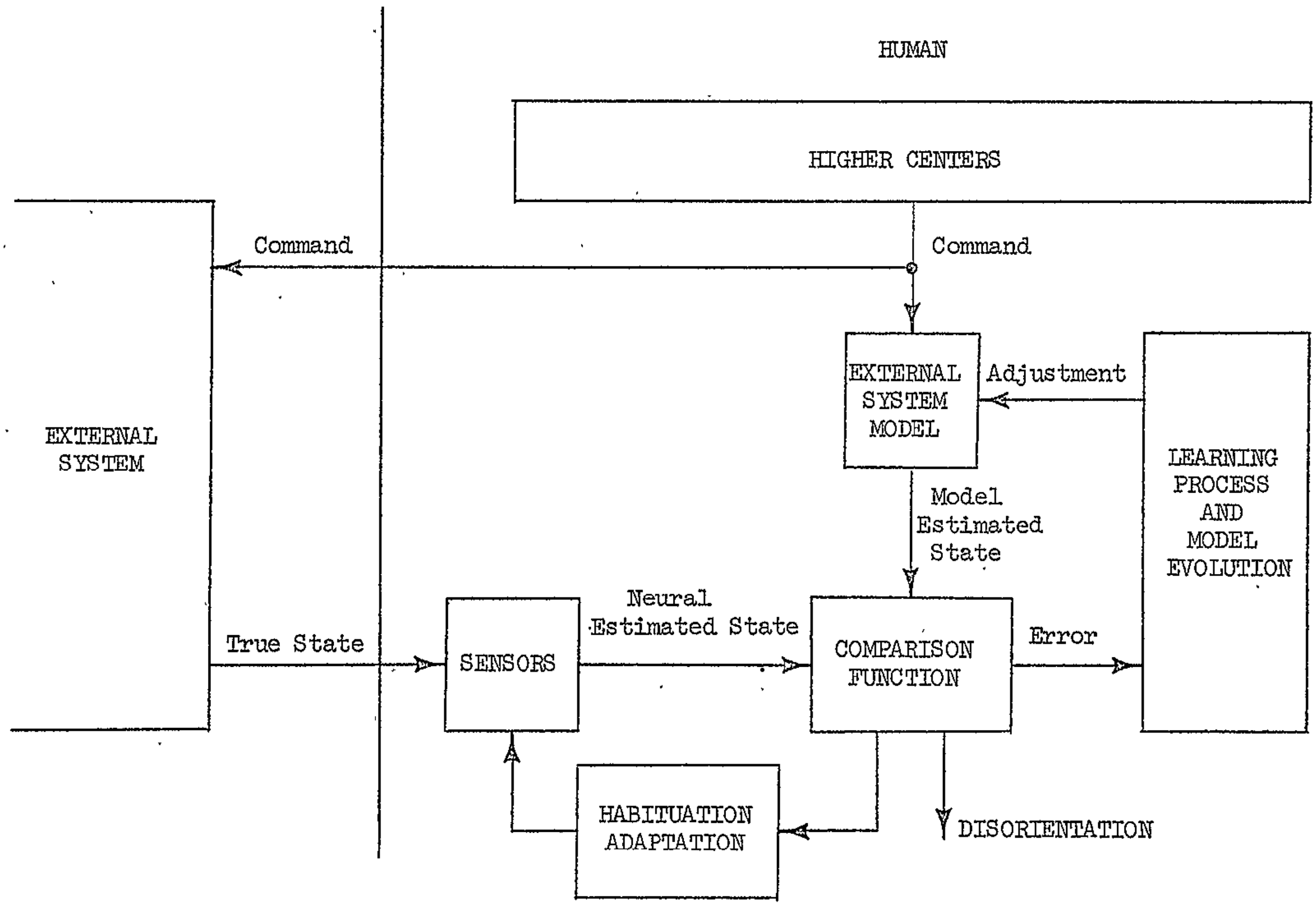


Figure 2-7. Interpretation of Young's Integrated Perceptual Model.

6) Attention sharing

7) Disturbance (unexpected) versus command (expected) effects

8) Habituation (decay of response with repeated stimulus)

9) Adaptation (decay of response with steady stimulus).

The model in its present form also permits an explanation of observed simple tracking performance. Some recent experimental progress on the modeling of visual and motion effects on human tracking are reported in Ref. 14 by Junker and Levison. Their results clearly show the effects on tracking performance of command-type (expected) motions and disturbance-type (unexpected) motions. They are currently researching the effects of motion washouts. Although Young's representation of human sensory processes is complex and partly substantiated, it nevertheless holds the promise of giving an explanation of sensory behavior suitable for simulation equipment design.

The notion of an "ordered hierarchy" of perceptual processes that are successively matched to the total stimulus by an "internal executive" is appealing to researchers. The overlapping response functions, coupled with the internal adapted model appears to have all the ingredients necessary to explain the wide range of behavioral skills possible ranging from acrobatics to piloting and the multitude of effects related to training and disorientation.

2.2 CURRENT SIMULATOR CAPABILITIES; COMPARISONS WITH PERCEPTION

2.2.1 Visual Systems

In Section 2.1.1, the essential features of human visual perception were described. In overview, they are:

- Field of view
- Resolution/contrast/luminance sensitivity (including color)
- Depth perception.

There are, of course, static and dynamic aspects of these factors, great variability among people, and degradation with age. Nevertheless, for the pilot population, visual perception is a highly-developed wide-ranging property that comprises the mainstream of sensory activity. To build an electro-optical device compatible with these characteristics is no small task and the electro-optics and electronics industries have not done badly on this score.

Two schools of thought prevail in designing simulator equipment. The first advocates "face validity," that is, to replicate the world as closely as possible. The second school advocates "stimulation but not replication." The first is relatively easy to identify but technically difficult to implement; the reverse is true for the second. Moreover, determining required stimulation and evolving tests that establish validity is more esoteric. Consequently, the practical drivers of the simulation technology are the advocates of the first approach.

In the case of visual systems, this is certainly true and the result has been astonishing. Closed-circuit television, point light source projection, and computer-generated imagery have been developed to high levels by the simulation industry for the bulk of applications. Even in the case of computer-generated imagery, the face-valid approach is taken. This technology is obviously one where only cardinal elements of a scene can be represented owing to the computer limitations, but still, little research is being done on discovering what elements of a computer-generated scene are necessary to perform a given task.

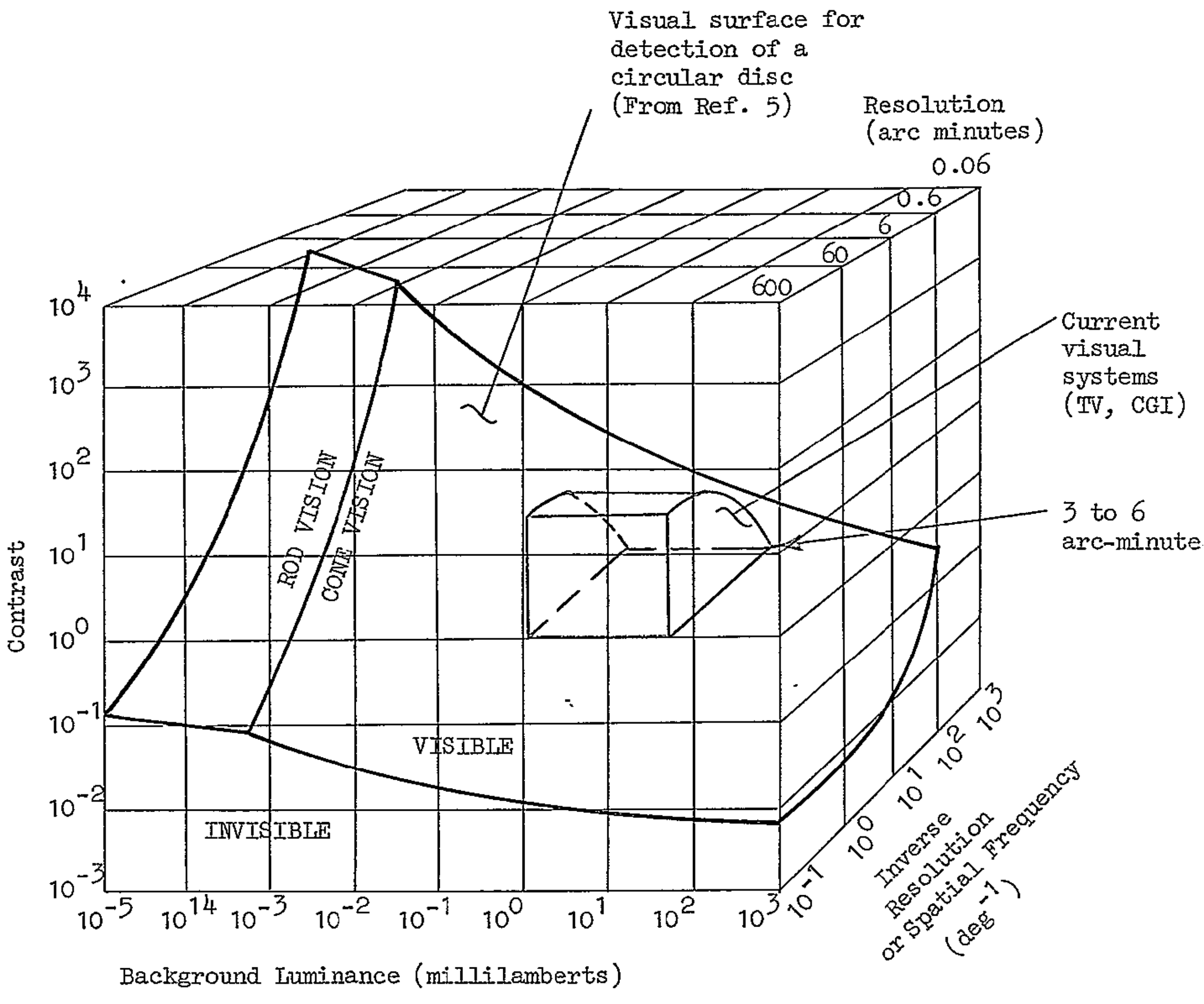
Current simulation visual systems may be compared in terms of the three categories of visual perception previously outlined. This is done in Table 2-1 and Fig. 2-8, where visual performance is shown together with that of the normal eye (Ref. 5). Figure 2-8 includes human visual data on the contrast required to detect a circular target. The systems chosen for comparison are:

- High-performance closed-circuit television
- Point light source projection
- Computer-generated imagery.

TABLE 2-1

PERFORMANCE OF THREE CURRENT VISUAL SYSTEMS COMPARED WITH THAT OF THE NORMAL EYE

VISUAL CHARACTERISTIC	NORMAL EYE	HIGH-PERFORMANCE CLOSED-CIRCUIT TV	POINT LIGHT SOURCE PROJECTION	COMPUTER-GENERATED IMAGERY
Field of View	$\pm$ 110 deg horizontal $\left.\begin{matrix}+50\\-80\end{matrix}\right\}$ deg vertical	$\pm$ 24 deg horizontal $\pm$ 18 deg vertical	$\pm$ 180 deg horizontal $\left.\begin{matrix}+90\\-45\end{matrix}\right\}$ deg vertical	$\pm$ 19 deg horizontal $\pm$ 16 deg vertical
Resolution/ Contrast/ Luminance/Color Sensitivity	Minimum separable resolution (fovea) 0.7 - 10 arc-minutes Periphery 100 arc-minutes Vernier (fovea) 0.03 - 0.1 arc-minutes Minimum perceptible (stars) 0.001 arc-minutes - - - - - - - - - - - - - - Luminance range 10^{-5} to 10^{3} foot-Lamberts - - - - - - - - - - - - - - Contrast threshold 10^{-3} to 10^{3} - - - - - - - - - - - - - - 128 color hues detectable	Minimum separable resolution (on-axis) 7 arc-minutes Edge of field 12 arc-minutes - - - - - - - - - - - - Luminance range 1-20 foot-Lamberts - - - - - - - - - - - - Contrast ratio 1-20 - - - - - - - - - - - - 8 color hues detectable	Resolution not a criterion. Edges of objects are spread as their range decreases - - - - - - - - - - - - - - Luminance range 0.1-1 foot-Lamberts - - - - - - - - - - - - - - Contrast ratio 1-10 - - - - - - - - - - - - - - Arc-lamp color with hues of transparency	Resolution on axis 7 arc-minutes Resolution at edge 10 arc-minutes Highlight brightness 6 foot-Lamberts Contrast ratio 1-20 Shades of gray detectable 10 8 color hues detectable
Depth Perception	Monocular: Accommodation < 1 meter Convergence < 20 meters Scene interpretation? - - - - - - - - - - - - - - Binocular: Stereopsis from binocular disparity < 2600 meters?	Monocular: Collimated display produces accommodation to optical infinity provides no clues except those from scene interpretation. Normal except no shadows or motion parallax. Binocular: Binocular disparity absent. No stereopsis	Monocular Real image display set to screen radius. Provides no clues except those from scene interpretations. Normally hidden faces of objects are visible. Binocular: Binocular disparity absent. No stereopsis	Monocular: Collimated display produces accommodation to optical infinity provides no clues except those from scene interpretation. Normal except no shadows or motion parallax. Binocular: Binocular disparity absent. No stereopsis



NOTE: Contrast $= \dfrac{\text{Maximum Luminance - Minimum Luminance}}{\text{Minimum Luminance}}$

Figure 2-8. A Comparison of Current Visual Systems (TV, CGI) with Human Detection Performance

Note that in terms of the three broad categories of comparison, the visual concepts produce a system with either a wide-field, low resolution and few scene details, or one with narrow field, moderate resolution and many scene details. The luminance range is a fraction of that to which the eye can adapt to and all the concepts described produce no binocular disparity that can produce stereopsis. At most, they allow accommodation to optical infinity or to the distance of a screen, typically 8 or 10 feet from the eye.

In dynamic terms, scene resolution of the CRT-based systems degrades with scene slew velocity. For example, for television systems, a yawing or pitching slew rate of 40 degrees per second can cause resolution to degrade to a 1/10 of the static value. The degradation associated with the eye, however, is only about 1/2 of the static value at these slew rates. The point light source concept, of course, does not suffer from dynamic resolution loss because it uses no scanning mechanisms with associated time delays. Hybrid versions of the three are in use, however, that overcome some of these difficulties. For example, the ASPT uses seven collimated CRT pancake windows in a mosaic to achieve a wide field of view without a proportional loss of resolution. The LAMARS and DMS concepts use a mixture of point light source and television projectors to achieve a wide field, low resolution view of the sky and horizon with a narrow-field view of a high-resolution target. The Advanced Attack Helicopter Training Simulator uses two television "windows" to achieve a wider field of view.

In summary, current visual systems approach the field of view and resolution of the eye but not nearly the contrast/luminance range. None of the concepts produces any meaningful binocular depth cues. All facilitate some depth perception through the inclusion of monocular clues.

2.2.2 Motion Systems

Platform Motion

There are four features of any platform motion device that define its performance. They are:

- Maximum performance envelope; acceleration, velocity, position limits
- Minimum performance; thresholds
- Bandwidth; dynamic response
- Drive logic; relation between simulated aircraft motion and simulator motion.

Maximum performance is the motion "envelope" the device is capable of. These limitations are a consequence of limited travel and motive power. While they must be considered in any design, they bear no relationship to human perception because they must be avoided in practice.

Minimum performance (thresholds) are important compared to perception thresholds because they must be lower; otherwise, the platform feels unnatural (bumps, jerks, etc.). The thresholds of perception have been determined by many investigators. Hosman, et al, determined them on a transport training simulator (Ref. 2) and found the rotational threshold to be a function of frequency. More importantly, they determined the levels to be dependent on task loading. If the pilot was busy, his threshold level increased. Rough approximations to these levels are listed below:

- Sinusoidal rotation threshold:

$$\text{Acceleration} = 0.2\,\omega \text{ deg/sec}^2$$

$$\text{Velocity} = 0.2 \text{ deg/sec}$$

$$\text{Position} = \frac{0.2}{\omega} \text{ deg}$$

where ω is in radians per second.

- The sinusoidal translational acceleration threshold is independent of frequency and is about 0.01 g.

The capability of the transport training simulator with which the thresholds were determined obviously was sufficient. This device, however, incorporates hydrostatic bearings and, as such, has low friction and noise levels. For example, Hosman reports that for a heave drive resulting in a heaving sinusoidal acceleration of about 0.01 g, the heave noise level was about 0.002 g.

When a motion platform device is subject to non-linear phenomena such as friction, higher thresholds can be expected. The NASA Ames Research Center Flight Simulator for Advanced Aircraft (FSAA) is such a device. It uses screw jacks, rubber-faced tracks with toothed wheels, timing chains, etc., to transmit torque. Its threshold levels are reported in Ref. 15. They are higher than the rough approximation to Hosman's data. In spite of this, the FSAA is not widely described as a "rough machine." Occasional bumps and jerks can be felt when riding the FSAA and the platform structure can be rung with sharp control inputs. The point here is that the FSAA threshold levels in rotation of about two or three times the rough approximation to Hosman's data are <u>not</u> objectionable in practice. This is most likely due to the perception thresholds being higher for complex tasks such as landing an airplane. This supports Hosman's finding and suggests that <u>indifference</u> threshold levels are more important to simulation than are the minimum levels found in low task loading perceptual tests. The threshold or minimum performance required for effective motion simulation needs to be clarified.

To illustrate further the point that indifference thresholds are more important than perceptual thresholds the FSAA translational axes performance is cited. The lateral (sway) axis of the FSAA, like all the other axes, is configured as a velocity servosystem. This means that a step of input command voltage causes the actuator to reach a steady <u>velocity</u> after a short transient period. The value for the threshold given in Ref. 15 is $\pm$ 91 millimeters per second ($\pm$ 0.03 feet per second). This means that a 0.01 g step of side acceleration will integrate to this velocity after 1/10 second, an acceptably short time. According to Young (Ref. 8) the latency time for 0.01 g (time to detection) is about three seconds*. One is tempted to question the value of simulation to the 0.01 g level simply because of the long times required for detection. One is further tempted to speculate that the important design thresholds are closer to the acceleration values corresponding to the knee of the human latency curve where detection times are short. If this is so, then the design thresholds may exceed the minimum perceptual values by a factor of three or four times.

Bandwidth and dynamic response are terms used to describe the rapidity with which the motion platform responds. Bandwidth is the sinusoidal frequency where the response amplitude is 0.71 of the command value. The dynamic response can be described in many ways. A common method is to show that the sinusoidal response lies within a tolerance about the response of a specific model. Such a model is a simple second-order lag-type system that is described by a natural frequency and a damping ratio. Typical values for these are: a natural frequency of 3 Hertz and a damping ratio of 0.7. The tolerance is typically ± 20% of the phase function up to a frequency of 1 Hertz. A tolerance about the amplitude function may just as well be chosen and/or the frequency for matching extended.

Compared with human motion perception dynamics, typical platform dynamic response is faster. The upper 0.71 amplitude frequency of the simicircular canal's response is about 10 radians per second. Typical FSAA rotational bandwidths are between 20 and 28 radians per second. For translational motion (force) typical bandwidths of the FSAA are between 11 and 18 radians per second as compared to the 1.5 radians per second bandwidth of the utricles and the unknown (but probably higher) bandwidth of the kinesthetic senses.

If one were conducting perceptual tests, a requirement for motion bandwidths at least three or four times greater than those for the human receptor is reasonable. For piloted simulators, however, where the response of the pilot and aircraft combination is limited, it is still only necessary to provide a bandwidth of three or four times greater than that of the pilot/aircraft system. These values are rarely greater than aircraft

* Based on tests along the longitudinal (surge) axis.

characteristic frequencies such as those for the short period and roll subsidence, typically about 3 or 4 radians per second. It appears, therefore, that a motion bandwidth of about 12 radians per second is the minimum required.

Adams (Ref. 16) states that "for a single-axis control task, a general conclusion can be made that for these types of tasks, the servo drive characteristic should be equivalent to a linear second-order system with a natural frequency of 20 radians per second or higher."

This author (Ref. 12) has found from tests on the roll axis (single axis) that a bandwidth of 20 radians per second produces three-fourths of the performance improvement possible with a large (60 radians per second) bandwidth.

Digital computers perform their calculations in a finite time. A time delay results from this that is typically 3/2 of the frame time. What is important to simulation is that the total time delay from control movement to platform movement not exceed a specified value. Just what this value is remains open to question. Some recent test results obtained by A. M. Junker of the Air Force Aeromedical Laboratory suggest that a time delay of 80 milliseconds negates the effect of motion and that the delay should be even less. These results are for tracking-type experiments. If this is true, then the effective delay of a finite-bandwidth actuator and a computational delay should be about 0.08 second. When using actuators with a second-order lag response of 25 radians per second natural frequency and 0.7 damping ratio, a frame time of about 0.013 second is required. This results from an effective actuator delay (for sinusoidal inputs) of 0.06 second

$$0.06 + \frac{3}{2}\text{ (frame time)} = 0.08 \text{ second}$$

<u>Drive logic</u> is the array of computations that take simulated aircraft motions and use them in calculations of simulator motions. In its simplest form the operation is simply to multiply by unity. This makes the simulator motions equal to those of the simulated aircraft and, of course, the motion "fidelity" is also unity or the best possible.

Practically speaking this is never done. The simulator motions are scaled (multiplier is less than unity) and also "washed out" by functions that return the motion platform to a near-neutral position after a short time during which the simulator follows the simulated aircraft. When scaling and washout are used, as they must be, the motion fidelity is less than the best possible. The selection of motion drive logic is still an art because it is difficult to relate reduced motion to perceptual fidelity.

Usually the rotational motions are washed out to a level position by scaled washouts. The apparent forces at the pilot station of the simulated aircraft are used to drive the translational actuators of the platform, if any, through scaled washouts. The forces are also used to generate a slow rotation in pitch and roll so as to create the impression of steady longitudinal and lateral forces using components of the reaction to gravity.

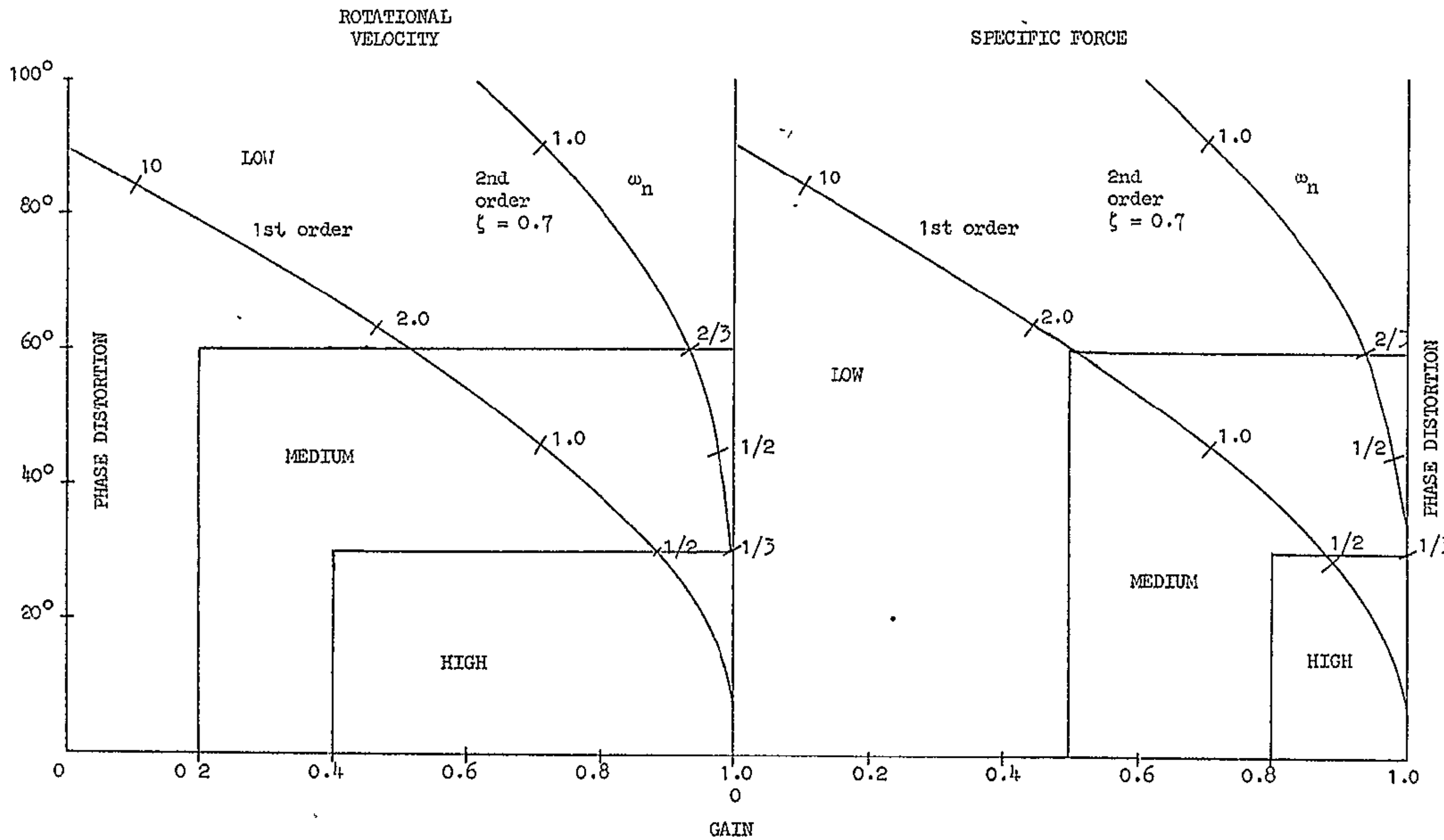
The net result is the following:

1) Fast rotational motions are "passed" while slower ones are not

2) Anomalous slow rotations are introduced to accomplish steady-state force simulation (longitudinal and side)

3) Fast normal force increments are passed, slower ones are not. Fast-acting longitudinal and side forces are passed if translational actuators on those axes are used. Slower acting forces on these axes are represented by tilting in the gravitational field.

In addition, washout forms may be linear or nonlinear, simple or complex. An attempt to relate perceptual fidelity to scaled washout is reported in Ref. 12. Two plots from this reference are given in Fig. 2-9. The first relates scaling and phase shift of the recovered angular velocity to fidelity regions delineated by the adjectives high, medium, and low. The notion here is that the scaling-phase shift property of the drive logic affects the fidelity in terms of pilot behavior. The angular velocity plot is for a frequency of 1 radian per second, the frequency at which the



HIGH: Motion sensations are close to those of visual flight
MEDIUM: Motion sensation differences are noticeable but not objectionable
LOW: Differences are noticeable and objectionable, loss of performance, disorientation

Figure 2-9: Motion Fidelity Versus Phase Distortion and Gain at 1 rad/sec semicircular canal response is best. The plot is shown in Fig. 2-9 together with curves for a first- and second-order linear washout.

A second plot is also given relating fidelity to the force recovery also at a frequency of 1 radian per second. This plot could be relevant to the normal axis where a washout is necessary to restrain the simulator for steady normal acceleration. The force plot, however, does not cover the whole picture in the case of force recovery fidelity. This is because, in the case of longitudinal and side force recovery, anomalous tilt rates are produced to achieve slow force recovery and these "false" angular rates are not treated by the criteria advanced. Attempts to define perceptual fidelity are being carried out by Young, et al, (Ref. 13) through the comparison of the motions perceived in the simulator and the simulated aircraft. This procedure should lead to a better knowledge of perceptual fidelity since use is being made of the present knowledge of human sensory models.

Practical drive logic must include scaling and washouts that appreciably "cut in" on human motion perception. Referring to the fidelity plots of Fig. 2-9, we see that second-order washouts with scaling of 0.5 and washout frequencies of 2/3 radians per second border on the low/medium fidelity boundary. Values such as these, however, are commonly used in simulator motion drives.

In summary, it can be said that the motion drive logic of most simulators must seriously reduce the "passed" motions in a range of frequencies where humans are still quite sensitive. Commonly-used washout break frequencies are 1/2 to 2/3 radians per second compared to the semicircular canal response from 10 radians per second down to 0.1 radian per second.

2.2.3 Control Loaders

Control loaders are the force actuators that are used to impart "feel" to the control manipulators. They are configured two ways generally. In the first, a strain gauge transducer near the grip is used to drive an actuator that physically moves the manipulator. In a sense the manipulator can be moved only by means of this actuator. The strain gauge output is introduced to a computer where the equations describing the position of the manipulator as a function of the applied force are solved. The manipulator position is then fed to the actuator. In this way a variety of force characteristics may be simulated by the same hardware.

The second method uses an electro-hydraulic actuator that is configured as a force servo, i.e., a command voltage input results in a force being applied to the manipulator. Naturally, if it were not restrained by the hand under such conditions, for example, it would move to its stop. In the latter mechanization, position and velocity transducers driven by the manipulator send their signals to a computer where equations for the force as a function of displacement and velocity are solved. The force computer is then used to drive the force servo.

Both kinds of control loaders can be found in simulators and each accomplishes its function but with differing performance.

The simulation of control feel is important to simulation for the same reason it is important to flight. Aircraft manufacturers have long recognized that the control feel is an important part of the overall handling qualities built into the aircraft. Care is exercised to get the feel right and aircraft specifications reflect this. The loader concepts described generally do a good job provided the actuator's bandwidth is high. Whereas the position servo bandwidths approach 20 Hertz, the force servo bandwidths approach acoustical frequencies. This is necessary in order to achieve the fast response required to simulate nonlinearities such as friction and dead zones. Because of this, control feel is difficult to model, and control loaders are difficult to tie in to digital computers. An example of control loader implementation is given in Ref. 17 in which the effects of digital computing lags are documented. When a loader system has been successfully implemented, the fidelity associated with force simulation is very high. Subjectively, differences between aircraft and simulator cannot be detected* and the force differences can easily be kept below 1 to 2 ounces.

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* Pilots sometimes complain that the stick forces in a simulator are noticeably different during high g maneuvers although they may closely match the aircraft's forces. The inference is that this is an illusion caused by the lack of high g forces acting on the rest of the body in the simulator.

2.2.4 Sound Generators

The technology associated with music systems has produced hardware that achieves a high sound fidelity. With the advent of multi-channel systems, the complex wave patterns that produce the richness of sound can be synthesized.

Although exotic sound systems could be applied to simulation, they usually are not. The richness and depth of sound produced in the cockpit apparently need not be duplicated in the simulator in order to provide essential aural information. For example, the fidelity of compressor whine need not be high in order to give a compressor speed cue.

Sound generation equipment for simulation purposes, therefore, is relatively simple and straightforward. White noise generators create basic noise that is filtered according to the general pitch desired. These signals are then multiplied by steady or periodic waves to produce aerodynamic hiss, runway or exhaust rumble, and compressor whine. Periodic multiplication produces rotor or propeller sounds depending on the frequency of the periodic multiplier. Two speakers are used in the cockpit so that some stereo sound effect is produced that would alert the pilot as to a specific engine failure.

Sound simulation is important because timely failure detection is often performed using sound. When cockpit sound levels are high, additional strain on the crew is produced that results in more workload and difficulty in communicating. These factors are sometimes the central issues behind a simulation. In some instances, the sound creates a clue to an important parameter such as rotor speed and can be used by the pilot to help to regulate it.

2.3 DESIGN OF SIMULATOR EXPERIMENTS

Flight simulation is, after all, the art of mimicking flight. It is done to facilitate either pilot training or the study of a flight problem. In this respect, simulation is much like flight test. Three ingredients are always identifiable: the selection of a flight condition, the definition of maneuvers and tasks to be performed starting at that condition, and the evaluation of the results according to a criterion. The effect of each on the experimental design follows.

Selection of Flight Conditions. Obviously this factor influences the size of the experiment since a finite time is allocated to each condition. The sequence in which the conditions are presented may affect the results as can the time allotted to each. For example, if insufficient time is allocated to a difficult task, the training effect may contaminate the results. This factor hardly affects data acquisition requirements although it does affect the software required to initialize the simulation.

Definition of Maneuvers/Tasks. At each flight condition, the crew members are required to manipulate the aircraft and subsystems. Each phase of the maneuver must be defined as well as the operation of all subsystems. This portion of the plan should enhance repeatability and lead to easy definitions of the evaluation criteria.

Evaluation. During and/or after the performance of each maneuver phase, a method of evaluating the results is needed. The measures may be subjective in nature such as the Cooper-Harper Pilot Rating or equivalent or objective. Objective measures may be simple or complex. A major simulation benefit compared to flight test is that every bit of data is located somewhere in the computer complex and may be retrieved using the proper software and peripherals. The data "extraction" may be simple, requiring no further processing except scale adjustment. On the other hand, extensive on-line or post-test data processing may be required if performance measures are sought. A performance measure is a mathematical function that relates the quality of the task performed using selected data from the test. These measures may range from simple statistics taken at discrete "windows" in time to complex functions expressing performance in the time or frequency domain. Algorithms performing fast Fourier analysis are easily implemented on today's digital computers and can be tailored to perform off-line assessments as desired or on-line hardware diagnostic analyses. No special requirements exist for such analyses except enough mass-storage memory.

It is perfectly feasible today to store on mass-storage devices every bit of data generated during a simulation. Generally, tradeoffs must be made by the user between run time, number of variables, and sample interval. Data generated months ago may be retrieved and used as inputs for off-line analyses of the users' choice. It is even possible to reconstruct missing or unrecorded data through the use of the original algorithms used in the simulation. For example, if it were desired to record every data bit in a long series of simulations, without an excessive memory requirement, the digitized control inputs need only be recorded and later played through the original program.

In spite of the ability to automate most data acquisition functions, the picture of the using engineers stooped over a strip chart recorder during simulation periods will probably never disappear. The "first look" and monitoring function value of the user can hardly be underestimated. This function, however, has been modernized through the use of graphic displays. By interfacing a graphics terminal to the computer complex, the ability of the user to monitor and acquire information is perhaps increased by an order of magnitude compared with that using traditional strip chart recorders, plotters, and alphanumeric displays. The reason for this is the ability to program a dynamic status-and-results display using the geometrical concepts that were used to formulate the test. For example, a three-dimensional graphics display of a helicopter carrying an external sling load is extremely valuable in rapidly assessing the dynamic status of the combination.

In summary, the important functions and qualities of a good experimental design follow:

- Clearly outlines the research questions.
- Focusses the simulation tool on these questions.
- Outlines pretest, test, and post-test procedures including all checkout phases.
- Defines evaluation criteria in terms similar to those used to define the tasks and maneuvers.
- Includes a validation phase.

- Assigns just enough time and samples to give statistically significant results.
- Assumes realistic simulator utilization.
- Is based on some theoretical premise.

The reader is again referred to the simulation example cited in Section 1.4.1 for insights into experimental design.

SECTION 3

SUMMARY AND OUTLOOK FOR THE FUTURE

3.1 SUMMARY OF STATE OF SIMULATOR TECHNOLOGY

3.1.1 Philosophical Evaluation of Simulation Validity

When validity of current simulation is judged in terms of its usefulness, it is high. The wide use of the tool by Government and Industry for both engineering development and training is obvious. In another sense, the tool is useful because it is so cost effective compared with other methods of achieving the same result.

To bring the various design groups together in examining their aircraft product as a system is no small task, but yet it happens routinely in engineering simulations.

Philosophically speaking, the greatest benefit of simulation is the discipline of thought it creates. To create a simulation, one must expend a great deal of thought defining the various systems and their interactions. The result is a view and knowledge of the aircraft that is unified and applied. It is the first place the designer can verify his concepts.

When one looks at the technology itself, great gaps appear and the validity of some components is obviously low. The drivers of the technology are those who accept "face validity." When the required quality cannot be achieved with today's hardware, efforts at validation are mounted. The rather esoteric nature of simulation validation, however, is verified by the small number of such efforts reported in the literature.

In the area of computers, the validity is considered highest. Today's computers are able to solve in a timely fashion the equations representing the mechanics of flight associated with today's aircraft. The view is offered that the modeling art and computing go hand-in-hand and are therefore never very far apart. Remember that early simulations were computer simulations only, performed in non-real time. As this art developed, the computer technology followed perhaps being partially driven by it.

The validity of cockpits is also high. A realistic replica of a modern aircraft cockpit is relatively straightforward to build. Electronic equipment is available that can readily interface computers with the variety of instruments and controls that are available.

The validity of visual systems is considered to be medium. Today's technology is characterized by either narrow field-of-view low resolution systems that are combined in a mosaic to extend the field or hybrid systems incorporating several concepts, e.g., point-light and television projection. The range of luminance levels and contrast that can be simulated is a fraction of what exists in nature or what can be seen by the normal observer. Also the resolution of these systems is, at best, about 3 to 6 arc-minutes as opposed to the 1 arc-minute normal resolution of the eye.

The reason that visual systems work as well as they do is because their use is limited to tasks that do not require sophisticated visual hardware.

Motion systems have not advanced much in the last decade. Besides some clever innovations such as the six-post concepts, no new technological advances have appeared on this score. The fact that most motion systems in use today have performance levels requiring large attenuation in apparent motion parameters suggests that their validity is low. Only the large systems offer a fidelity that is considered medium to high. From another viewpoint they all probably contribute to face validity of the total simulation. The "g" seat concepts are as yet not completely developed to where their validity may be determined.

3.1.2 Areas of Deficient Fidelity

The areas of deficient fidelity are those where high pilot/aircraft performance levels are sought. These include:

- The landing maneuvers. Below an altitude of about 15 meters (50 feet), the simulation of landing including touchdown and rollout cannot be performed with the high fidelity associated with no training effects. Deficiencies in modeling the aircraft close to the ground, visual system effects, and motion attenuation may all contribute to the problem.

- Terrain flight with helicopters. When vigorously maneuvering close to the ground to maintain course, helicopter pilots require fields of view, scene details, and dynamic performance not available from current visual systems.

- Formation flight. For perhaps the same reasons that high-fidelity landing simulation cannot be performed at this time, formation flight cannot be simulated with resulting realistic pilot workload and performance.

In addition to the areas of deficient validity, a number of unresolved questions exist relating to simulation technology, e.g., design of hardware and establishment of requirements. They are:

- What are appropriate subjective and objective fidelity measures that can be used to describe the quality of simulation for both engineering development and training?

- What scene details are required of a computer-generated image system in order to accomplish specified flight maneuvers and what are their optical properties?

- What fields of view are required in order to accomplish specified maneuvers?

- What is the effect on fidelity of computational time delays and actuator dynamics?

- What is the effect on fidelity of motion drive logic (washout)?

- What is the training value of platform motion devices?

- What is the training value of any element of a simulation?
- What are appropriate criteria for specifying the accuracy of mathematical models?
- What are appropriate and simplified methods for handling the frame time problem?
- Can effective color visual simulation be accomplished using only two basic colors?

3.2 FUTURE PROSPECTS

The anticipated peace-time environment highlighted by economic pressures and energy constraints will surely stimulate research and development of simulation. The military services are seeking full mission simulators for training. The airlines desire to increase the fidelity of their trainers to where all training can be conducted in simulators. The Air Force and Navy presently own and operate large research and development simulators and the Army is developing one.

Industry users continue to update and improve their facilities to support their new aircraft programs and the simulation equipment manufacturers continue in their development efforts using as a basis the related technologies of computers, lasers, and electronics.

Several trends can be seen that will impact on future developments. In computation, current desires for helicopter and V/STOL advances presses the computer technology. Requirements for many computations corresponding to systems of many degrees of freedom (rotors, fans) will require short frame times per computation in order to perform the many computations required and still keep the total frame time within reasonable limits of 100 milliseconds or less. The industry is responding (for other reasons) with advances in architectural concepts. Parallel processing, although presently cumbersome to implement, shows great promise of being able to handle these gigantic programs. A large host computer of the IBM 370 or CDC 7600 class appears to meet these requirements now.

The advent of microprocessor technology in 1975 holds the promise for distributed processing. In simulation, dedicated microcomputers will be made integral with the visual and motion hardware elements they drive leaving the host computer free to compute the equations of interest.

Perhaps the most dramatic advances will occur in the area of visual systems. The Air Force, in seeking to satisfy its future training requirements, will develop full-mission simulators that include full fields of view, color, and resolution of better than 3 arc-minutes. Computer-generated imagery will provide the image basis for these displays forcing the camera/model image generation technique into obsolescence sometime after 1985.

Several candidate display concepts are under development that will allow full visual simulation. The mosaic of pancake windows will continue to be improved. The laser scanning display is an obvious application of that concept that will find its way into the simulation industry. The light-emitting diode (LED) display, however, holds the real promise for full visual simulation including color. Solid-state display segments are already developed for experimental use in television. The fact that backing from commercial interests is available for the solid-state display, whereas it is not for the other concepts, makes it the most probable one ultimately to be part of a full visual system. The requirement for control of the many thousands of LED's points to computers and computer-generated imagery as the most probable means of image generation. It is expected that the full visual system will be developed by 1990.

No dramatic improvements in motion simulation hardware are expected, except that the "g" seat will most likely replace, or at least supplement, the existing motion platform hardware. Present research trends, when taken optimistically, suggest that the requirements for motion cueing will be understood by about 1990. The record on this score for the past thirty years does not support this premise. If the platform technology should advance to the point where some effects of drive logic were known, and the "g" seat were to be well developed, the combination of these devices and full visual simulation would yield hardware that leaves little to be desired.

With such technology, full mission simulation would become practicality, and the need for research on validation and visual/motion cue effects would be reduced. The only problem that would remain is the one that will be with us forever: the intuitive modeling of new physical systems.

In the following paragraphs, some crystal-ball gazing is done in order to solidify some of the concepts advanced and also to give the readers some incentive to stimulate their own visions.

The period is the 1990 decade and the century is soon to turn. Simulation has become not only a routine part of aircrew training and engineering but it has also penetrated driving schools, and schools for trainmen, ship crews, heavy equipment operators, tank drivers, and the racing establishment. It has finally found its way into amusement parks and into fantasy centers where a variety of illusions impractical to create in everyday life are produced in safety and for a price.

A typical system contains a single-unit visual module that is used to stimulate visually a single individual. Its display is generated by approximately three million LED units controlled by a parallel processor interfaced to an image generation computer. The units are mounted on the interior of a 3 meter (10 foot) diameter sphere surrounding the seated subject who wears a helmet containing eye polarizers, trackers, and motion sensors. The field of view is complete and in two or three colors. The minimum spot size is one-half arc-minute and stereopsis may be produced by activating the eye plate polarizers and the helmet motion sensors. The luminance range is nearly complete from 0.0001 millilamberts (dark night) to 1000 millilamberts (a moderately bright sunny day). No apparent image blur exists for moderate slew rates.

The image may be synthesized from photographs or manually selected from a catalog of objects. Specific markings such as signs and head-up display (HUD) elements are inserted on-line by means of a graphics terminal format using the entire display.

The seat is a "g" seat and is mounted atop a modest platform motion device. The full spectrum of movements possible is available although attenuated, with the exception of very low frequency normal accelerations. Magnetic limb loaders are available for some high g maneuvers. Aural and olfactory simulation is available.

The visual/motion unit is a part of a complex that is tied to a central computing facility many miles away that is tied in turn to other facilities in the country. These facilities interface not only to Government simulation computers but also to private facilities generating cultural event programs. These consist of wide-angle views selected by the observer of cultural events (plays, etc.) as well as programs from the visual media.

Variations of the visual/motion module include provisions for other seats, window frames, and panel and control layout.

The simulation capability of the device is unlimited compared with the perennial modeling limitation. The question now is turned from "how do we stimulate four of the five senses?" to "what do we wish to stimulate them with?"

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